Minimizing Fresh and Wastewater Using Water Pinch Technique in Petrochemical Industries

W. Mughees, M. Al-Ahmad, M. Naeem

Abstract—This research involves the design and analysis of pinch-based water/wastewater networks to minimize water utility in the petrochemical and petroleum industries. A study has been done on Tehran Oil Refinery to analyze feasibilities of regeneration, reuse and recycling of water network. COD is considered as a single key contaminant. Amount of freshwater was reduced about 149 m³/h (43.8%) regarding COD. Re-design (or retrofitting) of water allocation in the networks was undertaken. The results were analyzed through graphical method and mathematical programming technique which clearly demonstrated that amount of required water would be determined by mass transfer of COD.

Keywords—Minimization, Water Pinch, Water Management, Pollution Prevention.

I. INTRODUCTION

EXCESSIVE usage of industrial water affected it’s future availability. Reduction of water consumption has received attention of many researchers. El-Halwagi and Manousiouthakis suggested a technique to produce a mass exchange networks [1].

Many industries are saving their economy by practicing on this waste recovery applications. Pinch Analysis was proposed many years early [2]. After some time a graphical method was offered to determine the freshwater target. This proposed method got the attention of many researchers [3] later on many industrial practices proved the success of this technology. Sorin and Be’dard presented the evolutionary table method to estimate the freshwater target [4]. Proposed graphic method “the water surplus diagram” was to target the fresh water [5]. Even though his method created the right pinch points, it was tedious. Manan et al. after some time proposed a non-iterative numerical method, water cascade analysis, [6] to target the freshwater. He addressed that their method can provide important insights on pinch-causing streams and sinks and sources in the process. The sinks and sources are considered as sources. However, freshwater and waste water is also placed under sources category as some of the waste streams cannot be used/reused as sources to the unit. Pinch technique graphical method has been used to carry out the required objective and also mathematical programming has been developed to verify the results. Results from mathematical programming have showed the allocation of best possible network of source stream(s) to the demand stream(s) also. The results of this work are more precise than the referred previous work discussed in the literature.

II. METHODOLOGY & CASE STUDY

The selected process/unit is firstly divided into sinks and sources streams. Sinks streams are categorized as inlet streams of the selected unit/process and the outlet streams are considered as sources. However, freshwater and waste water is also placed under sources category as some of the waste streams cannot be used/reused as sources to the unit.

Target for fresh water is determined by considering all the sinks and sources in the process. The sinks and sources are arranged in ascending order of their maximum property loads as property loads are analogous to mass loads [13]. El-Halwagi and Prakash have shown that the ascending arrangement of sources and sinks, respectively, provide a simplified target and design arrangement [7], [8]. The maximum property load of a sink is calculated by (1).

\[ M_{Sink, max} = G_j * z_{j, max} \]

where \( G_j \) is flow rate, \( M_{Sink, max} \) is admissible maximum load,
\( y^\text{max}_i \) is maximum property value for sink stream.

Similarly, the source maximum property is calculated by (2). Where \( W_i \) is the flow rate, \( M^{\text{Source, max}}_i \) is admissible maximum load, \( y^\text{max}_i \) is maximum property value for source stream.

\[
M^{\text{Source, max}}_i = W_i \cdot y^\text{max}_i
\]  

(2)

After calculating the loads of each sink and source stream, sink and source composite curves are created, respectively, using superposition.

![Fig. 1 Water Streams Flow-Sheet in Refinery](Image)

![Fig. 2 Property-Based Material Recycle Pinch Diagram](Image)

Required fresh water demand is calculated by sliding source composite curve on the fresh line depicting on the x-axis while keeping it below sink composite curve. Source composite curve is pushed until it touches the sink composite curve to a certain point. This point of interaction is named as Property-Based Recycle Pinch Point and can be seen in Fig. 2.

Kazantzti and El-Halwagi has provided some design rules for constructing the pinch diagram for minimum usage of fresh water, maximum use of recycled waste water and minimum waste water [13] and these are;

- Property load should not be passed through Pinch Point i.e. the two composites should touch
- Fresh water should not be used in any sink unit above the Pinch Point
- Below the Pinch Point, waste should not be discharged from sources

The procedure identifies the targets for fresh, recycle/reuse and waste without going into detailed network design.

In this research, the case study is performed on Tehran oil Refinery [14]. Fig. 1 shows the overall simplified flow sheet of the process in the refinery. Tables I, II and IV list the data for the under study case. Based on these values, optimized water network is determined. Water flow rate is needed to achieve mass transfer of contaminants required for water optimization. However, contaminant selection is dependent on the industry requirements [14]. The overall process is utilizing 505m³/h water and allocation of water streams is well designed including reuse of wastewater. Table II shows three...
sinks (cooling tower, de-salter and plant, potable, fire water) which uses water about 340m³/h and COD is selected as a single contaminant case study. Table IV shows two sources (boiler blow down and outlet utility).

### TABLE I

**STREAM FLOW RATES AND CONSTRAINTS**

<table>
<thead>
<tr>
<th>Stream Number</th>
<th>Flow Rate of Streams m³/h</th>
<th>Stream Constraints ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>505.0</td>
<td>COD = 0.0</td>
</tr>
<tr>
<td>S10</td>
<td>20.0</td>
<td>COD = 0.0</td>
</tr>
<tr>
<td>S13</td>
<td>113.0</td>
<td>COD = 0.0</td>
</tr>
<tr>
<td>S18</td>
<td>168.0</td>
<td>COD = 0.0</td>
</tr>
<tr>
<td>S19</td>
<td>160.0</td>
<td>COD = 0.4</td>
</tr>
<tr>
<td>S21</td>
<td>17.0</td>
<td>COD = 10.0</td>
</tr>
<tr>
<td>S22</td>
<td>59.0</td>
<td>COD = 2.0</td>
</tr>
<tr>
<td>S23</td>
<td>59.0</td>
<td>COD = 5.0</td>
</tr>
</tbody>
</table>

### III. RESULTS AND DISCUSSION

#### A. Graphical Method

To minimize the fresh water and wastewater through Pinch Technique using graphical method, load ($M$) of each sink is calculated using (1). The calculated maximum property loads for the sinks are listed in Table II. The sinks are arranged in ascending order of their increasing load. Next step is to develop the Sink Composite Curve as shown in Fig. 3 using data in Table III which list the sinks data in ascending order in term of their cumulative loads including flow rates. Similarly, the loads of sources are calculated Table IV and placed in ascending order of their increasing property loads as shown in Table V. Fig. 4 represents the Source Composite Curve based on the cumulative loads data in Table V.

### TABLE II

**SINKS DATA**

<table>
<thead>
<tr>
<th>Sinks</th>
<th>Flow Rate G m³/h</th>
<th>COD (Z ppm)</th>
<th>Maximum Load (m³/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Tower</td>
<td>37.0</td>
<td>1.0</td>
<td>0.000037</td>
</tr>
<tr>
<td>De-Salter</td>
<td>59.0</td>
<td>2.0</td>
<td>0.000118</td>
</tr>
<tr>
<td>Plant, Potable, Fire Water</td>
<td>160.0</td>
<td>3.0</td>
<td>0.00048</td>
</tr>
</tbody>
</table>

### TABLE III

**CUMULATIVE SINKS DATA FOR SINK COMPOSITE CURVE**

<table>
<thead>
<tr>
<th>Sinks</th>
<th>Flow Rate (G m³/h)</th>
<th>Cumulative Load (m³/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Tower</td>
<td>37.0</td>
<td>0.000037</td>
</tr>
<tr>
<td>De-Salter</td>
<td>59.0</td>
<td>0.000155</td>
</tr>
<tr>
<td>Plant, Potable, Fire Water</td>
<td>160.0</td>
<td>0.00048</td>
</tr>
</tbody>
</table>

### TABLE IV

**SOURCE DATA**

<table>
<thead>
<tr>
<th>Sources</th>
<th>Flow Rate W m³/h</th>
<th>COD Out Y ppm</th>
<th>Maximum Load (m³/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler Blow down</td>
<td>20.0</td>
<td>4.0</td>
<td>0.000008</td>
</tr>
<tr>
<td>Outlet Utility</td>
<td>65.0</td>
<td>2.0</td>
<td>0.000009</td>
</tr>
<tr>
<td>Fresh Water</td>
<td>-</td>
<td>0.0</td>
<td>-</td>
</tr>
</tbody>
</table>

### Fig. 3 Sink Composite Curve

### Fig. 4 Source Composite Curve

In Fig. 5, the sink composite curve and source curves are drawn on the same scale to determine the *Pinch Point*. 
In this graphical method, the horizontal and vertical axis represents the flow rate and load, respectively. The source composite curve is dragged to the left until it touches to one of the point to sink composite curve while keeping in mind that source composite curve should not cross the sink composite curve as previously mentioned in the designing rules.

This method is much easy and effective for calculating the fresh water requirements and to check the maximum recycle. In fig. 5, the sink line on the left is out of the reach of source composite curve show that 38.5 m$^3$/h amount of fresh water is necessary for sinks in addition to another water demand of 152.5 m$^3$/h shown on the right side. By adding these quantities, the total fresh water demand is 191.0 m$^3$/h that is needed for the sinks. As it is seen that the amount of fresh water is reduced from 340.0 m$^3$/h to 191.0 m$^3$/h, which shows a reduction of 149.0 m$^3$/h and about 43.8% fresh water reduction in terms of single contaminant COD.

B. Mathematical Modeling

Mahmoud M. El-Halwagi [15] has developed a mathematical tool of optimization and to provide a systematic solution of problems. An optimization formulation provides a solution in the area of minimization or maximization of an objective constraint. Mathematical programming deals with the formulation, solution, and analysis of optimization problems or mathematical programs. If the objective functions as well as the constraints are linear then it is called as linear program (LP); otherwise, it is will be a nonlinear program (NLP).

The sinks and sources are selected as constraints to formulate an optimization model. Sets formulation model has been established [15] based on (1) and (2) that accurately describes the amount of the objective fresh water demand using mathematical relationships. LINGO is one of the optimization tools that provide the solution for linear, nonlinear, and mixed integer linear and nonlinear programs. Using sets formulation optimization also evaluates and identifies one of the best possible solution and water distribution network.

A set is a collection of objects and is typically denoted by upper-case letters A, B, X, Y, and so on. The LINGO coding program is developed based on sets formulation using (1) and (2). The coding developed is:

```
!LINGO INPUT SETS FORMULATION CODE;

min=Fresh;
SETS:
  SOURCES /1..2/: W, Y, Waste;
  SINKS /1..3/: G, Zmax, Z, F;
FLOW CONNECTIONS (SOURCES, SINKS): Split;
ENDSETS
DATA:
  W=20 45;
  Y=0.000004 0.000002;
  G=37 59 160;
  Zmax=0.000001 0.000002 0.000003;
ENDDATA
Fresh=@SUM(SINKS(j): F(j));
XF=0;
@FOR (SOURCES(i):
  @SUM(SINKS(j): Split(i,j))+Waste(i)=W(i));
@FOR (SINKS(j):
  @SUM(SOURCES(i): Split(i,j))+F(j)=G(j));
@FOR (SINKS(j):
  @SUM(SOURCES(i): Split(i,j)*Y(i))+F(j)*XF=G(j)*Z(j));
@FOR (SINKS(j): Z(j)<=Zmax(j));
Waste_Total=@SUM(SOURCES(i):Waste(i));
```
Fig. 5 Final Property Based Recycle Pinch Diagram

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh</td>
<td>191.000</td>
</tr>
<tr>
<td>Xf</td>
<td>0.000</td>
</tr>
<tr>
<td>WASTE_TOTAL</td>
<td>0.000</td>
</tr>
<tr>
<td>W(1)</td>
<td>59.000</td>
</tr>
<tr>
<td>Y(1)</td>
<td>0.000</td>
</tr>
<tr>
<td>G(1)</td>
<td>37.000</td>
</tr>
<tr>
<td>G(2)</td>
<td>59.000</td>
</tr>
<tr>
<td>G(3)</td>
<td>160.000</td>
</tr>
<tr>
<td>ZMAX(1)</td>
<td>0.1000000E-05</td>
</tr>
<tr>
<td>ZMAX(2)</td>
<td>0.2000000E-05</td>
</tr>
<tr>
<td>ZMAX(3)</td>
<td>0.3000000E-05</td>
</tr>
</tbody>
</table>

Fig. 6 Source-Sink Water Network Distribution
LINGO Output Results are shown in Table VI. The results from LINGO have verified that the amount of fresh water required is 191.0 m$^3$/h with a reduction of 149.0 m$^3$/h of fresh water. The program provides a best possible distribution of water streams to the sinks also. The proposed water network design from Sources to Sinks distribution is represented in Fig. 6. The final flow-sheet of the Tehran Oil Refinery with 43.8% fresh water reduction is shown in Fig. 7.

IV. CONCLUSION

This study was based on single contaminant approach and COD was selected for consideration. This work has been performed by a new technique comparison to the studies performed earlier. This technique has shown a very good percentage reduction of 43.8.0% of fresh water in three processes. Analyzing the results from mathematical programming proved the exact requirement of fresh water. In addition to LINGO programming, the best possible water networking was suggested based on COD contaminant. Besides to this, double contaminant can be more precise to reduce the water loss.

ACKNOWLEDGMENT

Authors are grateful to the Deanship of Scientific Research Centre at College of Engineering, King Saud University (KSU), which rendered technical support in this study. Moreover, this research work greatly benefited by providing suggestions and helpful information from one of the faculty member Engr. Farag A. Abdel-Eleem in chemical engineering department, King Saud University and Dr. Mahmoud El Halwagi from Texas A & M university USA.

REFERENCES