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Water network synthesis in refinery

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Abstract−Minimizing fresh raw water and wastewater effluent produced by industry has rigorously been studied over the past two to three decades. However, most studies have focused on rather theoretical illustration with little consideration of technical constraints in industry. Furthermore, use of massive industry data significantly increases the complexity of the problem, and no research paper has covered such a case study with practical solutions. This paper reviews the latest technology of water network synthesis and its applications, and provides a detailed guideline of the whole study procedure with a reference to case study based from refinery complex. Two main methodologies of water-pinch technology and a mathematical optimization programming are reviewed individually, and they are applied to a case study. Economic and operational constraints are embedded into optimization of water network synthesis in order to provide more reliable and achievable solutions for the minimization of fresh water consumption and reduction of waste water effluents. This generic approach can be similarly applied to other industries such as petroleum, steel, and paper manufacturing.

Key words: Simulation, Optimization, Water Network, Waste Treatment, Refinery

INTRODUCTION

Over the past two to three decades, minimizing water usage in industry has rigorously been studied for diverse subjects such as cooling water systems, water treatment systems, and desalination systems. More recently, since the early 1990's, the methodology of optimum water network synthesis has received significant attention in trying to reduce consumption of fresh water by maximizing water re-use. Typically, two basic strategies have been individually studied by many researchers such as water-pinch study which uses a graphical illustration and a mathematical programming based on super-structure of water networks. As a result, many case study results have been presented so far. However, most studies have focused on academic illustration with simplified water networks, and only a few papers covered actual industrial size of case studies. Furthermore, operational constraints were often not taken into account for water network synthesis. Therefore, potential water savings often became rather optimistic compared with actual operating results. This paper introduces a generic guidance for the study of water network synthesis in industry, considering necessary operational constraints, whilst avoiding unnecessary complexity of the networks.

Refineries are a big consumer of fresh water, as much as oil. In fact, typical water consumption of a refinery ranges from 0.5 to 1.5 barrels of water per barrel of oil processed. It has been proved that the best efficiency of water consumption in a world class refinery can adhere to 0.5 bbl of water per bbl of oil [1]. Typical distribution of water consumption in a refinery is shown in Fig. 1. Cooling water accounts for about 50% of total water usage in a refinery, followed by 20% for boiler feed water, 11% for fire water and 10% of water consumption in process units. Water consumption of potable water and backwash totals about 6% and 5%, respectively.

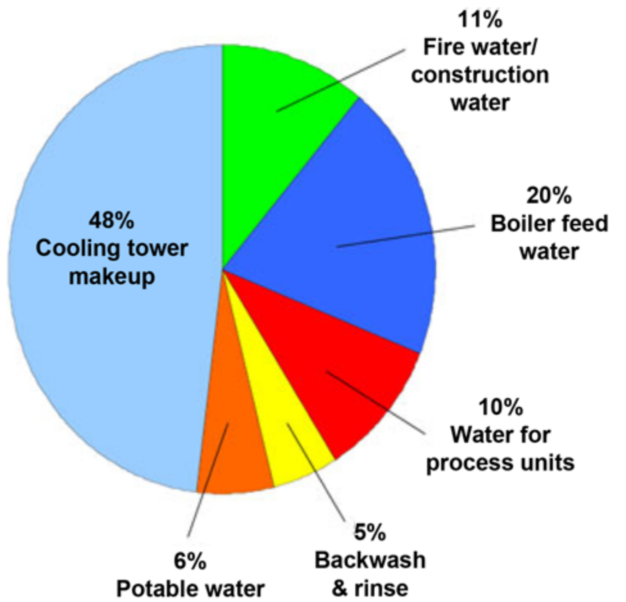

Fig. 1. Water consumption in refinery (Arena and Buchan [1]).

To gain insight into current water demand of a refinery with regards to region and its availability, relative water scarcity of the refinery is plotted against total refinery capacity in each region as shown in Fig. 2 [1]. Currently, the Middle East, North Africa and Asia belong to a water-stressed area, while Europe, Central and South America have a relatively rich water supply.

As a next step, the total refinery capacity, its water demand and availability are predicted for the year 2025. Overall, refinery capac-

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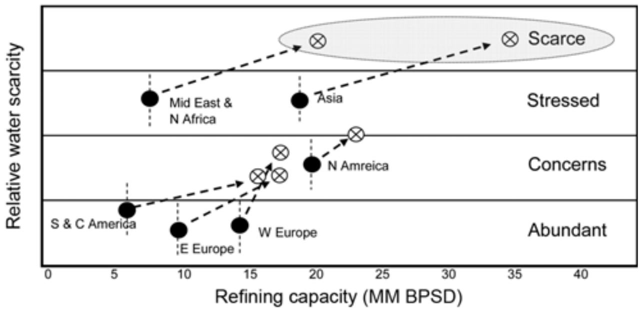

Fig. 2. Current and future relative water scarcity in refinery over the region (Arena and Buchan [1]).

ity and its water demand are likely to increase, and over 40% of refining capacity will be in water-scarce areas by 2025 as shown in Fig. 2 [1].

Furthermore, recently introduced strict governmental regulation on water usage and release of waste water effluent has been a significant driving force for the refinery industry to focus on the reduction of overall fresh water consumption and increase in efficiency of waste water treatment systems. Consequently, many refineries performed water saving projects and managed to achieve their targets of savings of a) purchased water cost, b) influent water treatment cost, and c) effluent water treatment cost. Fig. 3 emphasizes the efforts that have been made by refineries to reduce water consumption over the past decades [2].

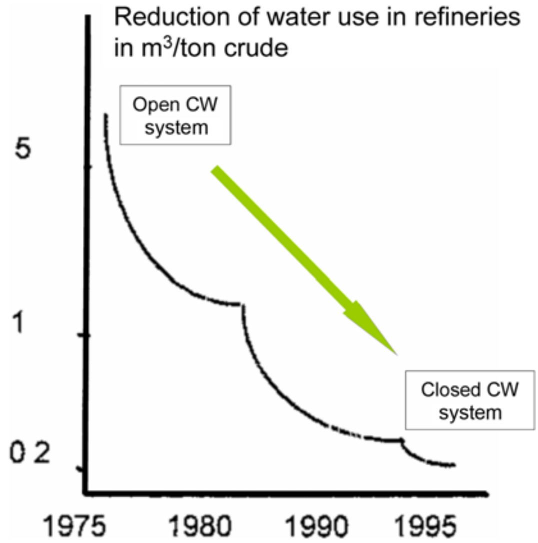

Fig. 3. Water consumption in refinery (Smit and Smit [2]).

METHODOLOGY OF WATER MINIMIZATION

1. Pinch Technology by Using Conceptual Graphical Design

Pinch technology was originally developed for the optimization of heat exchanger networks by Linhoff [3]. Since then, it has been used as a powerful tool to examine process integration potentials with respect to heat transfer.

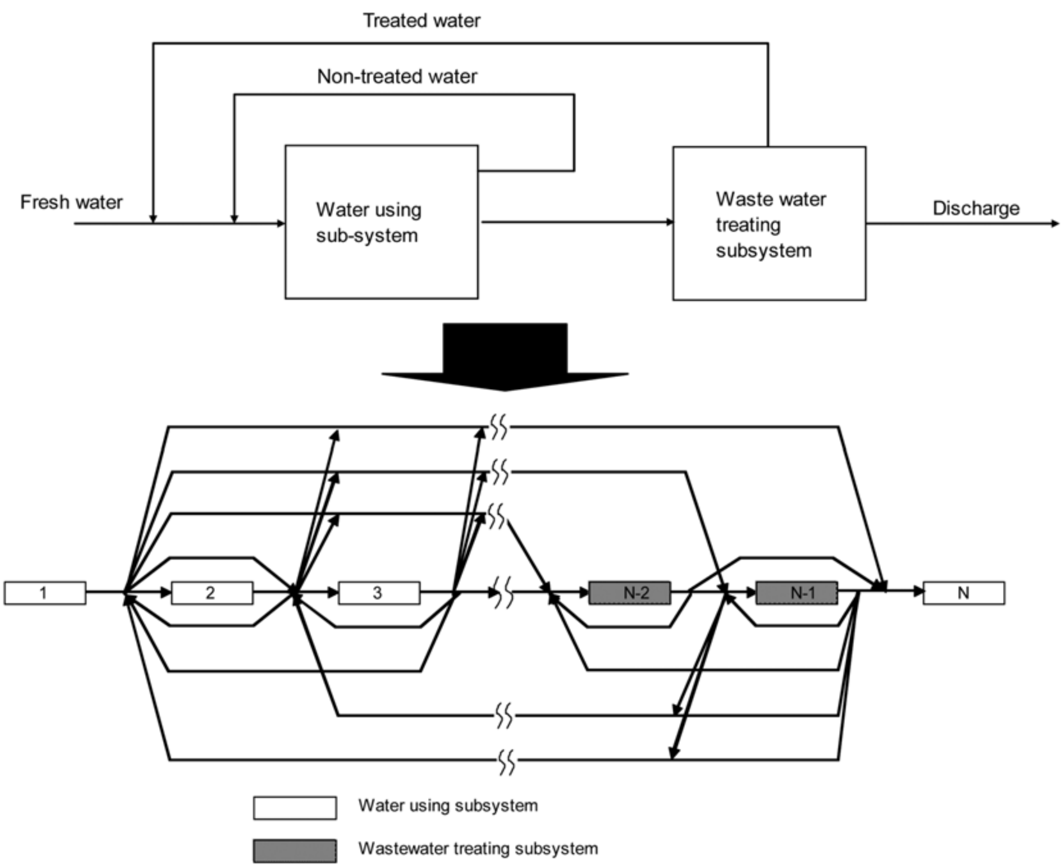

Fig. 4. General system structure of refinery water use and treatment (Takama et al. [9]).

The similarity between heat and mass transfer of the pinch technology was first addressed by El-Halwagi and Manousiouthakis in 1989 [4]. They focused on the synthesis of optimum mass exchange networks for the species between rich and lean streams. Minimum cost for the separation agent and minimum number of mass exchange units in the network were set as a target. For illustration, a single key contaminant was applied. Since then a number of papers have been published, explaining the application of pinch technology to Water minimization [5-8]. Wang and Smith illustrated a conceptual approach by using a pinch analysis to maximize water re-use in process industries with both single and multiple contaminants [6]. Also, improved design of distributed effluent treatment system was illustrated by using a pinch technology [7].

Since a graphical tool is used in pinch technology, it can easily provide insight with respect to current state of water use and maximum target to achieve. However, pinch analysis becomes increasingly difficult to apply to larger problems with multiple water contaminants because of complex interactions.

2. Mathematical Optimization

Another approach for water network study is to use mathematical optimization to treat multiple contaminants and constraints with a consideration of economic cost evaluation in a complex water network system. Compared with pinch analysis, this mathematical optimization can cover increased complexity of water network problems for industrial reuse, wastewater minimization and distributed effluent treatment system in a more efficient way.

Mathematical optimization was initially applied to water network study by Takama et al. in 1980 [9]. As shown in Fig. 4 a system for water use and treatment is represented in a super-structure for mathematical optimization. Among N systems, the subsystems 1 and N are used as input and output systems, respectively, while each subsystem has a mixing and splitting point. The input system is a source of fresh water which can be supplied to any subsystem, and output system is used as a destination of wastewater. Non-linear programming was used to solve mass transfer of water networks based on a fixed mass load.

Since then, many researches have focused on the optimization of water networks by using linear or non-linear programming [10]. However, due to intrinsic characteristics of complexity and significant amount of data to tackle for an actual industry problem, a superstructure model was used by Doyle and Smith based on a combined approach of linear and non-linear programming [11]. Algáez et al. continued this line of work and proposed solving a two-phase procedure for the solution of a non-convex MINLP [12]. Huang et al. and Benko et al. also individually illustrated programming solution of water recovery network synthesis [13,14]. Later, Jacobs et al. presented the combined use of pinch and linear programming techniques [15].

Despite continuing effort to find an optimal solution of water networks by solving a mathematical optimization of MINLP/NLP, it often reaches to local optimum point especially when an inappropriate initial point leads to local optima as a solution. To resolve this problem, stochastic optimization such as evolutionary algorithm (EA), simulated annealing (SA) and ant colony optimization (ACO) has been developed to find the optimum solutions of non-convex problems [16-20].

WATER NETWORKS IN REFINERY

An overview of typical water flow in a refinery is shown in Fig. 5. Fresh water supply feeds a steam generation system through a boiler feed water treatment system (e.g., demineralization plants) and cooling water system as well as process units. Effluent from process units, utility and treatment systems is discharged to a water treatment unit after sulfur removal.

Typical water cost ranges in refinery are shown as follows [21].

- Fresh water: \$0.26/m^3-\$0.55/m^3
- Wastewater treatment: \$0.52/m^3-\$1.04/m^3

For the development of water balance, existing water supply and its consumption at each local site should be identified. However, it is very common to find it difficult to identify all water supplies or consumptions in refinery. Therefore, it requires significant amounts of time and endeavor for data collection. As illustrated in Fig. 1, 79% of water consumption takes place from cooling towers, fire water and boiler feed water systems in a refinery, and process units account for about 10% of total water consumption. Therefore, water data collection of these main water consuming units would be prerequisite for water study. On the other hand, consideration of small water streams in process units will increase complexity of the optimization problem without much economic benefit from the solution. For the reason, it is very important to focus on major key water streams by preventing possible increase of unnecessary complexity of water network synthesis.

Typically, the following major units or systems in a refinery should

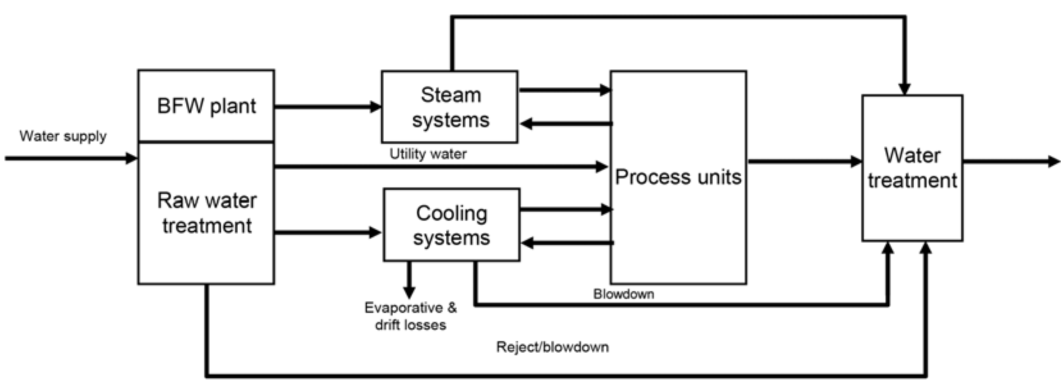

Fig. 5. Typical water flow in refinery.

be considered for water saving study.

- Fresh water system
- Demineralized water network
- Hydrant
- Sour water stripper
- Major process units (inc. desalter)
- Cooling tower
- Boiler blowdown
- Utility water
- Live steam
- Wasted water effluent to water treatment system

Each water-containing inlet and effluent stream in the above system has been identified, and the composition of contaminants is either directly measured or estimated from mass balance. Furthermore, allowable maximum contaminant level of each stream to individual unit should be identified as a process constraint. To simplify the super-structure, the common use of each type of water has been grouped together. For example, a set of cooling towers in a refinery are represented as one big cooling tower, and this enables a clear picture of the overall water system to be presented with better understanding.

With regard to the type of contaminant, it should be considered carefully depending on process type of petrochemical and refinery industry. Table 1 shows typical contaminants in a refinery.

Table 1. List of typical water contaminants in refinery

TDS (total dissolved solids)	Alkalinity
H_2S	Dissolved oxygen
NH_3	Sulfur
pH	Phosphate (PO4---)
Aromatics	Chloride (Cl-)
COD	SS (suspended solids)
Oil	Butane
Ca++	P (total phosphorus)
Fe+++	Boiler additives
Hardness	Cooling tower additives

Table 2. Standard refinery water effluent to sea [22]

Parameter	Unit	Refinery average
Temperature	C	45
pH	S.U	5.5-9.0
Chemical oxygen demand (COD)	mg/*l*	200
Biological oxygen demand (BOD)	mg/*l*	30
Total suspended solids (TSS)	mg/*l*	45
Oil/grease	mg/*l*	10
Phenols	mg/*l*	1
Sulfides	mg/*l*	0.5
Nitrogen (i.e. Ammonia)	mg/*l*	10
Phosphates (inorganic)	mg/*l*	0.5
Cynides	mg/*l*	1
Iron	mg/*l*	2
Free chlorine	mg/*l*	0.6
Chromium as CrO_4	mg/*l*	0.3
Zinc	mg/*l*	0.001-0.05

It is essential to consider the impact of these water quality parameters on potential water saving. In general, it is extremely difficult and time consuming to analyze all the above contaminants from water streams, and to develop a mass balance of the water network. Therefore, a set of key contaminants should be taken into account for water network study at the initial stage, and the other remaining contaminants are considered locally before its application during detail revamp design study. Key contaminants should be selected based on process characteristics of the refinery and also local authority regulation of water effluent release. Typical refinery water effluent to sea is shown in Table 2 [22].

It has been easily observed that lack of operation data adds difficulty to water study. For this reason, any unmeasured data should be back-calculated based on available data as much as possible. For example, TDS levels at the inlet and outlet streams of a desalter should be taken into account for the modeling of the unit. However, in many cases TDS values at the inlet streams especially from process units are not available. In such a case, the TDS value should be back-calculated through a mass balance in most cases from the outlet stream.

The main water related unit in a refinery is introduced below. The model should be developed based on water and contaminant balance, and a mechanism of water or contaminant generation or reduction in the unit should be taken into account if required.

1. Demineralized Water

Municipal water feed to the refinery should be upgraded to boiler feed water quality by further treatment. Solids in water are removed from filters, and this filtered water goes through a bed of cation and anion resins. Demineralization plant features anionic and cationic ion exchange columns, and these columns are regenerated periodically using HCl and NaOH. Typical water specification after demineralized plant is shown in Table 3 [22].

Typical water balance diagram of the unit is shown in Fig. 6.

Table 3. Typical demineralized water specification

	Disalted water, $CaCo_3$
Calcium	10
Sodium	40
Bicarbonantes	5
Sulfate	10
Chloride	35
Alkalinity	5
TDS	60

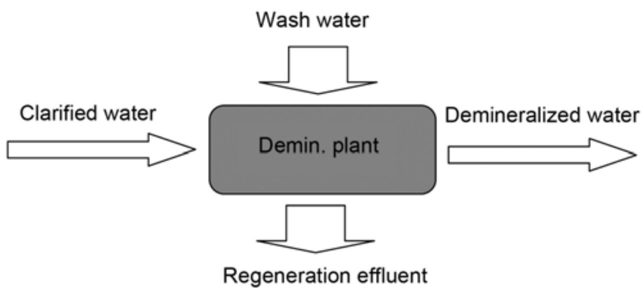

Fig. 6. Water balance diagram of demin. plant.

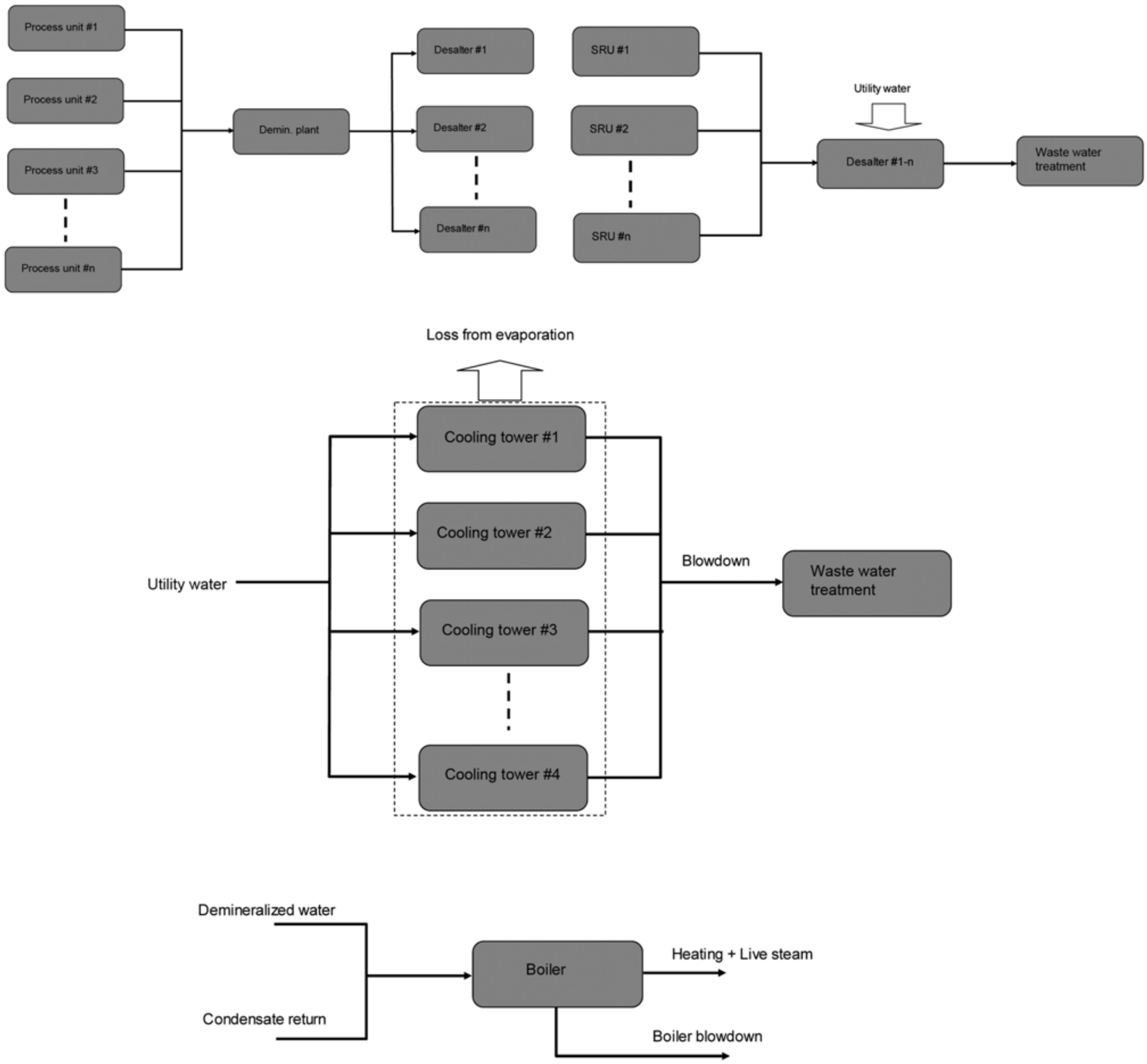

Fig. 7. Water balance of sulfur recovery unit (SRU), desalters, cooling towers and boilers.

2. Sour Water Stripper System

Sulfur recovery unit removes H_2S and NH_3 from the wastewater. Stripped bottoms contain moderate levels of TDS, H_2S and NH_3. The water and contaminants balances are shown in Fig. 7. Process units in the figure include hydro desulphurization unit, sour stripper unit, catalytic cracking unit, and crude distillation, for example. In general, a desalter unit in a refinery does not require high grade of water, and the stripped water is normally reused in the desalter unit.

3. Desalter

A desalter is one of the most water consuming units in a refinery and a big wastewater producer. In general, the recommended volume of wastewater is 3% to 7% of the total crude charge. Typically, stripped sour water is used as desalter wash water. Occasionally, non-stripped sour water is used in a portion of the desalter water, and the sulfur content of the crude often decides the maximum allowable amount of non-stripped sour water to be injected to desalter. Separated water streams are typically contaminated with oil, COD, TDS and moderate levels of H_2S and NH_3. Water and contaminants balances are shown in Fig. 7.

4. Cooling Tower Systems

A cooling tower is the most water consuming unit in the refinery as shown in Fig. 1. The blowdown stream contains significant amounts of TDS. It was illustrated that the blowdown from the recirculating system can be typically increased from 3 or 4 cycles up to 4 to 5 cycles [23]. A set of cooling towers are shown in Fig. 7.

5. Boiler Blowdown

A boiler represents indirect heating steam and live steam boilers in a refinery. An average concentration ratio can be calculated from the blowdown rate. For the simplification of water network modeling, steam generation can be limited to the live steam only, of which condensate flows to the main process units (e.g., SRU, Desalter, etc.). The balance of boiler water is shown in Fig. 7. Boiler blowdown should be included in the modeling to account for contaminant balance.

6. Utility Water

In general, it is very difficult to identify all the streams of utility water. Therefore, elimination of small stream users can reduce complexity of water network superstructure.

7. Steam System

To simplify the modeling of water network, all steams should be lumped together. Steam is used for indirect heating and motive energy, live steam injection for direct heating and steam stripping and for atomization. Where steam is injected into a process it generally condenses and mixes intimately with the process fluids (generally oil), becoming contaminated. Water generally separates from oil in the boot of an overhead condenser and is then routed either to waste water system, sulfur recovery unit, or the drain. For the purpose of the site water balance, the live steam requirement is identified.

8. Effluent to Waste System

A water treatment system includes three different systems as follows [24].

- Pretreatment of wastewater can involve either physical or chemical treatment, depending on the nature of the contamination. The types would be solids separation, coalescer, flotation, membrane, stripping, evaporation, adsorption, ion exchange, wet oxidation, chemical oxidation, sterilization, pH adjustment, chemical precipitation.
- In a secondary treatment, a concentrated mass of micro-organisms is used to break down organic matters into stabilized waste.
- Tertiary treatment prepares the aqueous waste for final discharge. It includes filtration, ultra-filtration, adsorption, nitrogen and phosphorous removal and disinfection.

Typical procedures of water treatment system in refinery are described in Fig. 8.

The water balance of waste water treatment system is shown in Fig. 9. It should be noted that waste water effluent streams are destined to different waste water treatment system, depending on the characteristics of contaminant and its level.

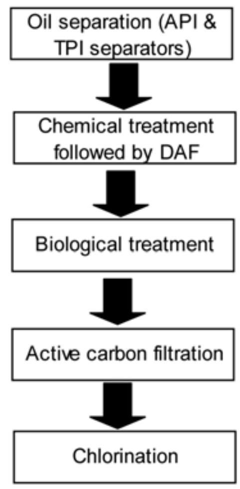

Fig. 8. Waste water treatment steps in refinery.

9. Overall Water Balance Summary

Once mass balance of water streams at each unit is developed, an overall water balance in a refinery can be developed. In general, there is some deviation between measured and balanced data. Therefore, reconciliation works is required for the balance of water system.

CASE STUDY

1. Water Pinch Study

In this work, a comprehensive overall water balance of the refinery has been developed to evaluate how water is used throughout the

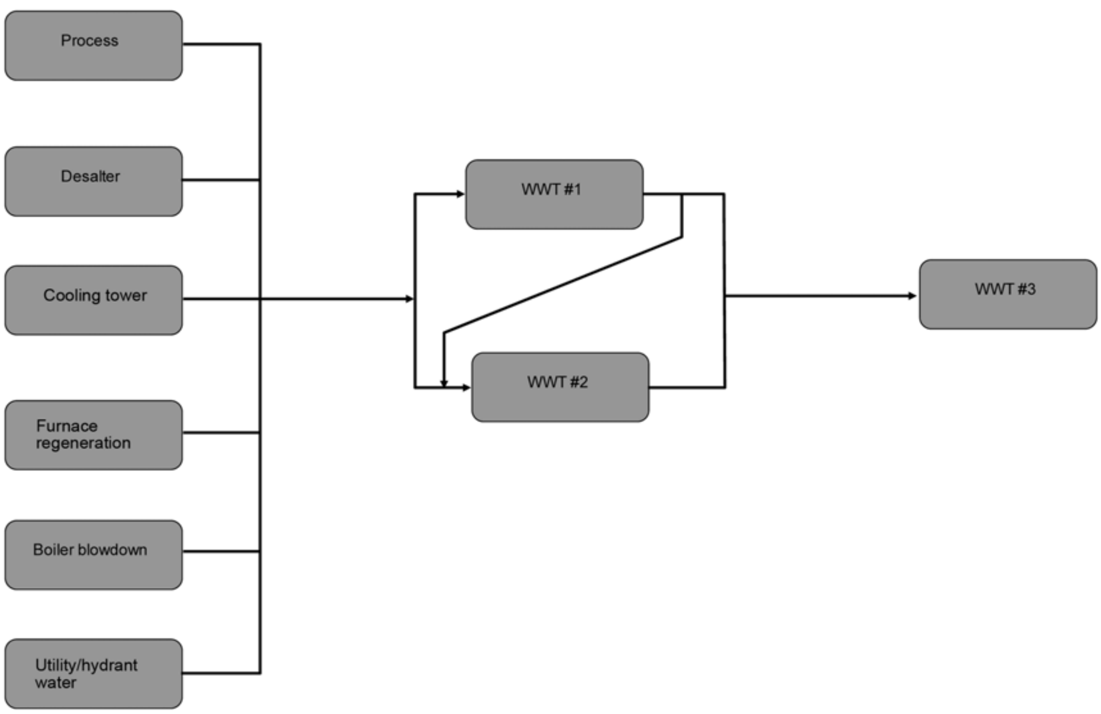

Fig. 9. Water balance of waste water treatment system.

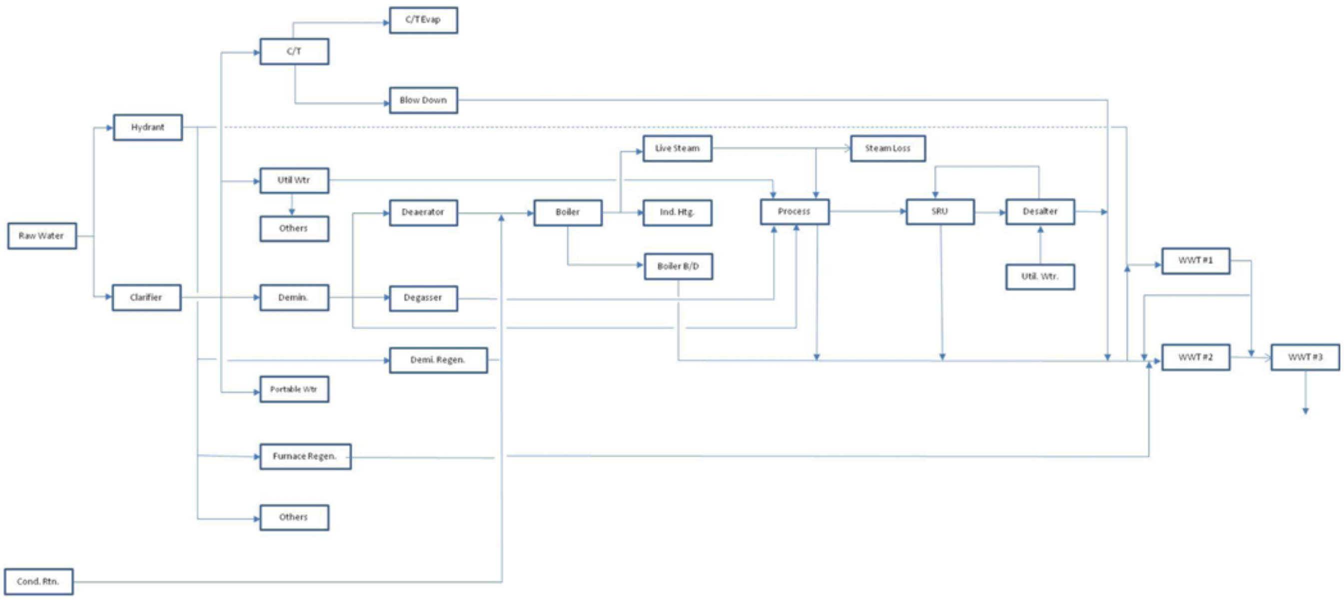

Fig. 10. Water balance networks in refinery.

Table 4. Overall water balance in refinery

	In	Out
Raw water supply	100%	
WWT #1		15%
WWT #2		29%
Cooling tower evaporation		18%
Drinking, etc.		4%
Boiler water make-up		14%
Unaccounted utility water		4.5%
Unaccounted demin. water		6%
Unaccounted hydrant water		9.5%
Total	100%	100%

refinery. This balance includes all water sources and sinks, including fresh water, demineralized water, stream, evaporative losses and effluents routed to water treatment system.

Water network data is collected from a refinery, and an overall water balance diagram is developed as shown in Fig. 10. Furthermore, the overall water balance of the refinery is shown in Table 4. It shows that hydrant water including fire use, cleaning and other purpose takes into account of about 14% of total water consumption. For the remaining water, major water consumers on site are the cooling tower makeup and the boiler feed water. These two consumers account for more than 43% of the total water import. The cooling towers and the steam system are also the major wastewater producers, which account for more than 28% of the total effluent discharge.

The level of major key contaminants such as H_2S, NH_3 and TDS is measured at each stream, and they are used for the balance of each unit. Also, generation or removal of contaminants across the unit is estimated based on annual operating data. Because of confidential agreement of data protection, the detailed figures of contaminants are not listed in the paper.

Based on developed water and contaminant balance, a water pinch study was initially considered to obtain potential maximum saving of raw water and waste water effluents. Furthermore, it allows initial scope of water saving projects.

For a pinch analysis, the controlling contaminant of both the cooling towers and the steam system is TDS, so it is used as the key contaminant of water pinch analysis.

From the contaminant mass balance, TDS contamination levels are calculated for the cooling tower blowdown, water treatment blowdown and boiler blowdown (including the waste heat boilers and process steam generations). For all the other water streams, TDS contamination levels are either estimated from the mass balance of water streams or directly obtained from the measured data. In some cases, the maximum TDS levels of the users are estimated from the process data based on maximum allowable amounts.

Fig. 11 shows composite curves of the existing water system. The water sources shown as the curve on the left hand indicate the amount of water available for re-use and the purity levels. The water purity level is represented by the following formula:

$$\text{Water purity level (TDS), ppm} = \text{Standard concentration} - \text{Actual concentration}$$

The water sinks shown as the curve on the right hand indicate the amount of water demand and the water purity requirements. The overlap of these two curves shows the existing water re-use on site. The existing water supply of the raw water is shown as a gap at the top between the two curves. The existing effluent discharge is shown as a gap at the bottom between the two curves.

Fig. 12 shows that the composite curves are pushed horizontally towards each other. The pinch point is shown at the point of 1,300 Water Purity level, which corresponds to cooling tower makeup as a sink and utility, furnace and process regeneration effluent water as a source. This would maximize water re-use within the processes and minimize water demand and effluent discharge. The minimum water supply and effluent targets are as shown in Fig. 12.

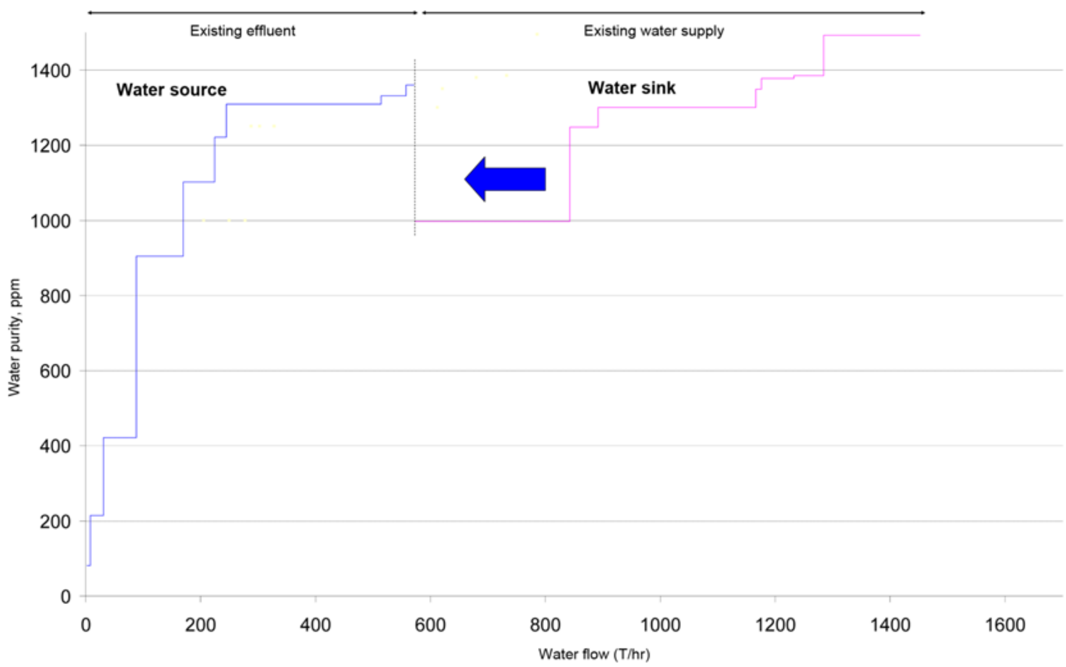

Fig. 11. Water pinch-current (TDS).

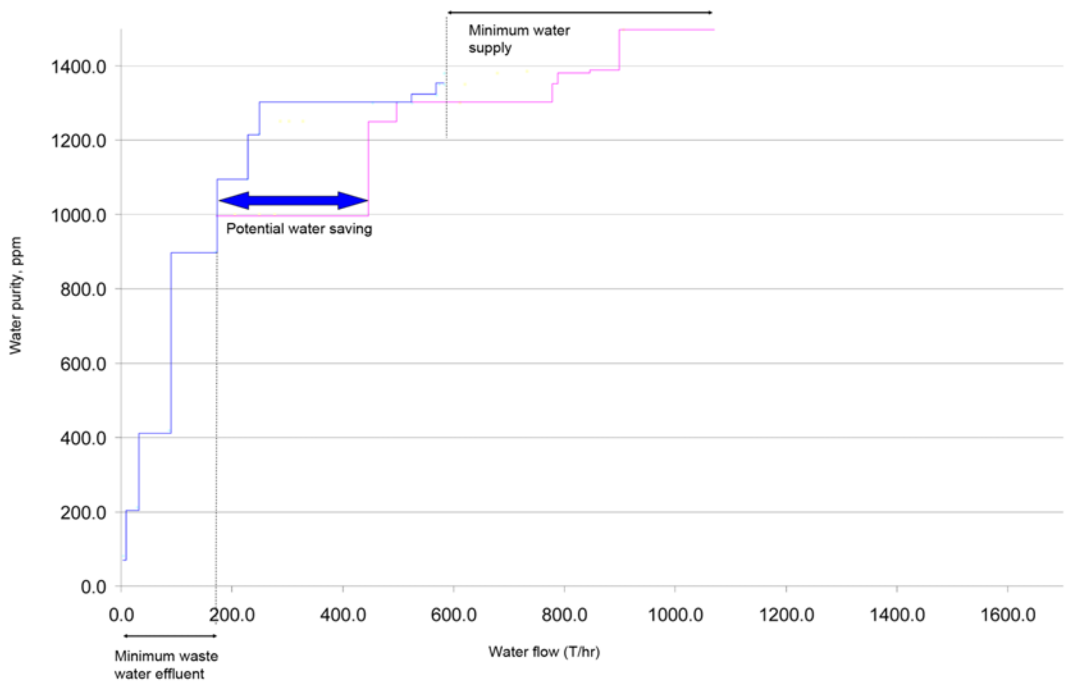

Fig. 12. Water pinch-targeting (TDS).

With regard to TDS contaminant, the pinch target shows that there is a potential to reduce current water supply by about 45% and the effluent discharge by about 71%. However, water regeneration treatment is likely to be required to remove other contaminants such as oil, H_2S, and NH_3.

Water pinch shows an ultimate water target to achieve. On the other hand, it does not provide detailed solutions for improvement for the following reasons.

- Water pinch considers only one contaminant each time.
- One snapshot is used for analysis.
- It is rather impossible to implement all possible projects to meet the target, especially with small amounts of streams.

Therefore, the next step is to develop a mathematical optimization model which accommodates all types of contaminants in a dynamic way.

2. Water Network Synthesis

Overall procedure of the water network synthesis is shown as follows.

1. Development of current network structure (e.g., process unit, cooling tower, boiler, etc.)

2. Specification of current flowrates, types of contaminants, and values of contaminants at water source

3. Specification of degree of contaminant pick-up in process model and degree of contaminant removal in treatment model

4. Running of simulation and comparing the results with measured values

5. Specification of minimum and maximum flow limits for each unit

6. Specification of maximum allowable values of contaminants for each unit

7. Specification of raw water, treatment, repiping and constraint violations cost units

8. Water network synthesis and analysis.

For the modeling, the following four types of components are considered and the balanced data is applied, as illustrated in Section 3.

- Water sources
- Process operations
- Treatment operations
- Water discharge

Major water contaminants of H_2S, NH_3 and TDS have been obtained from the refinery for a case study. Due to the difficulties of securing data, some of them are estimated from water and contaminant balance of the units. For each process model, the behavior of each contaminant in a process is characterized in terms of mass transfer between process and water and expressed as an outlet concentration (ppm-equilibrium). Therefore, the simulation is able to predict changes in outlet contamination as a function of feed contaminant levels from water stream. The total feed and products flows to/from all process models are fixed during the synthesis stage.

Optimization of the existing water system can be achieved at different levels. At the lowest level the use of available water sources only can be optimized, which will result in a cost reduction, but not a net saving in water flow. At the second level a reduction in both water consumption and costs can be achieved by creating opportunities of direct water re-use and recycling. A far-reaching degree of re-use and recycling can be achieved at the third level by re-use and recycling of process water, which is regenerated with appropriate treatment techniques. At this level the highest reduction in both water use and costs can be obtained. However, the investments and therefore the capital costs can highly increase, depending on number and complexity of the process changes (treatment techniques, number of re-pipes, additional pumps and buffer tanks).

All the existing constraints are specified in order to prevent impractical solutions after optimization. For example, waste water from a desalter is not allowed to be reused in any other units due to its high contamination level. Use of boiler blowdown as cooling water makeup was tried in some refineries. However, it is excluded from the optimization in this study due to its potential interaction between polymers used as dispersants in boiler water and the polymers used as dispersants in cooling water systems. The other examples are shown as follows.

1. It is not allowed to recycle of hydrant water in the superstructure due to potential contamination and its supply instability.

2. Regeneration units (e.g., Demin. Plant, furnace and process units): The water effluents from regeneration units are destined only for the water treatment system.

3. Demineralized water flows to the desalters, following current structure with a variation of flow rates only.

4. Utility water to desalters: It follows existing piping structure with a variation of water flow rates only.

5. The cost of new piping connection is implied to the synthesis in order to minimize unnecessary water stream generation with small amounts of flow rates.

6. Small water streams are excluded from the water balance to avoid unnecessary complexity of water networks and computational

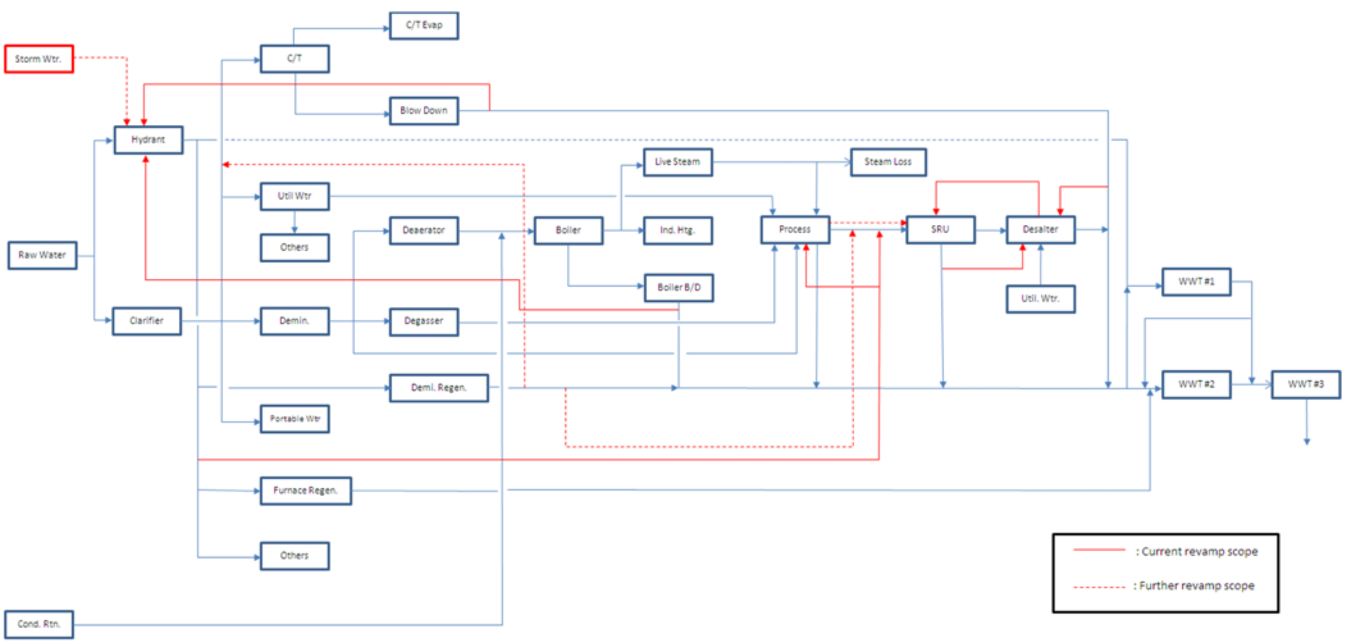

Fig. 13. New water balance networks in refinery.

burden for optimization.

Furthermore, it is quite crucial to specify maximum allowable contaminant level of each unit. For example, the maximum allowable contaminants level should be specified for the feed stream of sour stripper and waste water treatment system. This information can be obtained from each process licensor or manufacturer of the system.

For the modeling and optimization of water network synthesis, commercial programs are available for industrial use (e.g., 'Water Target™' from KBC Energy Service, 'Water®' from Process Integration Centre of The University Manchester, etc.). In this work, 'Aspen Water™' was used for a case study. A superstructure of water networks with 26 potential water sources and 30 water sinks is developed for optimization. Some process operation constraints are overwritten, and it enables further simplification of the optimization programming and prevents impracticality of the solutions. Optimization results of water network synthesis provide a pathway to water saving solutions with detailed modification scope, specific amounts of possible water saving and its contaminant outcomes.

The updated water network is shown in Fig. 13, and some of identified items for revamp are listed below.

1. Cooling Tower blowdown is one of the most pure water effluents without oil contaminants. Therefore, it can be used as hydrant water make-up or desalter feed.

2. Deminalized water should not be used for sulfur recovery units since it is too high quality. Instead, low quality water should be used such as effluents from process or utility system via recirculation.

3. Some water effluents from processes are less contaminated with very low oil concentration. The water effluents shall be used to desalters.

4. Increase of desalter effluents recirculation to sour water stripper can be considered. For example, it was shown that 50% of desalter could be recycled without operational problem.

5. Boiler blowdown is one of the effluents which do not contain oil. Since most of its contaminants is TDS, it can be used as hydrant water make-up or any other purpose including desalter feed.

6. Treated water from a degasser is very high quality water. Therefore, its use should be minimized by replacing it with low grade water wherever possible such as sour water stripper feed.

7. Some more water can be used from stripped sour water to desalter so that it saves some utility water.

Some more items below can be considered to maximize water saving further.

8. Effluents from Demin. Regen. can be considered as a make-up feed to cooling tower. The effluents are generally treated with alkali, while acid is injected to water in cooling tower to prevent growth of algae, bacteria and other micro organism. Therefore, it can save water and chemicals together.

9. Recycle of treated water effluents can be considered for recycling to some process and utility units including cooling tower make-up.

10. Storm water can be considered for hydrant water make-up. Alternatively, it can be used for steam generation after treatment in ultra filter.

The results show that overall raw water saving reaches up to about 28% of existing water consumption. Furthermore, the water treatment saving is about 37% of the existing treatment capacity.

CONCLUSIONS

A generic methodology of water network synthesis by using both a water pinch technology and mathematical optimization of a network super-structure is illustrated. Furthermore, the paper presents a detailed guideline for the modeling of water and contaminant mass balance of individual units, and provides basic strategy of water network synthesis, focusing on practical application to industry.

For a case study, reconciled water and contaminant data which was obtained from annual operating data in refinery complex is used for the balance of whole water streams. As the first step, the maximum water saving target was identified by using water pinch technology. Secondly, mathematical modeling of water network structure was developed based on the balanced water data to identify more detailed roadmap for the improvement of water networks for the purpose of raw water saving and cost reduction of waste water effluents.

Initial pinch technology showed maximum potential raw water saving by up to 45% with reduction of effluent discharge by about 71%, based on a major key contaminant. Then, mathematical optimization was carried out by taking into account the operational and economic constraints, and the results showed that about 28% of existing water consumption could be saved with about 37% reduction of waste water effluents. The later methodology also provided detail roadmap for revamp.

REFERENCES

1. B. Arena and M. Buchan, *Water and the refinery*, AIChE Chicago Symposium (2006).
2. C. H. Smit and K. Smit, *Shell water effluent master plan-principles and applicability to other industries*, Industrial Water Management Conference (1999).
3. B. Linhoff and E. Hindmarsh, *Chem. Eng. Sci.*, **38**(5), 745 (1983).
4. M. M. El-Halwagi and V. Manousiouthakis, *AIChE J.*, **35**(8), 1233 (1989).
5. M. M. El-Halwagi and V. Manousiouthakis, *AIChE J.*, **36**(8), 1209 (1990).
6. Y. P. Wang and R. Smith, *Chem. Eng. Sci.*, **49**(7), 981 (1994).
7. Y. P. Wang and R. Smith, *Chem. Eng. Sci.*, **49**(18), 3127 (1994).
8. Y. P. Wang and R. Smith, *Trans IChemE*, **73**(A), 889 (1995).
9. N. Takama, T. Kuriyama and T. Umeda, *Comp. Chem. Eng.*, **4**, 251 (1980).
10. A. P. Rossiter and R. Nath, *Waste minimization through process design*, McGraw-Hill (1995).
11. S. J. Doyle and R. Smith, *Trans. IChemE*, **75**, 181 (1997).
12. A. Alva-Algáez, A. C. Kokossis and R. Smith, *AIChE Annual Meeting-Miami* paper 13f (1998).
13. C.-H. Huang, C.-T. Chang, H.-C. Ling, and C.-C. Chang, *Ind. Eng. Chem. Res.*, **38**, 2666 (1999).
14. N. Benko, E. Rév and Z. Fonyó, *Chem. Eng. Commun.*, **178**, 67 (2000).
15. J. Jacob, H. Kaipe, F. Couderc and J. Paris, *Chem. Eng. Commun.*, **189**(2), 184 (2002).
16. A. Garrard and E. S. Fraga, *Comp. Chem. Eng.*, **22**(12), 1837 (1998).
17. M.-J. Tsai and C.-T. Chang, *Ind. Eng. Chem. Res.*, **40**, 4874 (2001).
18. D. Prakotpol and T. Srinophakun, *Chem. Eng. Proc.*, **43**, 203 (2004).

19. S. Shafier, S. Domenech, R. Koteles and J. Paris, *J. Cleaner Production*, **12**, 131 (2004).
20. V. Lavric, P. Iancu and V. Plesxu, *J. Cleaner Production*, **13**, 1405 (2005).
21. J. P. Mclntyre, Industrial Water Management Conference (1999).
22. S. Parkash, *Refining Processes Handbook*, Elsevier (2002).
23. M. E. Goldblatt, *Cooling Tower Institute annual meeting*, Paper No. TD 94-89 (1994).
24. R. Smith, *Chemical process design and integration*, John Wiley & Sons (2005).