J. Int. Environmental Application & Science, Vol. 3 (1): 43-50 (2008)

Water and Wastewater Minimization in Dairy Plants using Water Pinch Technology

Sze-Fei Peng[1], Mohammed Farid[1,*], Ian Ho[1], Khaled A. Mahdi[2]

[1]*Department of Chemical & Materials Engineering, The University of Auckland, Private Bag 92019, Auckland, New Zealand,* [2]*Chemical Engineering Department, Kuwait University, P.O. Box 5969 Safat 13060, Kuwait.*

Received January 12, 2008; Accepted February 19, 2008

Abstract: Application of water pinch technology to a dairy plant resulted in freshwater consumption and wastewater effluent flow rate reduction of 60% and 65% respectively, simply by re-designing the water management system in the existing water treatment facilities. The volumetric flow rate of wastewater effluent to processed milk flow rate ratio significantly dropped from 1:3.2 to approx 1:1.1. The overall operating cost is found comparable as the decrease in river water intake costs are balanced by an increase in operating costs of the utility processes. Should trade waste charges be imposed on the plan, the new water network will show a 39% reduction in effluent discharge costs. In addition, a significant reduction in contaminant loadings in the discharge was reported for the new water network.

Keywords: *Water Pinch, Dairy Processing, Water Minimization, Optimization, Wastewater treatment.*

Introduction

Fresh water cost, wastewater treatment cost and stringent environmental regulations put overwhelming pressure on chemical industries to implement efficient water management strategies for their industrial water networks. Dairy industry is one of the largest water consuming industries. The volume of wastewater effluent to processed milk ratio ranges from 1:1 in Europe to 2.8:1 in New Zealand dairies industries. An optimal ratio is never reported in the literature. Clearly, the interplay of water quality in dairy processing, hence the final product quality, and the operating costs incurred from fresh water and wastewater treatment suggests necessary investigations to efficiently implement water management in dairies plants.

The design problem of an optimal water network can be stated as: *Given a set of water-using unit operations, it is desired to determine a network of interconnection of water streams to minimize the overall plant operating cost or the fresh water consumption while these units are processed with the water of permissible quality*.

Optimal water and wastewater flows in utilities networks are successfully attained using water pinch analysis, a mass analogy to the thermal pinch analysis of heat exchangers network (Linnhoff & Hindmarsh, 1983, Popoulias & Grossmann, 1983, El-Halwagi & Manousiouthankis, 1990). Many industries, especially petroleum refinery plants, report industrial water consumption to decrease from 25% to approximately 60% upon applying water pinch technique their networks (Bagajewicz, 2000).

Two procedures are used to perform water pinch analysis: a graphical method and a rigorous mathematical optimization approach. Pinch analysis consists of two steps: targeting and design. Targeting is a procedure to locate the water pinch, the minimum fresh water flow rate, and it is performed ahead of any network design or modifications. The pinch can be identified graphically using composite curve, also known as source and sink or purity profiles (Wang & Smith, 1994) or water surplus diagram (Hallale, 2002) supplemented with water cascade table (Tan *et al*, 2002, Manan *et al*, 2004).

[*]*Corresponding: e-mail: m.farid@auckland.ac.nz, Tel: +64-3737599; Fax: +64-3737463*

Based on the generalized mass exchange network synthesis (El-Hawagi & Manousiouthakis, 1989, El-Halwagi, 1997), Wang and Smith (1994) initiated the water pinch technique by introducing the limiting composite profile to locate the minimum fresh water and wastewater flow rates prior to the water network design. Then modifications to the network, such as reuse, regeneration and recycling, are explored. This mass transfer approach deals with water-using units as mass transfer operations, however, in water recovery network, water quantity can be more important than water quality. This inadequacy is corrected by introducing a new water sources and demand composite curves (Dhole *et al*.,1996). In general, graphical techniques are time consuming and more error prone, especially when the problem consists of numerous streams and multiple contaminants (Mann & Liu , 1999, Olsen & Polley, 1996).

Takama *et al*. (1988) attempted the first mathematical programming approach to water network for a petroleum refinery by optimizing a network of all water-using operations then removing irrelevant and uneconomical options. Searching for the optimum network, Papalexandndri *et al*. (1994) included all network alternatives in one hyperstructure and minimize the total cost using mixed integer non-linear programming. This method does not always generate the optimum (Hallale & Frasr, 1998).

The water pinch analysis main step is to establish the target or the objective function of the water network optimization. The target can be minimizing the fresh water flow rate or the overall operating costs. The later is known as "supertarget". This optimization is subjected to a set of constrains, mainly the mass balances and effluent or process concentrations limits. In most cases, the final mathematical model of the water network is a linear programming problem, where wastewater treatment units may introduce non-linearity.

Practically, different modifications to the water network can be generated and tested against the predetermined target. These new process modifications can include reuse, regeneration and recycling or a combination of them. Although they may be determined by careful manual inspection of the process, but a systematic approach would identify more water saving opportunities through pinch analysis. In this work, we use WaterPinch^{TM}, a program developed by Linnhoff to carry out the targeting and design of water network in a dairy plant.

Dairy Plant

The case study in this work is the Kiwi Co-op Dairies plant located in Hawera, New Zealand. The plant indicates an effluent to milk volumetric flow rates ratio of 3.2:1 as opposed to 1:1 in an average European dairies plant. We aim to minimize the water consumption by applying the pinch technology to several water management network configurations; the optimal configuration will be the one that utilize the least fresh water. In Figure 2, we show two main schemes, the first one (on top) summarizes the current water network in the dairy plant. All other schemes (on bottom) are tested configurations.

Model Representation

Due to the large size of the Kiwi Dairy site at Hawera, two facilities are selected for the pinch analysis, the powder plant and the whey products plant. The whey products plants are the largest consumer of fresh water and the powder plants are the dominant producers of processed water. These plants have a total operating capacity of 214 m^3/hr of milk received from the pre-treatment units. In the powder plant, the fed milk is first pre-heated in several heating units prior to a series of evaporators. Through these evaporators, water is lost producing a thick concentrate, which is homogenised then spray dried to form milk powder. A portion of the condensate from the evaporators is collected for the washing process; otherwise, it is discharge as effluent after ozonation. Both plants are shown schematically in Figure 1.

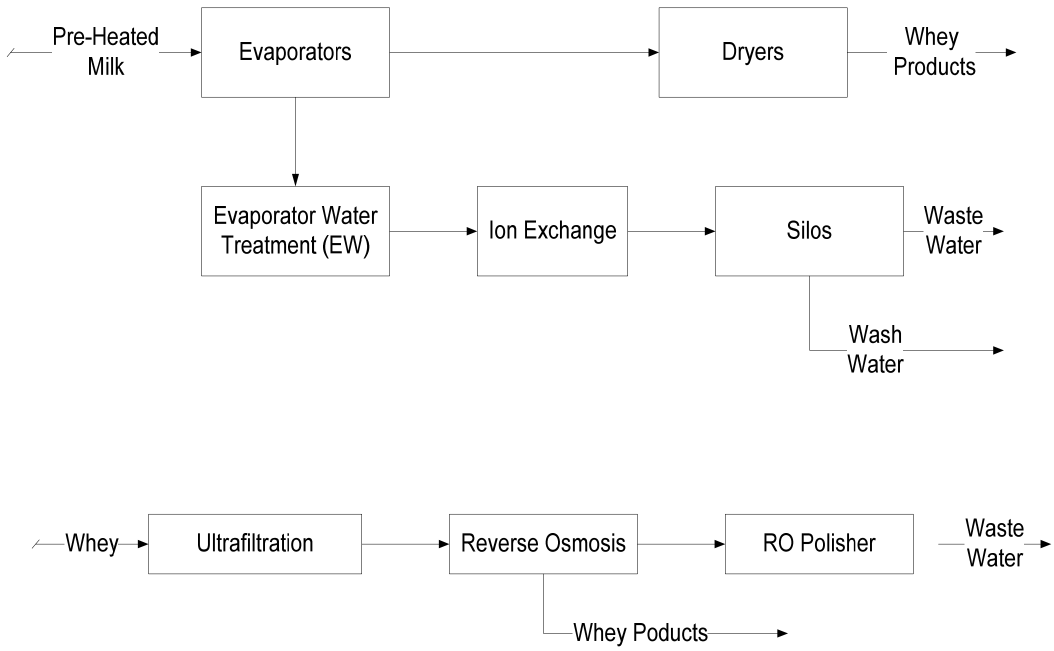

Figure 1. Schematic diagrams of the Powder (Top) and Whey Products (Below).

Whey products plant processes vary based on the type of end product required. Cheese whey and lactic whey are produced at this Hawera site. Initially, feed streams are first passed through an ultrafiltration (UF) unit followed by reverse osmosis (RO) to produce a more concentrated retentate stream, which is eventually evaporated and dried to produce Lactose. In this plant, final permeate streams, contaminated water, are discharged as effluent.

In any dairy plant, the cleaning process has the greatest water demand. The Cleaning in Place (CIP) process composes of three stages: product recovery, intermediate and final flush, shown in Figure 2. During product recovery, fresh water is used to flush out any remaining product from pipes and reaction vessels into product silos. Since there is some contact with the recovered products, high water quality is important. In the intermediate stage, caustic and acid washes are carried out with rinsing in between each cycle. Here, low water quality is permissible since caustic and acid washes render any microbial contaminants. The final flush stage, high water quality rinses all equipments and pipes for the next batch.

Methodology

The optimal water network configuration is found by testing several water network configurations as shown in Figure 2. WaterPinch™ program tests all possible water network configurations and select the optimal network that minimizes the cost objective function. The total cost will include the cost of fresh water, wastewater discharge fee and cost associated with contaminants mass loading. The optimal solution leads to minimum consumption rate of fresh water and less effluent and contaminants.

Pinch Analysis solution

The computational analysis started with mapping out the water network on site, identifying major water users in the water network and providing plant data, by Kiwi Dairies at Hawera, include: flow rate measurements and contaminants analyses. Four contaminants characteristics are considered: conductivity, turbidity, coliform and R2A (a general bacterial count used in the food industry).

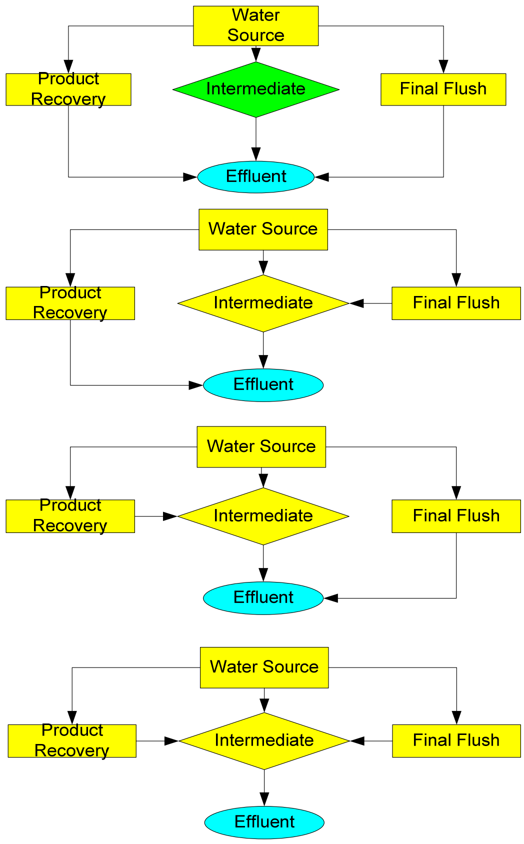

Figure 2. Several Water network configurations are analyzed by WaterPinch TM the original water network (Top) and all other possible configurations (Bottom). The optimal water network is the last one shown where all processes are redirected to intermediate processes before being sent to the effluent.

After the water map is constructed, the flow rates and contaminant gains across each operation are calculated followed by a minimization of the overall operating costs over the water network. The total objective cost of the pinch solution calculated from the variable costs and geographical based on a three-year animalisation. Exploring various concentrations limits and reuses opportunities systematically helped to achieve maximum water savings at a reasonable cost. This part is computer-driven as well as manually driven. Through optimization sensitivity analysis, we identify the most advantageous points of reuse and regeneration.

Modifications to the existing network as obtained from the pinch analysis are shown in Figure 2. The cleaning-in-place operations are all integrated as opposed to the original situation in which all three stages would use fresh water once through only. The outputs of the final flush and the product recovery stages are joined with the intermediate stage then sent to the effluent stream.

Water pinch solution to the current water network involves the following:

- Utilising the existing water treatment plant, a regeneration facility has been created. The permeate streams of the ultrafiltration and reverse osmosis units will be regenerated and combined with the retentate stream of the RO Polisher and the wash stream of the ion exchange unit.
- There will be an increase in RO polisher operating capacity from 31.1 m^3/hr to 59.6 m^3/hr, which is within design limits of the unit. Feed water to the polisher will come from the

evaporator condensate of the whey products plant and the entire permeate stream of the RO unit.

- The original process flushes 74.1 m^3/hr of evaporator water (EW) to the drain when silos ran out of capacity or the conductivity level is above the permissible level. The pinch solution shows that all EW can be saved, simply by installing more silos. To ensure that there is no microbial build up in the silos, EW should be ozonated prior to storage.
- The pinch solution help to de-bottleneck the existing water treatment facility since the need to treat river water has been reduced by 390.8 m^3/hr. The unit is way below its capacity.
- Effluent volumes from the whey products and powder plants have been reduced by 65%. With the pinch solution, streams that contribute to effluent discharge are limited to all intermediate stages.

Discussion

The targeting of the water pinch analysis in this paper is the total overall operating costs. Hence, we look at the savings associated with the recommended process modifications. Table 1 compares the original process to the process after modifications in term of utilities flow rates and associated operating costs. The main outcome is the large reduction in fresh water flow rate and wastewater flow rate. Treated river water which is simply water uptake from nearby rivers was originally at a flow rate of 652.3 m^3/hr, is reduced to 261.5 m^3/h, a 60% reduction. The effluent discharge was correspondingly 682.0 m^3/hr is reduced this by 65% to 237.5 m^3/hr.

Table 1. Costs and flow rate comparison for before and after pinch analysis.

		Original process	**Pinch Solution**			
Utility	*Operating Cost ($/$m^3$)/hr*	*Utility Flows (m^3/hr)*	*Utility Flows (m^3/hr)*	*Change (%)*	*Difference (m^3/hr)*	*Differential Cost ($/hr)*
Treated River Water	$0.74	652.3	261.5	-60.0	-390.8	-$289.19
Effluent Disposal Charges	$0.10	682.0	237.5	-65.2	-444.5	-$44.45
Water Treatment	$0.72	0.0	299.0		299.0	$215.28
Reverse Osmosis (RO) Polisher	$0.25	31.1	59.6	91.6	28.5	$7.13
Effluent Water (EW) Treatment	$1.50	172.0	247.0	43.3	75.0	$112.50
Ion Exchange	$2.50	369.0	368.0	0.0	-1.0	-$2.50
Total current differential cost						-$1.24
Added Trade Waste Charges (74% increase of current charges)	$0.074	682.0	237.5		-444.5	-$32.89
Total forecasted differential cost						**-$34.13**

* All costs are in New Zealand dollars.

Although the costs associated with effluent disposal is small in comparison with other operating costs at the time, it is important to consider the environmental impacts minimised from the reduction in volumetric and load disposal. Table 2 compares the contaminant level of the effluent stream before and after the pinch analysis. It shows that contaminant loading was reduced along with volume. A reduction in contaminant loading will benefit the environment as the potential to harm coastal and in-sea inhabitants are diminished. As well, this will relief the conditions for wastewater treatment should the need arise in the future.

Table 2. Comparison of contaminant mass loading of effluent before and after the pinch analysis.

	MASS LOADING (per m^3/hr)			
	Conductivity µS/cm	**Coliforms/100mL**	**R2A/1 mL**	**Turbidity, NTU**
Before Pinch	1,101,356	84,023	85,912	7,058
After Pinch	724,394	58,774	59,372	6,661
% Reduction	34	30	31	6

The modified network has increasing operating costs in the RO polishes and the evaporator water (EW) treatment. The operating capacity of the RO Polisher has been increased from around 31 m^3/hr to 60.0 m^3/hr. Furthermore; treatment capacity also sees an increase of a 43%. The total costs, shown in Table 3, for before and after pinch analyses are comparable as the decrease in river water intake costs are balanced by an increase in operating costs of the utility processes as their capacities are optimised.

Table 3. Results of the water pinch analysis.

PROCESS	Recommendation	COMMENTS
Powder Plant pre-start water.	Recycle & Reuse	The quality of water here is high, as the evaporators have just undergone cleaning-in-place (CIP) and is simply waiting for their turn to start operations with product feed. There are substantial savings here at 7.9m3/hr. The pre start up process takes approximately 3 hours, which makes the cumulative volume savings even more obvious. Other uses for this water includes reuse by CIP after it has completed 3 hours of recycling for the pre start up. This ensures that product quality is not affected by the continuous reuse of recycled water if contamination in water storage silos occurs.
Ultrafiltration and Reverse Osmosis Washing	Replace & Optimise capacity	The flush stage will now run on demineralised (demin) water only. This solution was generated as the RO polisher is now running at almost twice its original operating capacity, which leaves an excess of demin water. It was also discussed that the RO polisher water can be used to replace majority of the demin water used since this is the most expensive type of water to generate. The objective of installing the polisher was to reduce the volume of demin water required. This means that all processes that require demin water, namely diafiltration, can now use RO Polisher water.
Intermediate stage of Cleaning-In-Place (CIP)	Reuse	The majority of savings are from the Intermediate CIP stage. This process uses the most water compared to any other operation. The pinch solution here is to reuse water outflows from Product Recovery and Flush stages, which replaces up to one third of the water required for the Intermediate stage, see Figure 2. This solution is repeated for all other CIP sets in the Whey Products plant. It is also possible for other plants on site to adopt this change, as the basis for this solution is similar for all other CIP conditions.

It must be noted that a reinforcement of ongoing environmental regulations works in favour of the new water network. Since banning disposal of untreated effluent will face a 74%

increase of effluent disposal costs when compared to the current disposal charges. The must be treated or sold as trade waste on a “user pays” basis. Calculations reveal that if effluent were to be sold as trade waste at $5,500/peak flow rate in L/s in a 24 hour period/annum as estimated from the Trade Waste charges obtained from Auckland Regional Council’s Trade Waste Bylaw 1991. However, if the pinch solutions were implemented even with the trade waste charges imposed, there would be a 39% decrease from the current effluent discharge costs. This implementation will provide an annual saving of $138k.

Conclusions

Application of water pinch technology to a dairy plant resulted in freshwater and wastewater savings of 60% and 65% respectively. Should trade waste charges be imposed on the site, this would equate to a 39% reduction in effluent discharge costs. Using existing water treatment facilities, further reductions in contaminant loading will be possible, which will allow low contaminant effluent streams to be used in other areas of the plant. Through logical evaluation of the water using and contaminant streams, similar water-reuse strategies could have been uncovered. However, through water pinch technology the optimal solution is obtained in less time.

Acknowledgment: *The authors would like to thank Technology New Zealand for funding this project and to Neil Walker from Kiwi Co-op Dairies Ltd. (now FONTERRA) for his continuous support to the project. Dr. Khaled A. Mahdi would like to thank Kuwait University for sponsoring his sabbatical leave.*

References

Bagajewicz M. (2000) A review of recent design procedure for water networks refineries and process plants. *Computer and Chemical Engineering*, **24**, 2093-2113.

Dantzig G.B., Thapa M.N., (1997) *Linear Programming 1: Introduction*, Springer Verlag.

Dole, V.R., Ramachandan, N., Tainish, R.A., and Wasiiewski, M. (1996) Make your process water pay for itself, Chem. Eng., 103(1):100.

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

El-Halwagi M.M., Manousiouthankis,V. (1990) Automated Synthesis of Mass-Exchange Network with Single-Contaminant Target. *Chemical Engineering Science*, *45*, 2813.

El-Halwagi, M. M. and Manousiouthankis, V. (1989) Synthesis of mass exchange networks” *AIChE J*, 35(8) pp. 1233-1244.

Foo C.Y., Manan Z.A., Yunus R.M., Aziz R.A. (2004) Synthesis of mass exchange network for batch processes – Part I: Utility targeting. *Chemical Engineering Science*, **59**, 1009-1026.

Hallale, N., (2002) A New graphical targeting method for water minimization”. *Advance Environmental*, **6**, 377-390.

Linnhoff B., Hindmarsh, E. (1983) The pinch design method for heat exchange, *Chemical Engineering Science*, **38**, 745-763.

Manan Z.A., Tan Y.L., Foo C.Y. (2004) Targeting the minimum water flow rate using water cascade analysis technique. *AIChE J*, **50**, 3169

Mann J.G., Liu Y.A. (1999) *Industrial Water Reuse and Wastewater Minimization*, 1st ed. McGraw-Hill.

Olesen S.G., Polley G.T. (1999) A simple methodology for the design of water networks handling single contaminant. *Transacions of. I Chem E*, **75(B),** 305-308.

Olesen S.G., Polley G.T. (1996) Dealing with Plant Geography and Piping Constraints in Water Network Design. *I Chem E Shorter Communication*, **74(B)**, 273-276.

Papalexandri K.P., Pistikopoulos E.N., Floudas A. (1994) *Transacions of. I Chem E*, **72(B)**, 279-294.

Popoulias S.A., Grossmann I.E., (1983) A Structural optimisation Approach in Process Synthesis II. Heat-Recovery Networks. *Computers & Chemical Engineering*, **7**, 707.

Takma N., Kuriyama T., Shiroko K., Umeda T. (1980) Optimal water allocation in a petroleum refinery. *Computer and Chemical Engineering*, **4**, 251-228.

Wang Y.P., Smith R. (1994) Wastewater Minimisation. *Chemical Engineering Science*, **49**, 981-1006.