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A New Algorithm for Water and Wastewater Optimization in Multiple Contaminants Network using Water Pinch Technology

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Abstract: In this study, the principle of water pinch technology, the optimization of water, steam allocation network have been studied and minimization of freshwater utility and wastewater generation in one of the petroleum refineries of Iran is taken into consideration. In order to research in this field and simplify the relevant calculations, an algorithm was developed and applied for reforming the network. There after amount of freshwater utility in the refinery was reduced from 505 to 340 m^3 h^{-1} and operational costs of refinery (treatment systems and wastewater regeneration) were saved more than 700000 USD annually.

Key words: Water pinch technology, water reuse, water regeneration, recycle, targeting

INTRODUCTION

Generally, chemical industries utilize water and generate wastewater greatly. Due to increasing outside pressures for water minimization, industrial owners tend to water reuse as an economical and high quality approach. Water regeneration and partial treatment thereafter water reuse are sometime more economical and easier than discharging according to environmental treatment standards. Therefore, water and wastewater minimization as well as reducing expenditure of freshwater consumption and treatment system in the processing units are currently considered (El Halwagi, 2006; Hallale, 2002; Juliana *et al*., 2006).

Minimizing water utility and wastewater generation, maximizing water reuse and wastewater regeneration reuse and recycle can be considered by developing water pinch technology based on mass transferring. In fact, water pinch analysis is a systematic technique for analyzing water networks and reducing expenditures related to different water-using processes. This method applies an advanced algorithm to optimize water reuse, wastewater regeneration and treatment (Manan *et al*., 2006).

This lets engineers consider water-using processes before and after designing to minimize freshwater consumption and wastewater generation. This technology can analyze systems and estimate (Smith, 2005).

- Minimum freshwater flow-rate
- Minimum wastewater flow-rate
- Reasonable solutions for designing water-using networks and wastewater treatment systems to reach mentioned goals

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Water and steam allocation network in one of the newest refineries in Iran was selected as a case study to show abilities of water pinch technology. It was observed that amount of water consumption and wastewater generation was reduced considerably after optimizing the network b y water pinch technology. This problem has been explained in detail in the next part.

Since, this technology uses graphical methods and complex algorithms and calculations, researchers have designed a algorithm that can be used easily and increase accuracy as well. There are four general methods to minimize water consumption and wastewater generation as below (Tan *et al*., 2007; Yee *et al*., 2003).

Water Reuse

The outlet wastewater from a process can be reused as inlet stream by other processes. It reduces amount of required freshwater and generated wastewater, while it won't affect outlet contaminant load. The outlet stream from a process does not re-enter the same process. Figure 1 shows general thematic of this method.

Wastewater Regeneration Reuse

Partial treatment can remove contaminants from wastewater otherwise would prevent its reuse and then it is reused by other processes. Regeneration can be done by filtration, activated carbon adsorption, pH adjustment and biological treatment. Figure 2 shows this method in detail.

Wastewater Regeneration Recycle

Wastewater can be regenerated to remove contaminants that have been built up and then recycled. In this case, water can re-enter process in which it has previously been used. It is not necessary that water recycling happens around a particular process but it can be done the whole of system. Another remarkable point is distinction between water regeneration reuse and water regeneration recycling due to different applications. Figure 3 shows water regeneration recycling.

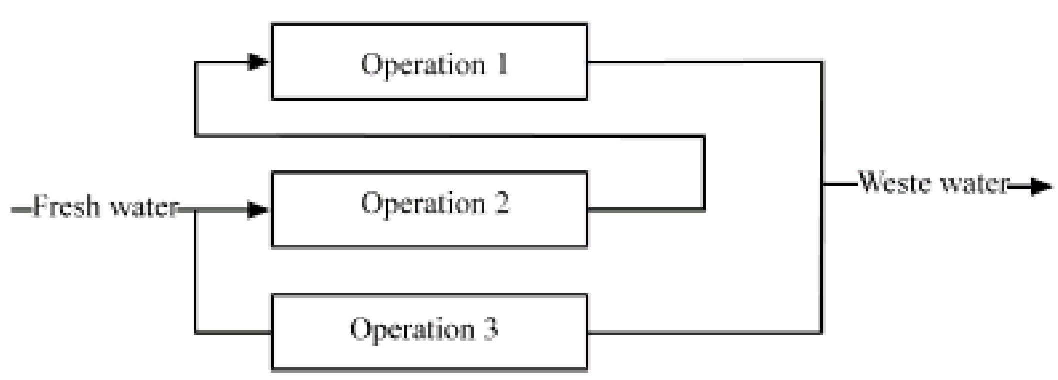

Fig. 1: Water minimization because of reusing it during processes

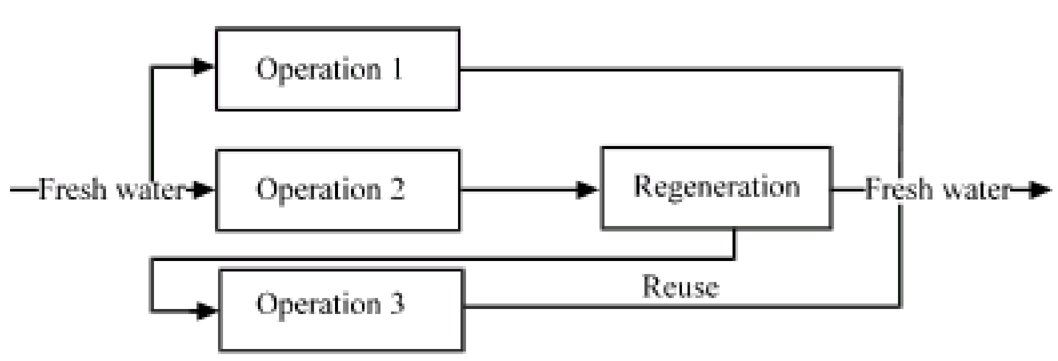

Fig. 2: Water minimization because of wastewater regeneration reuse

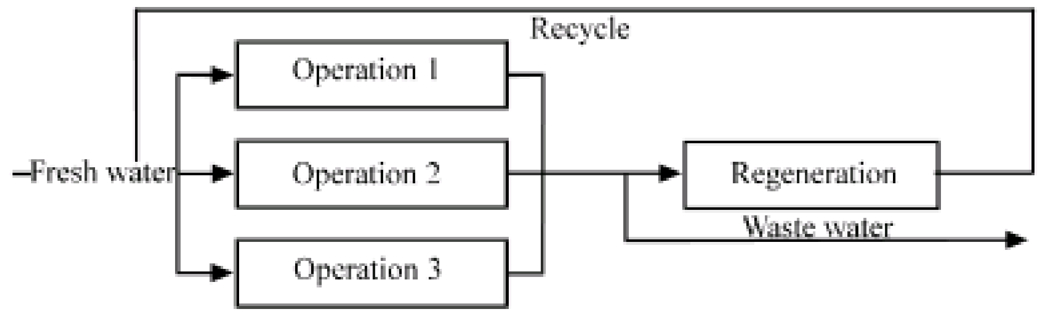

Fig. 3: Water regeneration recycling

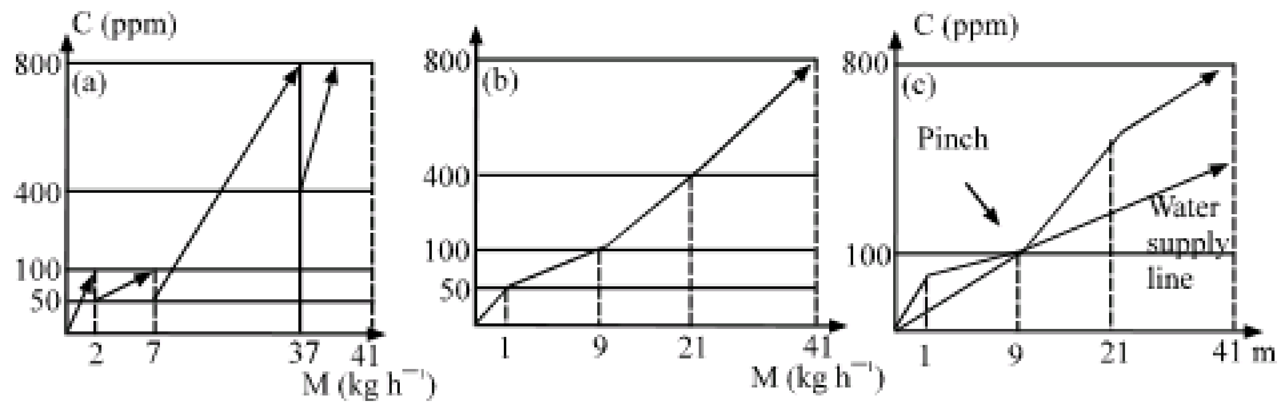

Fig. 4: Limiting water profile, water supply line and concentration composite curve

Process Change

In this method, water natural consumption is reduced. Using of air conditioning instead of cooling towers is a simple example for process change (Panjeshahi *et al*., 2009).

Water pinch analysis is a systematic technique for analyzing water networks and reducing expenditures related to different water-using processes. This method applies an advanced algorithm to optimize water reuse, wastewater regeneration and treatment (Ataei *et al*., 2009). In this technology, the water-using operation is considered as a pollution source that consumes water to remove some contaminants such as physical particles (suspended solid particles), chemical substances, COD, BOD, pH, electrical conductivity etc., these contaminants restrict water reuse in other processes. The simplest method for analyzing water-using systems is simulating them by mass transferring operation unit, so that contaminants are transferred from a rich stream to a lean one. This problem was considered firstly by El-Halwagi and Srinivas (1992) according to rules of heat pinch technology. Then Smith and Wang (1994) studied this problem seriously. They presented a method to maximize water reuse by designing Limiting Water Profile (LWP) and Concentration Composite Curve (CCC), then the pinch point was attained by designing Water Supply Line (WSL) versus these curves and maximum f low-rate of reuse was calculated. Figure 4 shows these curves (Wang and Smith, 1994). This research develops an algorithm that can be use to minimize freshwater utility and wastewater regeneration in the water network. It also highlights the possibility for Maximizing water reuse and wastewater regeneration and reducing expenditure related to different water-using processes.

MATERIALS AND METHODS

Water pinch technology has been currently developed and applied for several cases. Some possibilities such as wastewater regeneration reuse and wastewater regeneration recycle are other abilities of water pinch technology. In addition, this technology is used for multiple contaminant conditions. The solution of problems is based on above-mentioned curves, so that the network is designed by particular algorithms after targeting minimum

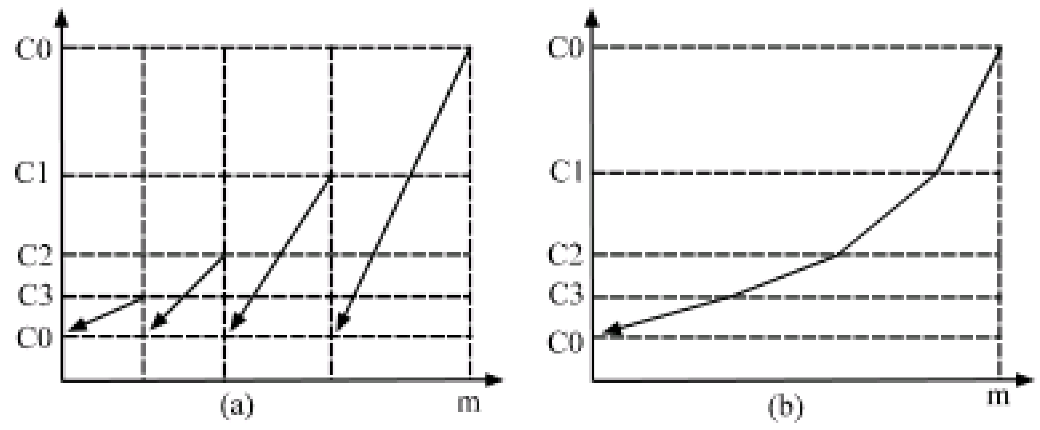

Fig. 5: Wastewater composite curves. (a) Wastewater stream and (b) composite curve

freshwater flow-rate. To design a final network first, a bar diagram is drawn then it is simplified to optimize designing. Drawing above-mentioned curves is necessary. Another point in this case is study on wastewater treatment systems. Allocated treatment system is the most general system, which was used for treating wastewater from several processes that need to treat by different technologies. This method is more effective and economical than the cases in which several wastewater streams are blended and then treated as a single stream in a central treatment system. In central treatment two streams which need different technology are blended and it causes the costs to be increased in comparison with the case in which different treatment systems are considered for each one (Wan Alwi *et al*., 2007).

We can design an allocated treatment system by this technology and draw mentioned carves (Fig. 5). The most important disadvantage related to this method is solving problems by graphs, because graphical methods have their own uncertainty as well as the time-consuming nature. To improve the mentioned disadvantages, an algorithm has been developed by using cascade method based on heat pinch technology introduced at the next part (Bagajewicz, 2000). The research is conducted in one of the petroleum refinery in the center of Iran from 2006 to 2009.

Development of the Algorithm

Drawing LWP, WSL and CCC curves need to spend much time and precision. To overcome this problem, the diagrams were converted to simple mathematical models. Therefore, it is possible to change equations into computer algorithms. To design the algorithm all diagrams and curves are converted to algebraic equations then entered the program, so data, which used in graphical methods are enough for using the program.

General goals of this algorithm are included: calculation of minimum flow-rate, pinch point, possibilities of regeneration with or without recycle and with multiple contaminant streams (In this case one of contaminants is considered as a reference contaminant), calculation of outlet concentration of contaminants and comparing wastewater treatment systems with one or more treatment processes.

The program has been designed in a way to be capable of comparing minimum flow-rate (in some cases without regeneration) with a system which has regeneration. In addition, this program has other capabilities such as water network optimization and cost minimization by mathematical programming techniques, modeling and simulating wastewater treatment network to achieve some data such as flow-rate and analyzing unknown streams of network.

The first part of the program is related to calculating required flow-rate for an industrial process. Figure 6 shows general relation between LWP and WSL for process i (Kuo and Smith, 1997).

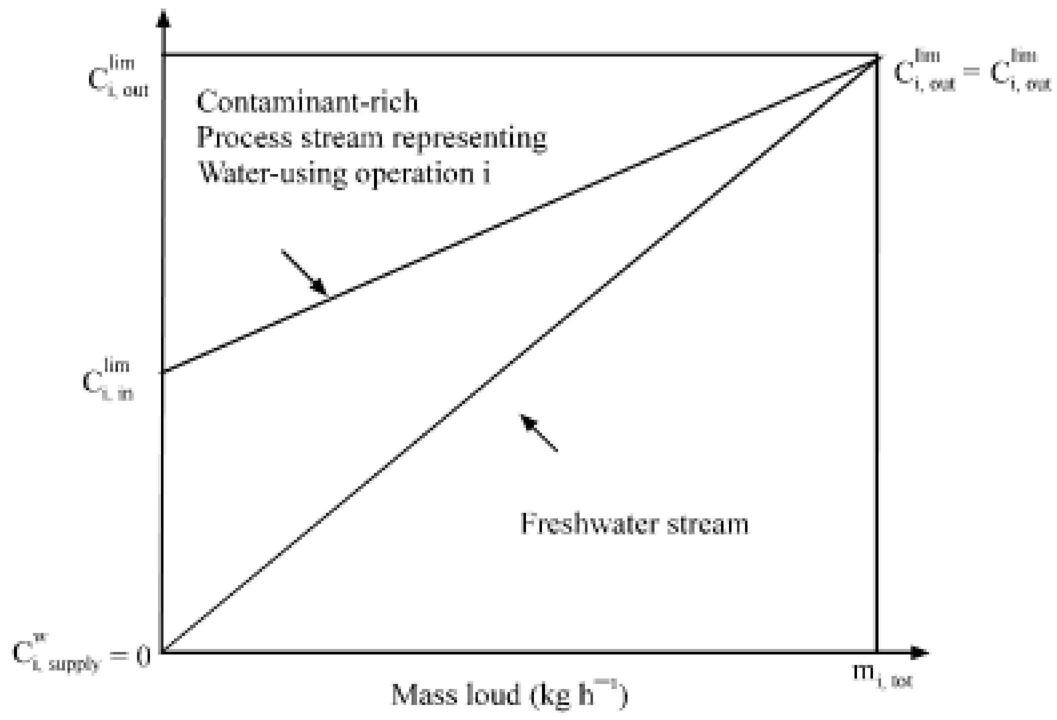

Fig. 6: The relation between LWP and WSL for process i

As it shows there is a reversal relation between water flow-rate for process i (f_i (t h^{-1})) and slope of WSL (Kuo and Smith, 1998):

$$s = \frac{\Delta c_i (ppm)}{\Delta m_{i,tot} (kg\ h^{-1})} \quad (1)$$

$$f_i \left(t\ h^{-1}\right) = \frac{\Delta m_{i,tot} \left(kg\ h^{-1}\right)}{\Delta c_i \left(ppm\right)} \times 10^3 = \frac{1}{S} \times 10^3 \quad (2)$$

$$f_i \left(t\ h^{-1}\right) = \frac{\Delta m_{i,tot} \left(kg\ h^{-1}\right)}{\left[c_{i,,out}^{w} - c_{i,in}^{w}\right](ppm)} \times 10^3 \quad (3)$$

If freshwater is used and minimum flow-rate is considered the below equation is obtained:

$$c_{i,in}^{w} = 0 \quad (4)$$

$$c_{i,out}^{w} = c_{i,out}^{lim}$$

$$f_{i,min} = \frac{\Delta m_{i,tot}}{c_{i,out}^{lim}} \times 10^3$$

This equation shows minimum freshwater flow-rate for a water- using operation. In the case that there are several operations, total flow-rate for a problem with single contaminant and without water reuse is calculated as below:

$$f_{min}(t\ h^{-1}) = \sum_i \frac{\Delta m_{i,tot} (kg\ h^{-1})}{c_{i,out}^{lim}} \times 10^3 \quad (5)$$

If there is possibility of water reuse, outlet stream from an operation can be used by another operation while amount of that contaminant does not affect the second operation.

This algorithm uses a method which named "Tabular Method" to solve these problems. Therefore, transferred mass can be calculated by these equations of cascade method at each interval and then flow-rate is obtained to separate the mass.

$$m_{i,k}(\text{kg h}^{-1}) = \frac{(\sum f_i^{\text{lim}})(\text{t h}^{-1}) \times (c^*_{k+1} - c^*_k)(\text{ppm})}{10^3} \quad (6)$$

$$\Delta m_k = \sum_k m_{i,k} \quad (7)$$

$$f_k(\text{t h}^{-1}) = \frac{\Delta m_k(\text{kg h}^{-1})}{c^*_k(\text{ppm})} \times 10^3 \quad (8)$$

The line, which touches the lowest point in CCC, shows minimum required flow-rate. According to these equations, a flowchart can be provided by computer to solve the problem (Fig. 7).

If there is water reuse after regeneration, below equation is used:

$$\Delta m_{pinch} = f_{min} \times c_{pinch} + f_{min}(c_{pinch} - c_0) \quad (9)$$

Also if recycling of regenerated water is permissible:

$$\Delta m_{regen} = f_{min} c_{pinch} \quad (10)$$

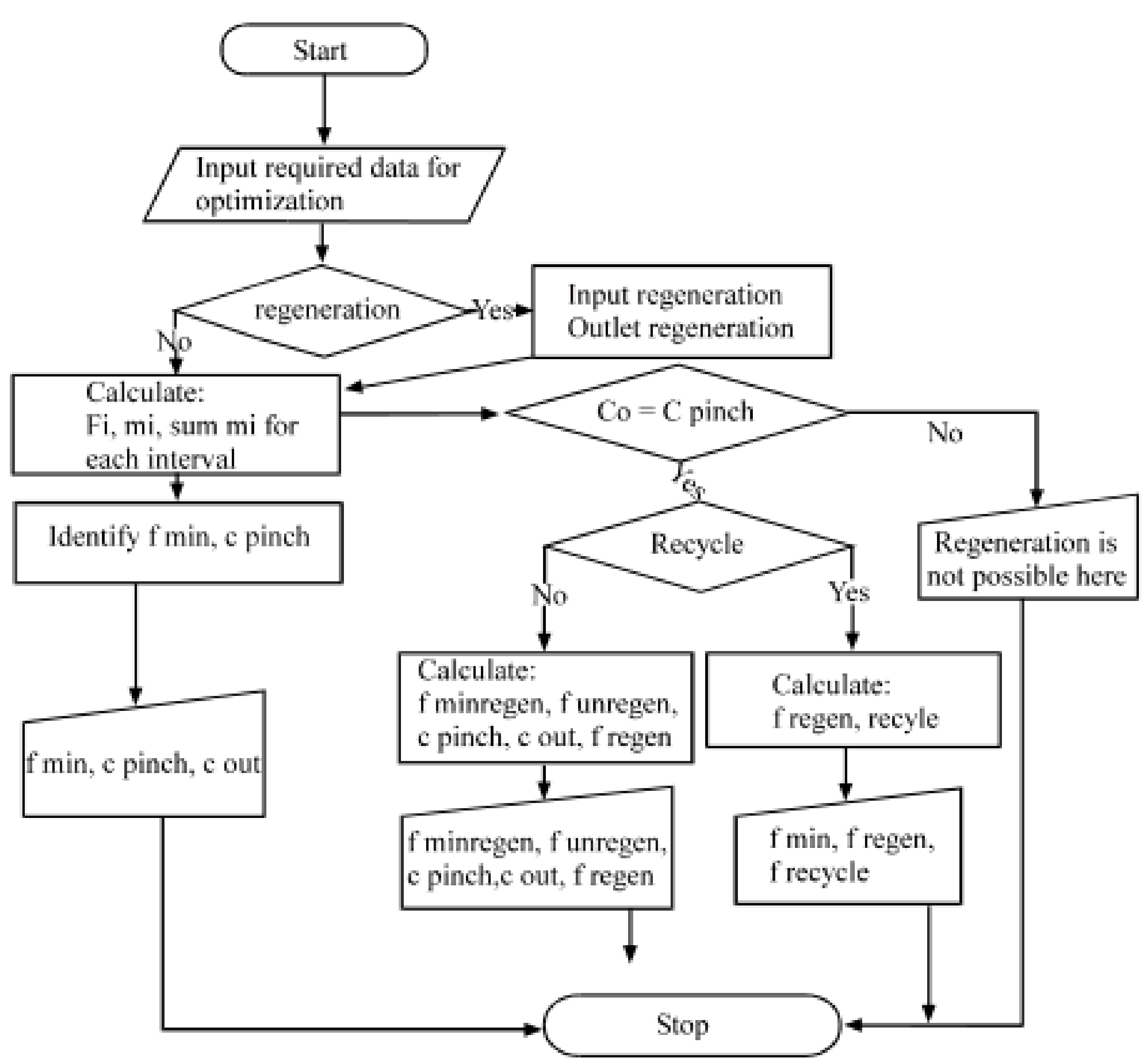

Fig. 7: Flowchart with single contaminant

$$\Delta m_{pinch} - \Delta m_{regen} = f_{regen}(c_{pinch} - c_0) \quad (11)$$

Therefore, regeneration flow-rate (f_{regen}) is not equal to minimum freshwater flow-rate (f_{min}). Sum of two above equation gives transferred mass load before pinch concentration.

$$\Delta m_{pinch} - \Delta m_{regen} = f_{regen}(c_{pinch} - c_0) \quad (12)$$

In addition, the regenerated water flow-rate is obtained by ordering this equation:

$$f_{regen} = \frac{\Delta m_{pinch} - (f_{regen} c_{pinch} / 10^3)}{c_{pinch} - c_0} \times 10^3 \quad (13)$$

All of these equations are obtained by analyzing before mentioned curves, which have been shown at program flowchart. Solving program with multiple contaminants is another ability of this algorithm. In this case, solution of problems is based on proportion of contaminants. It is supposed that mass transferring of contaminant j in process i is considered the ratio of mass transferring of each contaminant in this process. Therefore, the ratio of transferring is:

$$\frac{c_{i,A,out} - c_{i,A,in}}{c_{i,B,out} - c_{i,B,in}} = \frac{m_{i,A}}{m_{i,B}} = TR \quad (14)$$

The flow chart of these calculations is shown in Fig. 8 and flowchart of the program with several treatment processes is shown in Fig. 9.

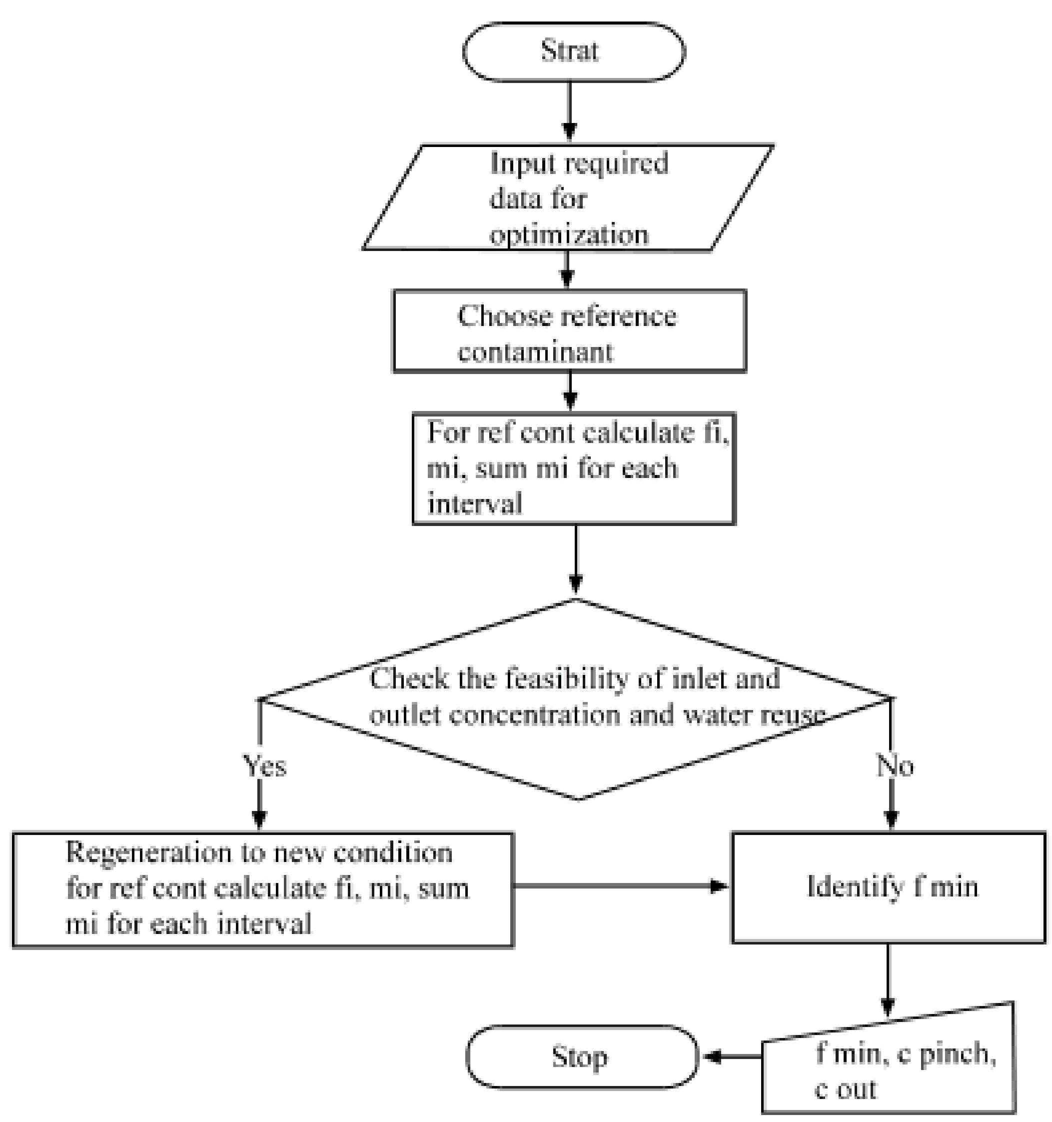

Fig. 8: Program flowchart with single contaminant

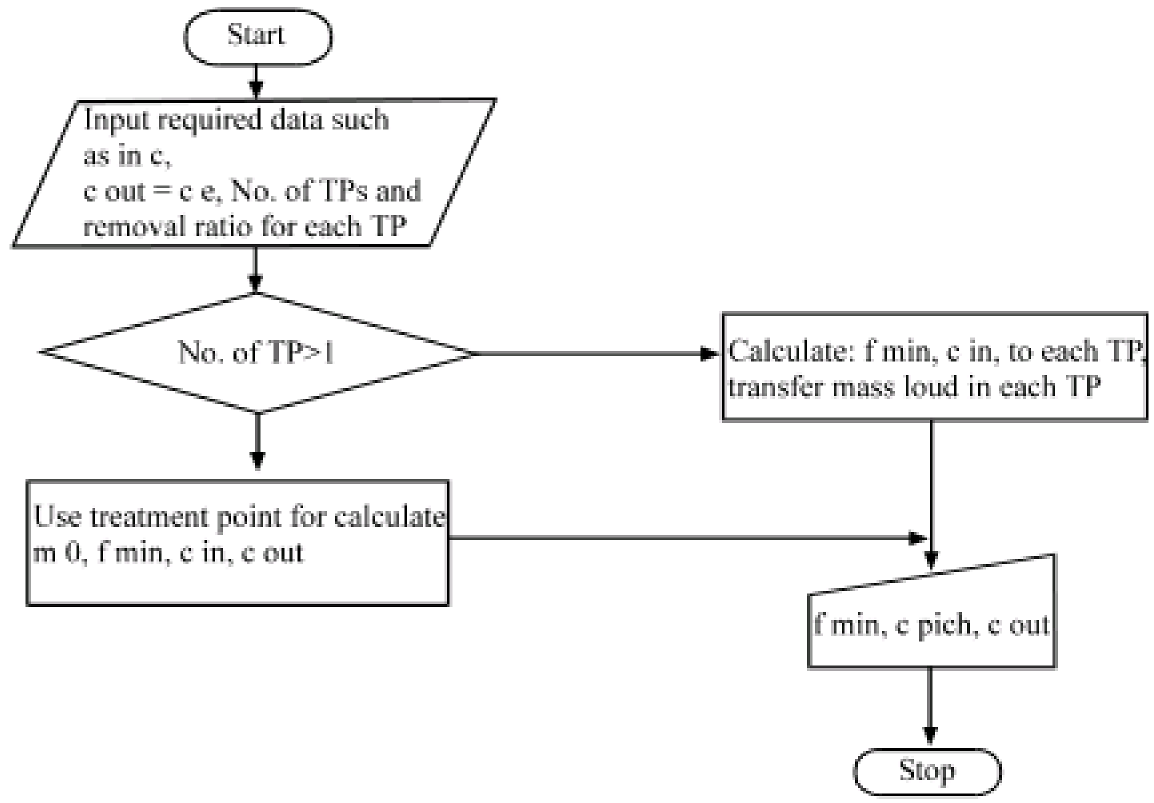

Fig. 9: Program flowchart with multiple contaminants

Running program for several examples indicated that the algorithm is applicable in all of cases.

In the next part, potential of water minimization has been assessed in a refinery as a case study. Water allocation network is targeted by using developed models and reformed to achieve the targets.

RESULT AND DISCUSSION

Case Study

Reforming water and steam allocation network in a petroleum refinery in Iran. To minimize fresh water consumption, water and steam allocation network can be targeted and reformed by some equations and algorithm which have been developed to simplify and increase accuracy of calculation in water pinch technology.

Generally, to assess potential of water and wastewater minimization in industrial units by water pinch technology it is necessary to collect limiting data about the kind of utilities and water-using processes. Then the industrial unit is targeted by developed algorithm of water pinch technology and finally the network is designed and reformed so as to obtain amounts of mass transferred, minimum freshwater and operational cost of wastewater regeneration.

Stages of this method in industrial processes are included:

- Study on water utility in the units
- Collecting limiting data
- Targeting units
- Designing and surveying economical issues in the project

Study on Water Utility in the Refinery

To supply required water for steam and electricity generation and other utilities in the studied refinery seven wells have been dogged.

Amount of water utility from the wells is about 545 t h^{-1} and with considering amount of utilized fresh water before entering the refinery, total water consumption is 505 t h^{-1} that included below cases:

- Fire water about 20 t h^{-1}
- Utility related to compensate cold water cycle in cooling towers is about 113 t h^{-1}
- Utility related to generate pure water and steam is 224 t h^{-1}
- Utility related to drinkable water is about 26 t h^{-1}
- Utility of units is about 112 t h^{-1}

Required cold water for chillers pumps, compressors and heat convectors is provided by cooling towers. Cold water flow-rate in this closed cycle is about 22000 t h^{-1} and the temperature of water is reduced from 49 to 29°C. Some water is reduced in the cycle about 217 t h^{-1} because of evaporation, losses and cold water processing utilities. This amount is provided by:

- 112 t h^{-1} by freshwater from wastewater
- 104 t h^{-1} by blow down wastewater of boilers, stripper water, reversed condenses and plant wastewater that has been regenerated during American Petroleum Institute (API), Dissolved Air Flotation (DAF) and Biological treatment processes. Blow down of cooling tower with blow down of the units, which generate pure water, enter evaporation pounds

The units of pure water regeneration included three sections, which have 180 t h^{-1} capacities for each. About 224 t h^{-1} water is used by this unit. Total amount of generated pure water and condensed water stream is equal to 640 t h^{-1} that provides required water of five boilers to generate water steam. Therefore, required water for boilers is provided as below:

- 208 t h^{-1} pure water that is provided by using 224 m^3 h^{-1} freshwater
- 432 t h^{-1} pure water that is generated from condensation of steam

Fire water is about 20 t h^{-1} and its wastewater with rain and other water streams flow into rain pounds

Utility of plant water is about 122 m^3 h^{-1} that is consumed for washing processes and planting. Its treated wastewater is 95 m^3 h^{-1} that is used by cooling towers.

Figure 10 shows simplified flowchart of water and steam allocation network in the case studied refinery.

Table 1 shows streams constraints in the network that have been numbered.

As Fig. 10 shows, the network has wastewater treatment and regeneration facilities and some required water for processes is provided by regeneration of wastewater from other processes. As it is seen the water and steam network in the case study has been designed very well and water utility as well as wastewater generation is in a good situation. Most of generated wastewater is reused or regenerated then reused. For example, most of water utilities by cooling towers and boilers are based on regeneration reuse technique or somewhere total required water for desalter crude oil unit is provided by regenerated sour water so no freshwater is used. Although, the primary design of the refinery is not based on water pinch analysis, water utility and wastewater generation is low naturally.

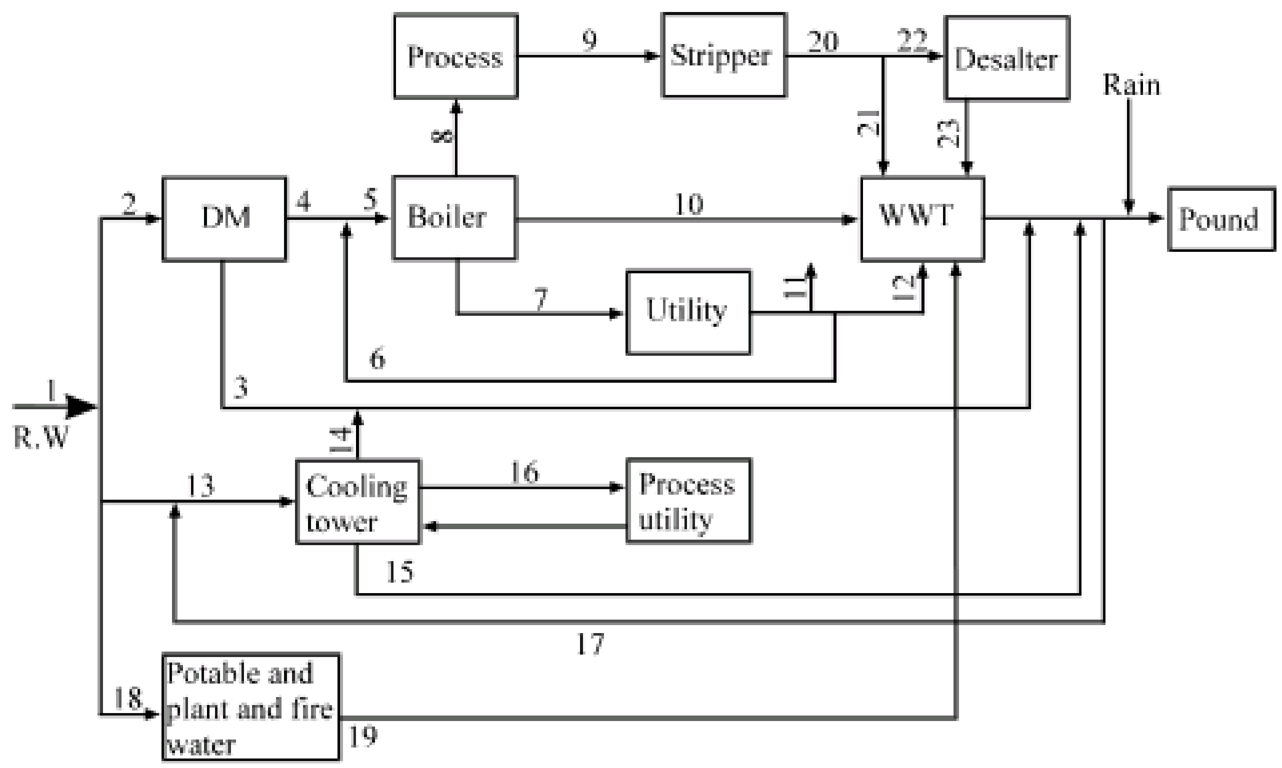

Fig. 10: Flowchart of water and steam allocation network in the refinery

Table 1: Flow-rate and stream constraints in the case study according to the order in Fig. 10

No.	Flow-rate	Stream constraints (conductivity μs cm^{-1} and others ppm part from pH)
1	505	pH = 7/9, T.COND. = 360, T.H = 150, M-ALK = 140, SiO_2 = 9/3, SS = 1, TSS = 2/15, T.Fe<0/05, CL_2<0/05
2	224	pH = 7/9, T.COND. = 360, T.H = 150, M-ALK = 140, SiO_2 = 9/3, SS = 1, TSS = 2/15, T.Fe<0/05, CL_2<0/05
3	208	PH = 9/2, T.H = Neg, SiO_2 = 0/023, SS = 1, TSS = 2/05
4	16	T.COND. = 71400, T.H = 840, SiO_2 = 1/3, SS = 10, TSS = 15/8, T.Fe = 11/1, CL_2<0/05
5	104	pH = 7/6, T.COND. = 1400, T.H = 270, M-ALK = 66, SiO_2 = 9/87, S.S = 2, T.SS = 2/66, T.Fe<0/05, CL_2<0/05
6	78	Water steam (t h^{-1})
7	542	Water steam (t h^{-1})
8	432	Ph = 9/1, T.COND.= 2/3, T.H = Neg., SS = 1, TSS = 2, T.Fe<0/05, CL_2<0/05
9	640	pH = 9/1, T.COND.<5, T.H = Neg., SS = 1, TSS = 1, T.Fe<0/05, CL_2<0/05
10	20	pH = 9/8, T.COND. = 90, TH = 0, T.Fe<0/05, PO_4 = 20
11	78	pH = 9/5, T.COND. = 14960, T.H = 10, M-ALK = 44, SiO_2 = 6/5, SS = 348, TSS = 850, T.Fe<0/12, CL<0/05, H_2S = 6586, NH_3 = 3948
12	45	pH = 9/1, T.COND. = 2/3, T.H = Neg., SS = 1, TSS = 2, T.Fe<0/05, CL_2<0/05
13	65	Water steam (t h^{-1})
14	113	pH = 7/9, T.COND. = 360, T.H = 150, M-ALK = 140, SiO_2 = 9/3, S.S = 1, T.SS = 2/15, T.Fe<0/05, CL_2<0/05
15	175	Water steam (t h^{-1})
16	37	pH = 7/1, T.COND. = 4350, T.H = 1250, M-ALK = 30, SiO_2 = 48/9, S.S = 1, T.SS = 2/95, T.Fe = 0/35, CL_2 = 2/5
17	22609	pH = 7/1, T.COND. = 4350, T.H = 1250, M-ALK = 30, SiO_2 = 48/9, S.S = 1, T.SS = 2/95, T.Fe = 0/35, CL_2 = 2/5
18	168	pH = 7/9, T.COND. = 360, T.H = 150, M-ALK = 140, SiO_2 = 9/3, SS = 1, TSS =2/15, T.Fe<0/05, CL_2<0/05
19	160	pH = 7/3, T.COND. = 930, T.H = 241, M-ALK = 23, SS = 22
20	76	pH = 5/5, T.COND. = 850, TH = 12, M-Alk = 44, SiO_2 = 6/6, SS = 13, TSS = 24/3, Tfe = 0/83, CL_2<0/05 H_2O = 3/4, NH_3 = 46
21	17	pH = 5/5, T.COND. = 850, TH = 12, M-Alk = 44, SiO_2 = 6/6, SS = 13, TSS = 24/3, Tfe = 0/83, CL_2<0/05 H_2O = 3/4, NH_3 = 46
22	59	pH = 5/5, T.COND. = 850, TH = 12, M-Alk = 44, SiO_2 = 6/6, SS = 13, TSS = 24/3, Tfe = 0/83, CL_2<0/05 H_2O = 3/4, NH_3 = 46
23	59	pH = 6.5, T.COND. = 1600, TH = 160, M-Alk = 40, SiO_2 = 1.4, SS = 20, TSS = 25, T.Fe = 3.12, CL_2<0.05

Table 2 presents systems and constraints. The real amount of operational costs for each treatment and regeneration system in the network has been estimated by studying available documents and current bills.

Table 2: Performance parameters and constraints of wastewater treatment and regeneration systems

Treatment process	Pollutants which are separable	RR	Maximum concentration (ppm)	Maximum flow-rate ($t\ h^{-1}$)	Flow-rate of current treated wastewater	Operational costs USD m^{-3}
A.P.I A, C	COD	0.285	350	280,72.6	162,59	0.25
	BOD	0.218	256			
	Oil	0.920	1000			
	SS	0.980	500			
Biological	Oil	0.920	12.5	280	162	0.90
	BOD	0.930	288			
	COD	0.610	260			
	SS	0.800	25			
DFA	BOD	0.091	Unlimited	280	162	0.60
	COD	0.025	Unlimited			
	SS	0.875	100			
	Oil	0.875	100			
Warm Lime Softener	TH	0.931	Unlimited	170	0	0.75
SWS	H_2S	0.999	7030	78	76	0.90
	NH_3	0.985	3374			
Sanitary, Bio	BOD	0.950	Unlimited	16	19	0.60
	COD	0.950	Unlimited			

Table 3: Maximum inlet and outlet flow-rate of water-using units

Equipments	F_{in} ($t\ h^{-1}$)	F_{out} ($t\ h^{-1}$)	F_{max} ($t\ h^{-1}$)
DM.W.	224	224	630
Boiler	640	640	1130
Process unit S.W	78	78	80
Utility	542	477	588
Cooling tower	217	41	389
Potable, fire and plant water	168	160	539

Table 4: Limiting concentration of streams

No.	Stream constraints (conductivity µs cm^{-1} and others ppm apart from pH)
8	pH = 8.3-9.2, T.COND<5, T.Fe<0.05, SS<0.1, T.H<0.2, T.HYDRAZINE = 0.02-0.05
(13), (14), (36), (37)	pH = 8.7-9.2, T.COND<5, T.Fe<0.05, T.H = 0
38	pH = 9.5-10.2, T.COND = 80-100, T.Fe<0.05, SS<5, PO_4<10-30, T.H = 0
25	pH = 8-8.5, T.COND<4000, T.Fe<1, SS<100, T.H<1250, M-ALK = 100-150, T.BC<10000, SRB = Neg., CHLORIDE<1000, CL_2<2, NACLO = 40-60
18	pH = 6-8, T.COND<1400, SS<20, PO_4<4, NH_3<1, H_2S<1, T.H<400, COD<100, BOD<70, SS = 5, T.BC<10000, SRB = Neg., NaCl<600
(29), (30), (31)	pH>5, NH_3<50, H_2S<7
32	pH = 5-9, CHLORIDE<20, COPPER<250
1	SS = 1, T.Fe<0.05, CL_2<0.05, SiO_2 = 9.3, pH = 7.9, T.COND = 360, T.H = 1502 SS = 1, T.Fe<0.05, CL_2<0.05, SiO_2 = 9.3, pH = 7.9, T.COND = 360, T.H = 150
6	SS = 1, T.Fe<0.05, CL_2<0.05, SiO_2 = 9.3, pH = 7.9, T.COND = 360, T.H = 150
28	H2S<7030, NH_3<3374, pH = 9-9.5
23	COD = 375, BOD = 300, FREE OIL = 250, SS = 5, pH = 6-8
40	COD = 375, BOD = 300, FREE OIL = 250, SS = 5, pH = 6-8

Since 76 $t\ h^{-1}$ wastewater by sour water regeneration system, 59 $t\ h^{-1}$ wastewater by API,C and 162 $t\ h^{-1}$ by American Petroleum Institute (API), Dissolved Air Flotation (DAF) and Biological systems and also 19 $m^3\ h^{-1}$ wastewater by sanitary treatment are treated, accordingly the total operational cost of these systems is calculated as below:

$$59 \times (0.25) + 162 \times (1.75) + 76 \times (0.9) + 19 \times (0.6) + 0 \times (0.75) = 378\ \text{USD}\ h^{-1}$$

Collecting Limiting Data

Figure 10 shows simplified flowchart of water and steam allocation network in the refinery. Limiting flow-rates of each water-using process has been presented in Table 3 and limiting concentrations of streams is shown in Table 4 according to the order in Fig. 10. As it is seen eight main constraints, which cause most limitation for water reuse and regeneration, were considered as limiting contaminants to optimize water utility and wastewater generation. These contaminants were oil, SS, COD, BOD, PO_4, TH, NH_3 and H_2S. These pieces of information have been collected from available documents in the refinery.

Network Optimization

Since, reformation of network based on targeting results for the whole network according to simplified flowchart is very complex, expensive and impossible so considering a part of the network, targeting and reforming it can be more practical. The optimum point may be found by this cheap method.

Selecting a part of water and steam network is made where there are not some utilities such as drinkable water, firewater, boilers and water steam because boilers as an example utilize just pure water or freshwater is consumed for drinking and demand in these systems is not reduced by water reuse and regeneration. Therefore, these utilities in the selected network cause complexity for targeting and designing. Of course, the targeting and reforming are done just on the selected sub-network and other parts of the network do not change. Figure 11 shows flowchart of current streams in the selected network and Table 5 shows current condition of optional network. In addition, Table 6 and 7 shows limiting data for eight contaminants in water streams and water-using systems of network, respectively. In

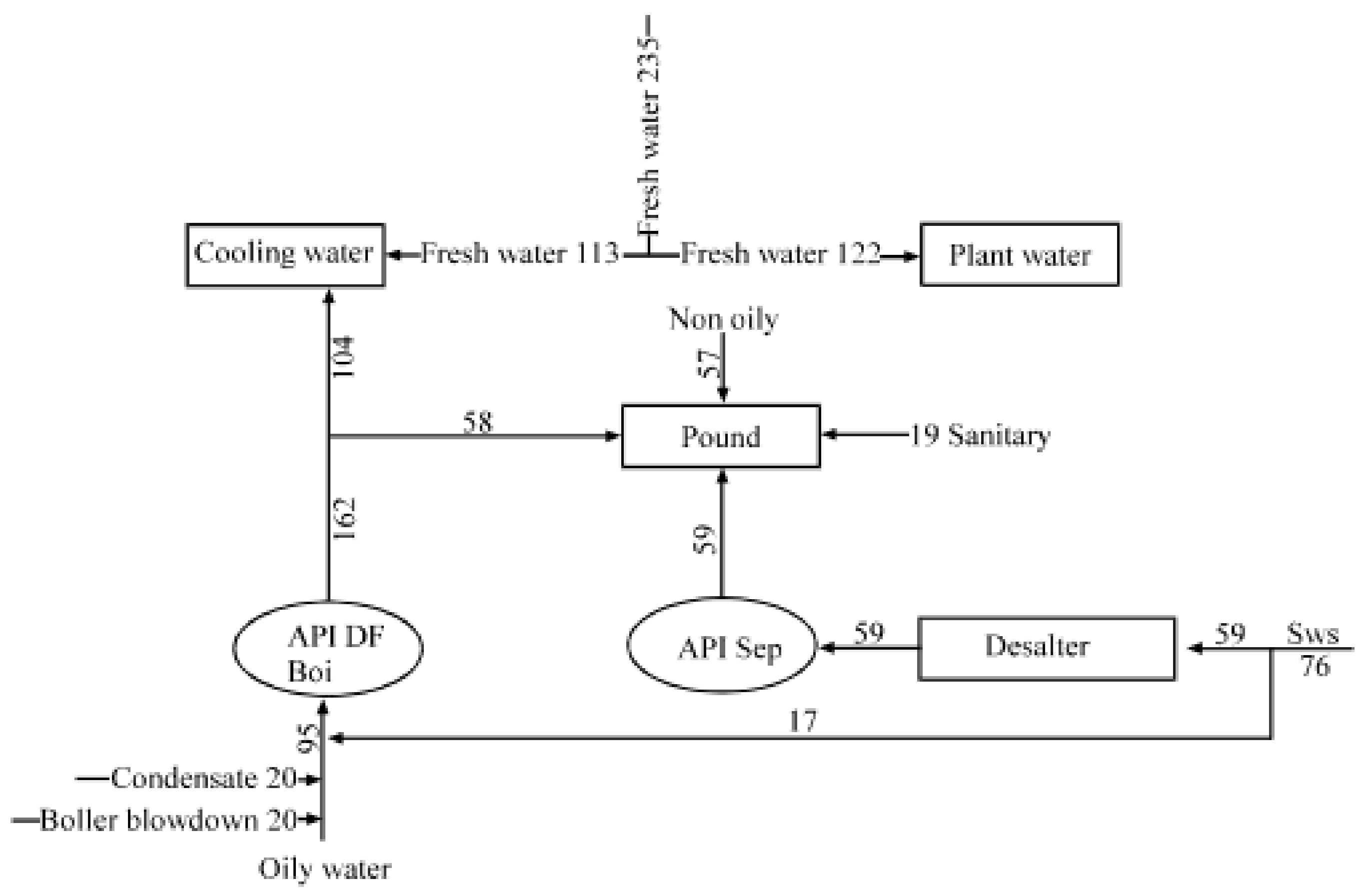

Fig. 11: Selected water network in current situation

Table 5: Current situation of the network

Parameter	Amount
Total required water for targeting network	235 t h^{-1}
Total wastewater discharged to evaporation pounds	193 t h^{-1}
Total treated water stream in API separator	59 t h^{-1}
Total treated water stream in API/DAF/Biological systems	162 t h^{-1}
Total regenerated water in softener system	0 t h^{-1}
Total treated water in SWS system	76 t h^{-1}
Total treated water in sanitary/Bio system	19 t h^{-1}
Total operational costs for wastewater treatment and regeneration system	378 USD h^{-1}

Table 6: Limiting data for eight contaminants in water streams (ppm)

Stream	F (t h^{-1})	SS	Oil	COD	BOD	TH	PO_4	NH_3	H_2S
Sanitary outlet	19	1	0	70	70	200	0	0	0
Oily water	95	5	250	375	300	310	0	0	0
Boiler blow down	20	4	0	0	0	0	30	0	0
SWS outlet	76	13	0	0	0	12	0	50	7
Desalter outlet	59	20	100	0	0	160	0	0	0
Non oily water	57	16	4	70	50	1150	0	0	0
Condensate water	30	1	0	0	0	0	0	0	0

Table 7: Limiting data for eight contaminants for main water utilities (ppm)

Main utility	F (t h^{-1})	SS	Oil	COD	BOD	TH	PO_4	NH_3	H_2S
Cooling tower	217	5	4	100	100	400	4	4	4
Desalter	59	13	20	4	4	20	0	50	7
Plant water	122	4	4	4	4	300	0	4	4

Table 8: Targeting results of network

Parameter	Amount
Total required water for targeting network	70 t h^{-1}
Total wastewater discharged to evaporation pounds	28 t h^{-1}
Total targeting costs from reducing water utility	105600 USD $year^{-1}$
Total treated water stream in API separator	31 t h^{-1}
Total treated water stream in API/DAF/Biological systems	95 t h^{-1}
Total regenerated water in softener system	57 t h^{-1}
Total treated water in SWS system	76 t h^{-1}
Total treated water in sanitary/Bio system	19 t h^{-1}
Total operational costs for wastewater treatment and regeneration system	295.1 USD h^{-1}
Total targeting saving in the selected network	768800 USD $year^{-1}$

targeting method, one of the contaminants that mentioned above is considered as a key contaminant and the whole network is targeted based on the key contaminant. As it was mentioned, the key contaminant does not change the main result of process integration in water pinch method but correct collection helps to calculate easily.

It is supposed that the output of selected network is about 8000 h y^{-1}, one US dollar is equal to 10000 Rials and price of water per m^3 is about 800 Rials (Table 8).
Selected network utilizes 235 m^3 h^{-1} freshwater currently that can be reduced by applying water pinch technology up to 70 m^3 h^{-1} while the other parts of refinery which use 270 m^3 h^{-1} remain unchanged. On the other, hand total freshwater demand for water and steam allocation network is reduced from 505 to 340 m^3 h^{-1} that is equal to 32.67%.

The selected network can be synthesized by using graphical designing method in water pinch technology to reach targeting results. Therefore selected water network in Fig. 11 is reformed according to Fig. 12. Comparison of Fig. 11 and 12 shows that water regeneration reuse has been increased but freshwater demand has been reduced considerably so that 25 m^3 h^{-1} required water of units and also 45 m^3 h^{-1} reversed water for cooling towers are provided by freshwater and the others are provided by water regeneration reuse

As it was mentioned the other parts of water and steam network which use 270 m^3 h^{-1} freshwater and include some utilities such as pure water generation, steam network and drinking water generation did not enter the selected network. They remained unchanged due to no possibility for water regeneration reuse.

Finally freshwater utility in the refinery was reduced from 505 to 340 m^3 h^{-1} and more than 700000 USD was saved in annual cost of the refinery. As it has been mentioned earlier and according to results of research, water utility and wastewater generation as well as expenditure related to different water-using processes have been minimized by developing algorithm based on water pinch technique.

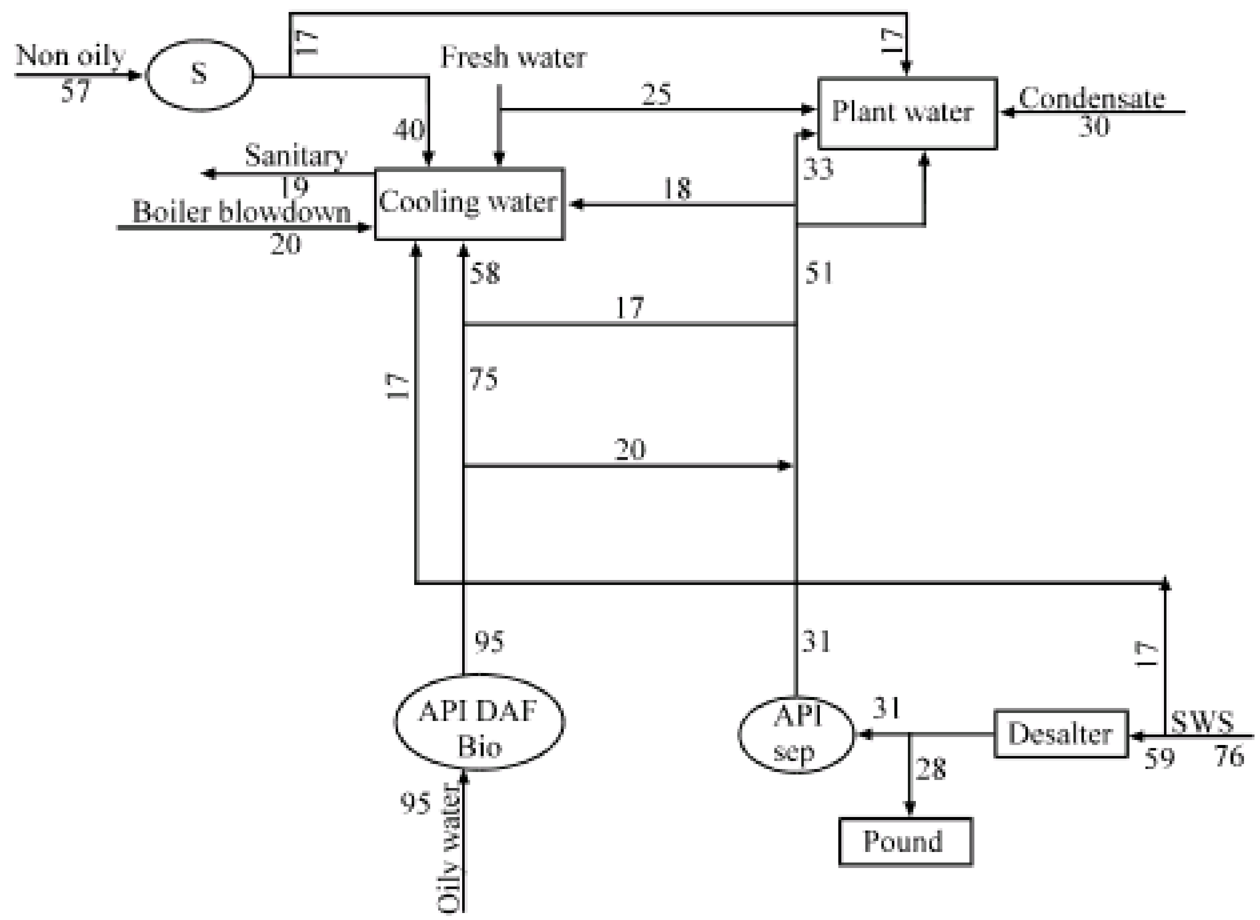

Fig. 12: Final design for the selected water network

CONCLUSION

In this study, water pinch technology was introduced as a systematic method to minimize freshwater utility and wastewater generation in processing industries. Furthermore, an algorithm was developed to convert diagrams and graphical methods to mathematical equations and increase accuracy of calculations.

Water and steam allocation network in a refinery in Iran was considered as a case study to illustrate abilities of this technology and to develop the algorithm.

The network of case study used 505 $m^3 h^{-1}$ freshwater and 270 $m^3 h^{-1}$ of it was used for some cases such as boilers, pure and drinking water generation and so on. Due to no possibilities for water regeneration reuse in above cases, they did not enter the selected network.

The selected network used 235 $m^3 h^{-1}$ freshwater in current situation and operational costs of wastewater treatment and regeneration systems were about 378 USD h^{-1}. This network was targeted and reformed by applying water pinch technology and the developed algorithm so that required freshwater and operational costs were reduced up to 70 $m^3 h^{-1}$ and 295.1 USD h^{-1}, respectively. Therefore, total freshwater demand of refinery was reduced from 505 to 340 $m^3 hm^3 h^{-1}$ that was equal to 32.67% and more than 700000 USD was saved annually.

NOMENCLATURE

SWS = Sour Water Stripper
WLS = Warm Lime Softener
RR = Removal Ratio
$C^{lim}_{i,in}$ = Limiting inlet concentration of contaminant i (ppm)
$C^{w}_{i,in}$ = Inlet concentration of contaminant I in water stream (ppm)

$C^{w}_{i,out}$ = Outlet concentration of contaminant I in water stream (ppm)
C^{*}_{k} = Concentration of contaminant at boundary k (ppm)
C^{*}_{pinch} = Concentration of contaminant at boundary pinch (ppm)
C_{regen} = Inlet concentration in to regeneration process (ppm)
C_{e} = Limiting environmental concentration (ppm)
C_{o} = Outlet concentration from regeneration process (ppm)
F^{lim}_{I} = Limiting flow-rate (t h^{-1})
F_{min} = Minimum fresh water flow-rate (t h^{-1})
F_{regen} = Regenerated water flow-rate (t h^{-1})
$\Delta m_{I,tot}$ = Total transferred mass load below boundary k (kg h^{-1})
Δm_{k} = Total transferred mass load below pinch (kg h^{-1})
Δm_{regen} = Transferred mass load before regeneration process (kg h^{-1})
m^{i}_{o} = Amount of limiting point of treatment in negative part of axis x (kg h^{-1})
T_{COND} = Total conductivity
TS = Total Solid
SS = Suspended Solid
TDS = Total Dissolved Solid
COD = Chemical Oxygen Demand
BOD = Biological Oxygen Demand
LWP = Limiting Water Profile
WSL = Water Supply Line
LCC = Limiting Composite Carve
FWP = Fresh Water Pinch
CCC = Concentration Composite Carve
S = Slope
TR = Transfer Ratio

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