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WATER REUSE AND WASTEWATER MINIMIZATION OF DAIRY INDUSTRY USING WATER PINCH TECHNOLOGY

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Abstract

Water is key element, which plays a vital role for all systems involved in the world. The process industries like chemicals, petrochemicals, petroleum refining, pharmaceuticals, pulp and papers, metals and minerals; steam electric power and certain food consumer products industries are major water consuming and wastewater discharging industries. Even though many conventional methods used for water reuse project, water-pinch technology (WPT) does not replace conventional water-reuse principles. Instead of it provides a means first to identify a goal for water-reuse and then to pinpoint key water-reuse opportunities that will allow us to design a water-using network to approach the minimum flow rate targets as closely as possible. The dairy industry-Hatsun Agro Products Ltd., Karumapuram Village, Salem Dist., has been analyzed for determining the minimum fresh water flow rate to water reuse and to minimize the wastewater generation. It has been done by a PC based software tool called 'Water Design'. The LP model has also been developed to achieve the minimum water flow rate. The study shown that the regeneration reuse by single contaminant can be effectively minimized the freshwater flow rate by 54 %.

Key words: Water reuse, Wastewater minimization, water pinch technology, Linear Programming.

1. Introduction

Water constitutes one of the major streams in the utility system and in the process industry. The Process industries like chemicals, petrochemicals, petroleum refining, pharmaceuticals, pulp and paper, metals and minerals, steam electric power and certain food consumer products industries are major water consuming and wastewater discharging industries. Therefore identification of sources of water supply, their conservation and optimal utilization is of utmost importance. Wastewater is generated in the different processes and utility systems, creating a stream, which eventually needs to be treated. However, industrial water reuse and wastewater minimization are common activities in the process plants nowadays. Process plants are now taking more serious measurement towards the minimization of fresh water consumption. Such measures result in a reduced effluent generation and reduced treatment cost. Hence, this issue of systematic design of water recovery network and wastewater minimization has gain much interests in research community, especially in past 5-10 years. 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 approach. The former technique normally divides the design problem into a two-step procedure, i.e targeting

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and design. The main advantage of this approach is that the minimum utility (water) consumption was 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.

In India, totally 96 units of dairy industries are located in the states of Uttar Pradesh, Maharastra, Gujarat, Tamilnadu, and Rajasthan. The annual processing/production capacity of total 96 units are 5.5×10.6^6 kilolitres. Dairy plants are found all over the world, but because their sizes and the types of manufactured products very tremendously. Hatsun Agro Products Ltd., is one of the dairy giants in our country, with much milk chilling, processing and packaging units. The brand names like Komatha, Arokya and Arun etc. in Tamilnadu are very popular among the varied milk products like pasteurized whole milk. Butter, Khoa, Ghee, Ice cream etc. It is located in Karumapuram Village of Salem district in Salem – Attur main road at 10 km east of Salem town.

The Hatsun has a milk-processing unit with daily processing capacity at 500 KLD of milk in Karumapuram Village. The products envisaged for production are NFD milk WD milk, Butter or ghee, Buttermilk and UHT milk and the by products of Hatsun Agro product Ltd., are butter / ghee, butter milk and UHT milk.

In the processing of milk the various processing involved such as thermization, pasteurization, Homogenization etc. The water usage pattern and characteristics of wastewater from various sources of dairy industry is shown in the table 1 and 2 respectively.

Table - 1: Water usage pattern

S.No	Area and Purpose of Use	Quantity Kl/Day
1.	Boiler (Make –up)	10
2.	Cooling Tower (*Make –up)	70
3.	CIP Cleaning	40
4.	Washings and Cleanings	60
5.	Domestic Requirements	10
Total		190

Table – 2: Characteristics of wastewater from various sources

Characteristics	Source					
	Process Hall	Packing Machine Hall	Air Compressor side	Cold Room	Cold Room Leak Cutting	Tub Washing
pH	4.9	6.5	5.6	6.3	6.2	6.5
Suspended Solids	900	375	486	742	160	310
COD	6692	4237	2436	3658	3304	2210
BOD_5	2890	1989	605	1320	1010	700
Oil & Grease	225	560	240	580	340	280
Alkalinity	225	625	300	400	300	400

(All results except pH are expressed in mg/1)

2. Methodology

Water Pinch Technology (WPT)

Process integration (PI) is a system engineering methodology used to evaluate the global energy saving potential of a process and also the overall potential for water and wastewater minimization. Pinch technology provides systematic methodology for energy savings in process and total site, based on thermodynamic principle. The development of pinch technology started in the late 1970's and it was initially developed for the optimization of heat exchanger networks (heat pinch) by Linnhoff (1983). The fundamental theoretical formulations for the application of pinch analysis principle to water problems where pioneered by El-halwagi and coworkers (1989, 1990, 1997) and by Smith and coworkers (Wang and Smith; 1994 a, b; 1995). The pinch technology is the branch of process integration. This process integration includes the concepts of thermal pinch technology, mass integration through pinch technology, water pinch technology and mathematical optimization in a stand-alone manner. Even the water pinch technology as a sub set of mass integration. We consider the interactions of rich stream (i.e. water using operation) and lean utilities (i.e. water streams).

The motto of water pinch technology is like "the best way to minimize pollution is not to produce it". Therefore find in-process solutions, before focusing on the 'end of pipe' Water pinch is a systematic technique for analyzing water networks and identifying projects to increase the efficient use of water in industrial processes. Advance applications make use of advanced algorithms to identify and optimize best water reuse, regeneration (partial treatment of process water that allows its reuse), and effluent treatment opportunities.

Wang and Smith (1994) introducing a water pinch method for targeting maximum water reuse, a single contaminant problems based on the construction of composite curve of the limiting water profiles for each operation. Water pinch technology was divided into three tasks such as analysis, synthesis and Retrofit.

Man and Liu (1999) introduced the method of superstructure to formulate the water network as linear programming (LP) and non - linear programming (NLP) for single and multiple contaminants systems respectively. Here, applying the LP to determine the minimum freshwater flow rate for water using operations involving a single key contaminant for dairy industry. This application utilizes the transshipment model that represents the transportation of the contaminant mass from water using operations to water streams.

3. Results and Discussion

The results presents an effective engineering approach to water reuse and wastewater minimization in the dairy industry (Hatsun Agro Product Ltd), where water reuse may be limited by single contaminant system and use the parameter of COD as a water quality parameter.

Based on the water usage and characteristics of wastewater generated the limiting process data has been shown Table - 3.

Table – 3: Limiting process data for dairy industry

Operation No.	Limiting inlet concentration (ppm) $C_{i,in}^{\lim}$	Limiting outlet concentration (ppm) $C_{i,out}^{\lim}$	Total mass load transferred $\Delta m_{i,tot}$ (kg/hr)
1	300	6692	42.70
2	2950	4237	1.07
3	0	2436	7.11
4	1200	3658	4.10
5	2150	3304	0.48
6	1950	2210	0.65

Using the water pinch technology tool for the water reuse and wastewater minimization for the Hatsun dairy industry is analyzed by using the following tools

Limiting Water Profile

The limiting concentrations ($C_{i,in}^{\lim}$ and $C_{i,out}^{\lim}$) may represent the highest possible concentration that still allows mass transfer from the contaminant rich process stream to the water stream to occur. The figure representing the water using operation as a true contaminant rich process stream

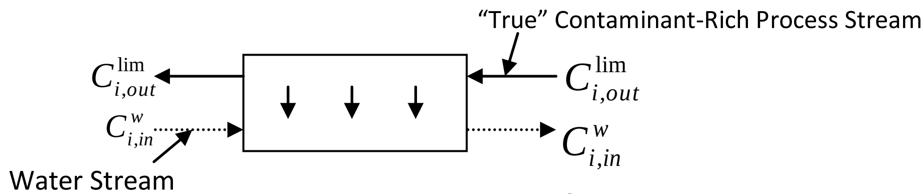


Fig. 1 Representation of water using operation

With these constraints the limiting water flow rate for operation i can be calculated by

$$f_i^{\lim}(te/hr) = \frac{\Delta_{mi,tot}(kg/hr)}{[C_{i,out}^{\lim} - C_{i,in}^{\lim}](ppm)} \times 10^3 \qquad \text{...... (1)}$$

Table – 4: Modified limiting process data with limiting water flow rate

Operation No.	Limiting inlet concentration (ppm) $C_{i,in}^{\lim}$	Limiting outlet concentration (ppm) $C_{i,out}^{\lim}$	Total mass load transferred Δ $m_{i,tot}$ (kg/hr)	Limiting water flow rate $f_i^{\lim}(te/hr)$
1	300	6692	42.70	6.68
2	2950	4237	1.07	0.83
3	0	2436	7.11	2.92
4	1200	3658	4.10	1.67
5	2150	3304	0.48	0.42
6	1950	2210	0.65	2.5

Once if the minimum freshwater flow rate is found for each water using operation, the total minimum fresh water flow rate for the single contaminant problem without water reuse is simply the sum of the minimum fresh water flow rates required by each operation

$$f_{i,\min}(te/hr) = \frac{\Delta_{mi,tot}(kg/hr)}{C_{i,out}^{\lim}(ppm)} \times 10^3 \qquad \text{...... (2)}$$

Table – 5: Minimum fresh water flow rate without reuse

Process No.	Limiting outlet concentration (ppm) $C_{i,out}^{\lim}$	Total mass load transferred Δ $m_{i,tot}$ (kg/hr)	Minimum fresh water flow rate $f_{i,\min}$
1	6692	42.7	6.38
2	4237	1.07	2.53
3	2436	7.11	2.92
4	3658	4.10	1.12
5	3304	0.48	0.15
6	2210	0.65	0.29

To determine the overall outlet concentration of contaminant in the water stream for this entire problem

$$C_{out}^{w}(ppm) = \frac{\sum_{i} \Delta_{mi,tot}(kg/hr)}{f_{\min}(te/hr)} \times 10^{3} \qquad \text{..... (3)}$$

From equation (2), the minimum freshwater flow rate has been calculated for each operation without reuse of water, and the total value of minimum freshwater flow rate is estimated as 13.39 te/hr. Also from the equation (3), the overall outlet concentration of the contaminant has been calculated without reuse, and the value of overall outlet concentration of the contaminant is 4190.44 ppm.

Concentration Composite Curve

The minimum fresh water flow rate in calculated from the following equation.

$$f_{\min}(te/hr) = \frac{\Delta m_{\ pinch}(kg/hr)}{C_{pinch}^{*}(ppm)} \times 10^{3} \qquad \text{..... (4)}$$

According to the Table – 5, the overall minimum fresh water flow rate for the system of dairy industry without water reuse is 13.39 te/hr., obviously process integration with water reuse significantly reduces the freshwater and waste water volumes.

Thus, the concentration composite curve shows the result for minimum freshwater flow rate and overall outlet concentration 9.94 te/hr and 5645.86 pm respectively, which was obtained from the water design software tool. Also this concentration composite curve locates the freshwater pinch concentration point at 2436 ppm in the composite curve.

The results show that the overall minimum freshwater flow rate with reuse, which was obtained from concentration composite, is less than the tabulated value without reuse. Therefore the process integration (concentration composite curve) with water reuse reduced the freshwater volume about 26 %, which was more economical.

Concentration Interval Diagram (CID)

The CID provides all necessary information to create a water using network, but it avoids the construction of concentration composite curve, but wastewater minimization that is not readily seen in the tabular method.

The flow rate was evaluated at each concentration interval boundary from cumulative mass load is calculated by using

$$f_{k}(te/hr) = \frac{\Delta m_{k}(kg/hr)}{C_{h}^{*}(ppm)} \times 10^{3} \quad \text{...... (5)}$$

In this approach, the fresh water pinch occurs at the point with the greatest water supply flow rate. The cumulative mass load and flow rate also has been obtained from the Table - 6 of the water design software tool. The Table - 6 represents the final CID, and it shows the minimum fresh water flow rate as 9.94 te/hr was well below the tabulated value that was water without reuse of 13.39 te/hr. The CID gives the same results as in the concentration composite curve. Also the Table - 7 represents the final CID for full regeneration flow rate.

Water Using Network Design

Regeneration reuse

In full regeneration all streams enter the regeneration process at a regeneration concentration, C_{regen}, and leave at a lower outlet concentration C_o, after contaminant removal. The flow rates of fresh water and regenerated water are identical and these flow rates are less in simple cases, when regenerating the wastewater stream at the freshwater pinch concentration that is

$$C_{regen} = C_{pinch}$$

The mass load of contaminant regeneration transferred to the fresh water stream prior to regeneration was

$$\Delta\, m_{regen} = f_{\min}\, C_{Pinch} \qquad \text{...... (6)}$$

The total mass loads of contaminant transfer prior to the freshwater pinch was

$\Delta_{m\ pinch} = f_{min} C_{pinch} + f_{min}(C_{pinch} - C_o)$ ...... (7)

Minimum freshwater flow rate for simple full regeneration

$$f_{min}(te/hr) = \frac{\Delta_{m\ pinch}(kg/hr)}{(2C_{pinch} - C_0)\,ppm} \times 10^3 \quad ...... (8)$$

Outlet concentration of the regenerated water stream or the outlet concentration of the water supply line

$$C_{out}(ppm) = C_{pinch}(ppm) + \frac{[\Delta m_{tot} - \Delta m_{pinch}](kg/hr)}{f_{min}\,(te/hr)} \times 10^3 \quad .... (9)$$

The minimum freshwater flow rate and outlet concentration for full regeneration reuse have been obtained from equation (8) and (9). The results of minimum freshwater flow rate f_{min} = f_{regen} = 6.15 te/hr and outlet concentration C_{out} = 6692.00 ppm. In full regeneration reuse concentration composite curve and CID, the minimum freshwater flow rate f_{min} = f_{regen} = 6.15 te/hr and outlet concentration C_{out} = 6692.00 ppm.

Preliminary Block Diagram

The preliminary block diagram has been constructed using water design software tool and the minimum fresh water flow rate also has been obtained by using the limiting process data for the dairy. The preliminary block diagram and network evaluation for optimum water using network have been shown in the Fig - 4 and Fig - 5 respectively.

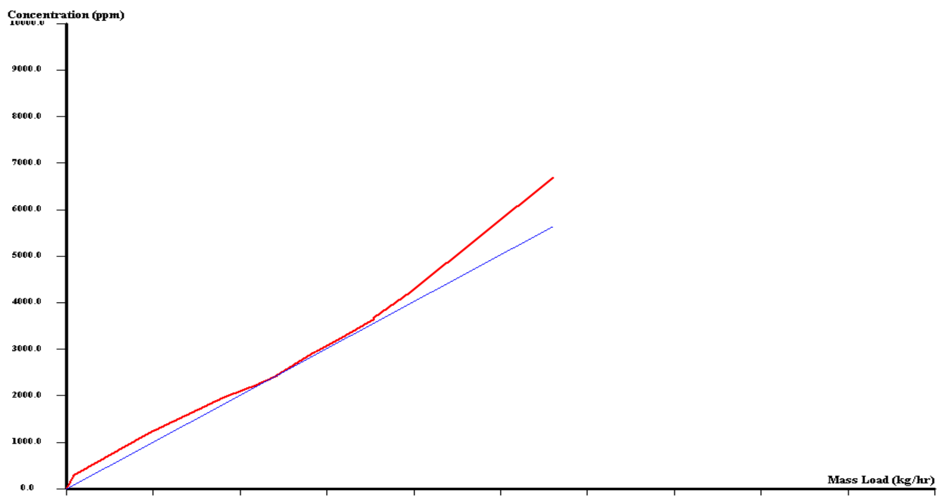


Fig – 2: Concentration composite curve with water supply and composite water supply line

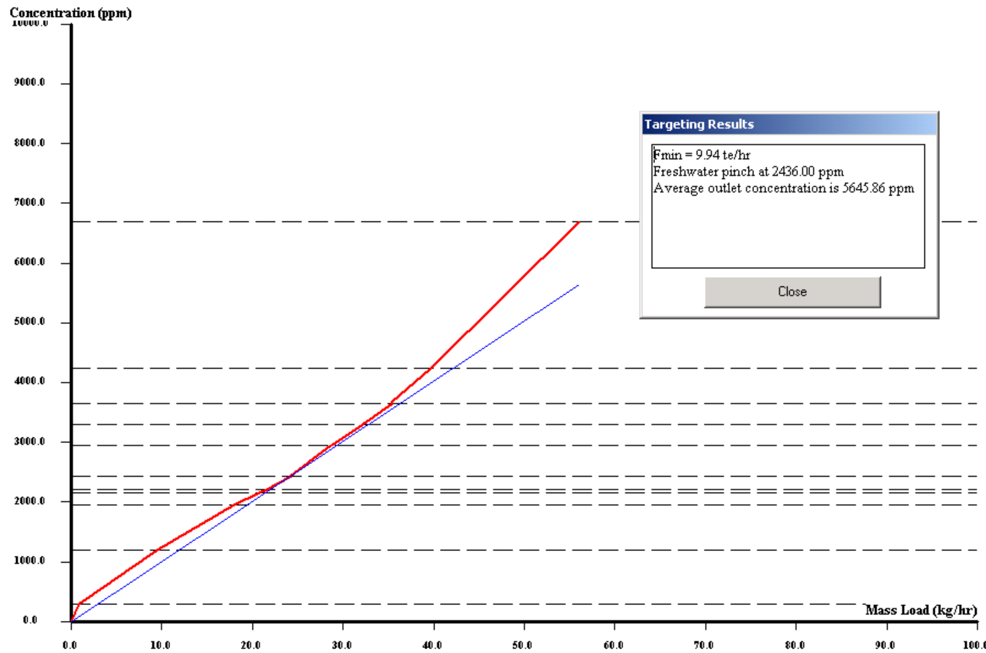
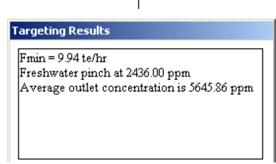


Fig – 3: Concentration composite curve with water supply, composite water supply line and concentration boundary interval

Table – 6: Final composite interval diagram (CID) with reuse

Concentration (ppm)	Operation 1 6.68 te/hr	Operation 2 0.83 te/hr	Operation 3 2.92 te/hr	Operation 4 1.67 te/hr	Operation 5 0.42 te/hr	Operation 6 2.50 te/hr	Mass Load (kg/hr)	Cumulative Mass Load (kg/hr)	Flowrate (te/hr)
0.00								0.00	0.00
							0.88		
300.00								0.88	2.92
							8.64		
1200.00								9.51	7.93
							8.45		
1950.00								17.96	9.21
							2.75		
2150.00								20.72	9.64
							0.85		
2210.00								21.57	9.76
							2.64		
2436.00								**24.21**	**9.94**
							4.50		
2950.00								28.71	9.73
							3.40		
3304.00								32.11	9.72
							3.25		
3658.00								35.36	9.67
							4.35		
4237.00								39.71	9.37
							16.40		
6692.00								56.11	8.38



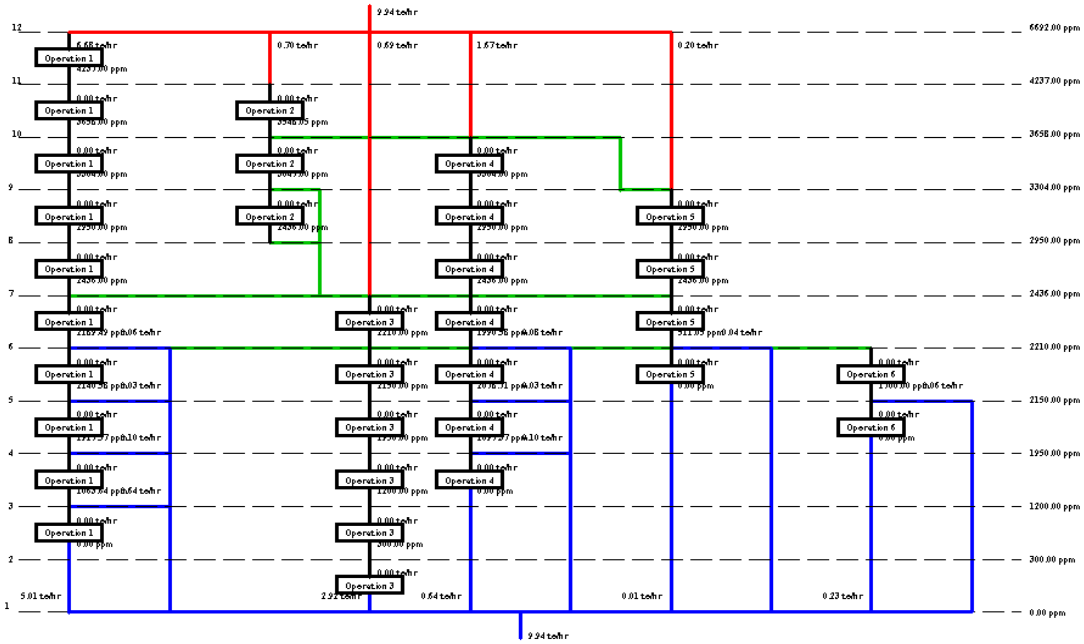


Fig. 4: Preliminary block diagram

Blue line represents fresh water

Green line represents water reuse

Red line represents wastewater stream

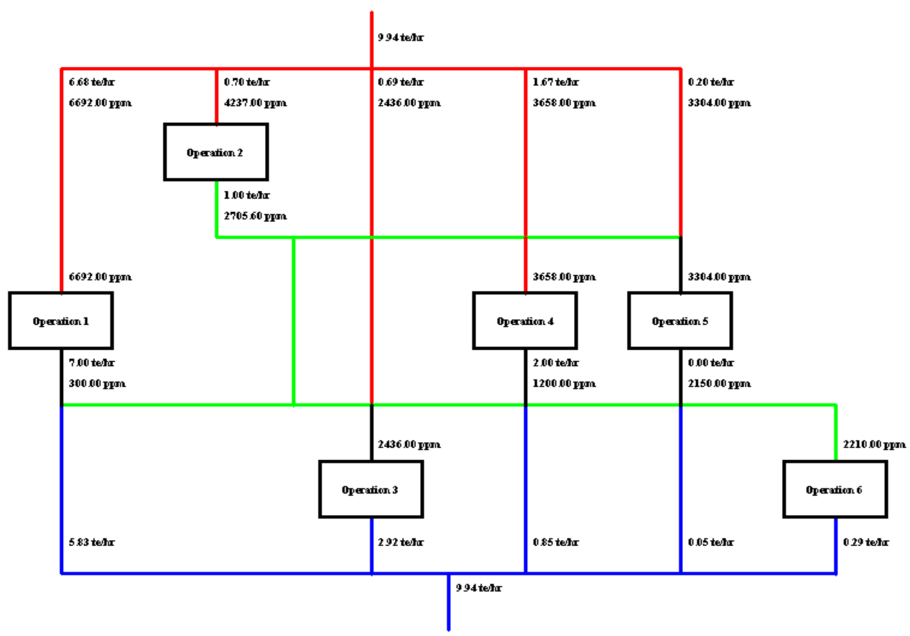


Fig. 5: Optimum Water Using Network Evaluation

Blue line represents fresh water

Green line represents water reuse

Red line represents wastewater stream

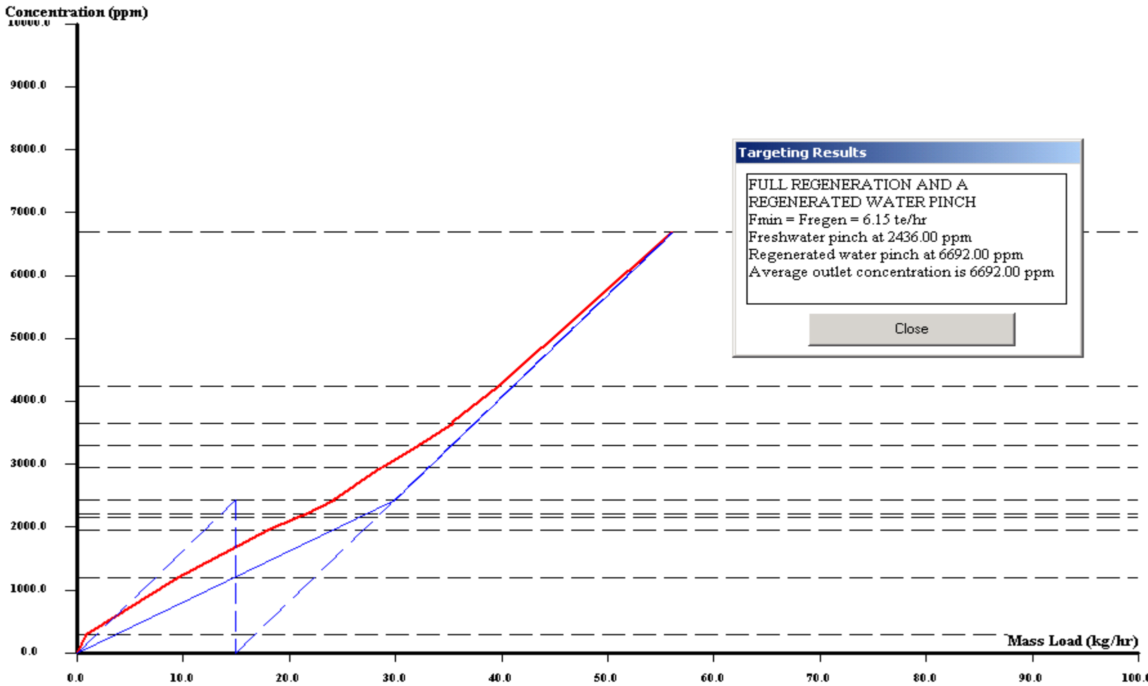


Fig. 6: Concentration composite curve and water supply lines with full regeneration reuse

Table – 7: CID with full regeneration reuse

Concentration (ppm)	Operation 1 6.68 te/hr	Operation 2 0.83 te/hr	Operation 3 2.92 te/hr	Operation 4 1.67 te/hr	Operation 5 0.42 te/hr	Operation 6 2.50 te/hr	Mass Load (kg/hr)	Cumulative Mass Load (kg/hr)	Flowrate (te/hr)	Full Regeneration Flowrate (te/hr)
0.00								0.00	0.00	
							0.88			
300.00								0.88	2.92	
							8.64			
1200.00								9.51	7.93	
							8.45			
1950.00								17.96	9.21	
							2.75			
2150.00								20.72	9.64	
							0.85			
2210.00								21.57	9.76	
							2.64			
2436.00								**24.21**	**9.94**	4.97
							4.50			
2950.00								28.71	9.73	5.33
							3.40			
3304.00								32.11	9.72	5.59
							3.25			
3658.00								35.36	9.67	5.80
							4.35			
4237.00								39.71	9.37	5.95
							16.40			
6692.00								56.11	8.38	**6.15**

Targeting Results

FULL REGENERATION AND A
REGENERATED WATER PINCH
Fmin = Fregen = 6.15 te/hr
Freshwater pinch at 2436.00 ppm
Regenerated water pinch at 6692.00 ppm
Average outlet concentration is 6692.00 ppm

Linear Programming model

To minimize the fresh water flow rate, introducing a simple linear objective function that equals the minimum fresh water flow rate, f_{min} $y = f_{min}$ ..... (10)

Consider the single concentration interval as shown in fig.

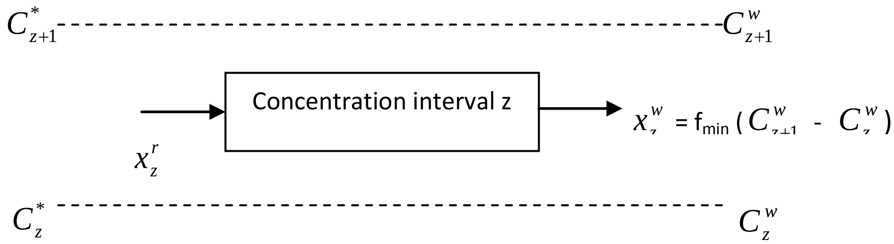


Fig. 7: Contaminant mass balance for concentration interval z

This figure illustrates a single concentration interval z. Here consider the lowest concentration interval (zero inlet concentration) z = 1 and highest as z = n_{int} (number of concentration intervals).

Single contaminant flow into concentration interval = z

Mass load of contaminant transferred from the rich process streams with in each interval z $= x^{r}_{z}$

Mass load of contaminant transferred from concentration interval z to the water stream $= x^{w}_{z}$

The contaminant mass balance over the concentration interval z gives

$$x^{r}_{z} = x^{w}_{z} \quad ..... (11)$$

Therefore change in the water stream concentration = $C^{w}_{z+1} - C^{w}_{z}$

$$\left\{\begin{matrix}\text{The mass load of contaminant transfer}\\ \text{red to the water stream}\end{matrix}\right\} = \left\{\begin{matrix}\text{Water stream}\\ \text{flow rate}\end{matrix}\right\} \times \left\{\begin{matrix}\text{Change in water}\\ \text{stream Concentration}\end{matrix}\right\}$$

ie $x^{r}_{z} = x^{w}_{z} = f_{min}\,(C^{w}_{z+1} - C^{w}_{z})$ z =1, ... , n_{int} ..... (12)

The mass transfer remains feasible, therefore it requires that the water stream concentration scale C^{w}_{z} is always less than or equal to the concentration interval boundaries (C^{*}_{z}) defined by the limiting process data. In addition, set

$$C^{w}_{z} = 0 \qquad z = 1$$
$$C^{w}_{z} \le C^{*}_{z} \qquad z = 2, ..., n_{int}+1 \qquad ..... (13)$$

Equation (10), (12) and (13) altogether represent a linear program for finding the minimum fresh water flow rate. To simplify the solution to LP rearrange the equation (12) for water stream concentration as a function of the mass load of contaminant in each concentration interval
i.e

$$x^{r}_{z} = f_{min}\,(C^{w}_{z+1} - C^{w}_{z})$$

$$C_{z+1}^{w} = \frac{x_z^R}{f_{\min}} + C_z^w$$

$$C_z^w = \frac{x_z^R}{f_{\min}} + C_{z-1}^w \qquad \text{..... (14)}$$

$$C_z^w = \frac{\sum_{i=1}^{z-1} x_i^r}{f_{\min}} \qquad \text{..... (15)}$$

Substituting equation (15) into the concentration scale constraints equation (14) reduces the problem to a single constraint

$$C_z^w = \frac{\sum_{i=1}^{z-1} x_i^r}{f_{\min}} \leq C_z^*$$

Rearranging the above equation, it becomes

$$f_{\min} \geq \frac{\sum_{i=1}^{z-1} x_i^r}{C_z^*} \quad z = 2, \ldots\ldots\, n_{int} + 1 \qquad \text{..... (16)}$$

The equation (16) provides for targeting the minimum freshwater flow rate through the mathematical optimization by transshipment model.

4. Conclusion

The Water Pinch Analysis carried for the dairy industry of Hatsun Agro Product Ltd., which was located in Karumapuram village, Salem Dist. The two main strategies (water reuse and regeneration re use) was carried for the Water Pinch Analysis. An integrated design method such as graphical and tabular method was applied to determine the minimum fresh water flow rate and to minimize the water consumption and wastewater generation. And also a systematic water network design has been applied for targeting the minimum flow rate of water usage. This study shown that the regeneration reuse approach, can be effectively minimized the fresh water flow rate by 54 %.

LP (Linear Programming) model known as transshipment model was applied to the analysis of water using networks, and obtained the minimum freshwater flow rate for water using operations involving a single key contaminant (COD). It has also shown that some reduction in contaminant loading in also possible by utilizing the existing water treatment facilities. Therefore, it can ultimately result in reduction of water costs and total costs for the dairy industry.

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