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Simultaneous Energy and Water Minimization-Approach for Systems with Optimum Regeneration of Wastewater

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Abstract: In this study, a new systematic design methodology has been developed for the simultaneous management of energy and water systems that also feature optimum regeneration of wastewater. In addition to allowing regeneration of wastewater, issues about heat losses inside unit operations have also been incorporated in the simultaneous management of water and energy. To implement such a design, two new design aspects are introduced; new method for non-isothermal mixing points identification and new separate system generation. The first aspect involves non-isothermal mixing, which enables direct heat recovery between water streams and therefore allows the reduction of the number of heat transfer units. An NLP model is formulated to identify feasible non-isothermal mixing points in the network regarding minimum operation cost, which satisfy minimum freshwater and utility requirements. The other aspect is the generation of separate system in heat exchanger network design. The flexibility of mixing and splitting of water streams allows separate systems to be created as a cost-efficient series of heat exchanger units between freshwater and wastewater streams. The new design aspects have been illustrated with a case study. The results demonstrated 56% of fresh water, 62% of hot utility, 100% of cold utility, 67% of number of heat transfer units and 60% of total cost saving relevant to the conventional design method.

Key words: Heat loss, non-isothermal mixing, separate system, heat recovery, NLP model

INTRODUCTION

Design of chemical processes should be based on a sustainable development to keep the natural environment clean. The efficient use of energy and water has received much attention to achieve good economic performance. While, cost-effective processes are favored by companies, increasing environmental concerns have stimulated a great challenge in the chemical industries.

Water is one of the most widely used raw materials in chemical and petroleum industries. Significant amounts of water are required in washing, stripping and manufacturing processes. As water resources face scarcities, ever-increasing prices and more stringent environmental regulations, much attention has been paid to reduce freshwater consumption and wastewater generation (Panjeshahi and Ataei, 2008).

Wastewater regeneration refers to a process that increases the opportunities for reusing of water. In other words, wastewater can be regenerated to remove contaminants and then the water recycled.

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By this method, regenerated water may enter the water-using operations in which the water stream has already been used. The regeneration is any operation that removes the contaminants that prevent reuse and could be filtration, pH adjustment, carbon adsorption and other processes (Tchobanoglous *et al*., 2002). Regeneration reduces both freshwater and wastewater volumes and decreases the mass load of contaminant (Mann and Liu, 1999).

There are conceptual and automated approaches as two traditional methods to design water networks with regeneration of wastewater. The former analysis exploits graphical tools to explore the possibilities of wastewater regeneration, whilst the latter employs mathematical optimization models to obtain a cost-effective solution (Bagajewicz *et al*., 2002; Savulescu and Alva-Argaez, 2008; Smith, 2005). The analysis of water management generally involves water distribution among water-using operations with the criteria of contaminant concentration levels (Bogataj and Bagajewicz, 2008).

In some cases such as sterilization and process-washing, temperature of water becomes as important as the quality of water. The water system is now subject to not only the constraints of contaminant concentration levels, but also those of the temperature levels. Water streams need to be heated up or cooled down to satisfy the temperature requirements of the operations and energy consumption becomes necessary for these heating and cooling tasks. Under these circumstances, energy and water management needs to be considered simultaneously (Zhelev, 2005). Therefore, the problem has become a combined analysis of water and energy systems (Fig. 1).

The simultaneous energy and water minimization was first addressed by Savulescu *et al*. (2005). In this methodology, several assumptions are made for problem simplification but these assumptions make the design inaccurate. Some of these assumptions are:

- Only reuse options are considered to minimize freshwater consumption
- Each water-using operation has a fixed temperature and runs isothermally
- The water flow rate through an operation does not change
- Only single contaminant operations are considered

It should be noted that in addition to reusing of water, other approaches such as process changes and regeneration of wastewater can be applied to fresh water saving and wastewater minimization in process industries (Mann and Liu, 1999). Moreover, for particular operations temperature of water changes, hence isothermally running assumption for practical water-using operations cannot be corrected. Furthermore, in industrial practices, many water-using operations have fixed flow rate requirements, such as in many vessel-cleaning operations (Mann and Liu, 1999). Also, there may be a fixed flow rate of water loss (e.g., cooling-tower evaporation) or gain (e.g., dewatering filter). Accordingly, the flow rate changes should be considered in design of water-using networks with minimum water and energy consumption. The presented design considers only the networks with single contaminant and the non-isothermal mixing point identification is based on water-pinch analysis

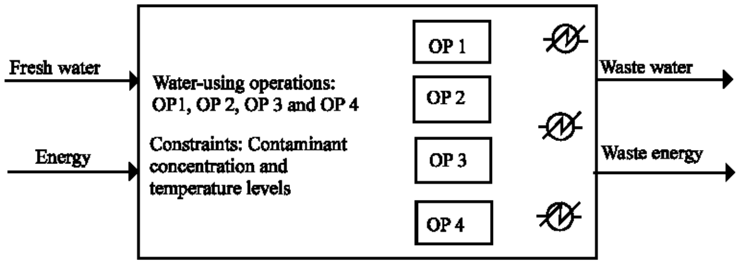

Fig. 1: Simultaneous water and energy management

and synthesis. Therefore, extension of this method for multiple contaminant problems may be tedious. Accordingly, an NLP model should be formulated to identify feasible non-isothermal mixing points, which satisfy minimum freshwater and utility requirements in both of single and multiple contaminant problems.

Two main stages are suggested for simultaneous water and energy minimization through methodology of Savulescu *et al*. (2005):

- **Stage 1:** A dual dimensional grid diagram for designing a water network
- **Stage 2:** Separate system approach for designing a heat exchanger network

This method is a sequential approach that follows a set of design rules in the first stage, to provide a water network with less heat exchanger units required. These rules, however, do not always guarantee minimum utility requirement. In other words, the actual utility requirement of the design is higher than the utility target and the design with small number of heat exchangers could be obtained but with utility penalty. Furthermore, in the presented design method, temperature of some water streams in the network may increase to above the normal boiling temperature. This temperature increasing can cause many operational problems for the process; however, increasing of the process pressure cannot be a no-cost and easy solution for these problems.

In the second stage, the idea of generating separate systems to simplify a heat exchanger network design was introduced. Nevertheless, the generation of separate systems has not been fully explored from the recognition that a smaller number of heat exchanger units could be acquired. Moreover, the optimum heat transfer area in each separate system should be explored by introducing a trade-off between the capital cost of heat exchanger and the power losses because of the pressure drops of each fluid to achieve minimum total annual cost.

Accordingly, a new methodology should be developed to construct a water structure without the utility penalty and the increasing of water streams temperature to above the normal boiling point and provide a heat exchanger network with minimum number of units and optimum heat transfer area.

This study addresses the simultaneous management of energy and water as an approach for systems with optimum regeneration of wastewater. In addition, the heat loss through operations has been considered in this new methodology. In other words, in addition to overcome the aforementioned limitations of Savulecsu design method, the first and second simplifier assumptions of it have been relaxed in this new simultaneous water and energy minimization approach and relaxation of the third and fourth of those, is the subject of present future study.

The new simultaneous water and energy minimization technique has been tested through a case study. Related coding in GAMS optimization package was used for the case study to get optimal values in the proposed design method computations.

MATERIALS AND METHODS

The new systematic design methodology has been developed for the simultaneous management of energy and water systems that also feature optimum regeneration of wastewater. In addition to allowing regeneration of wastewater, issues about heat losses inside unit operations have also been incorporated in this design method. The general features of the problem involve a set of water-using operations with specifications of flow rates, temperature and contaminant concentration levels, a selection of water sources with different qualities and a number of heat transfer units. It is assumed that a regeneration process is available with a performance that can achieve a fixed outlet concentration and also, recycling of the regenerated wastewater is allowed. It is desired to determine water and energy targets and specify the distribution of water among the water-using operations as well as the allocation of heat exchangers between these water streams in order to complete the overall network configuration.

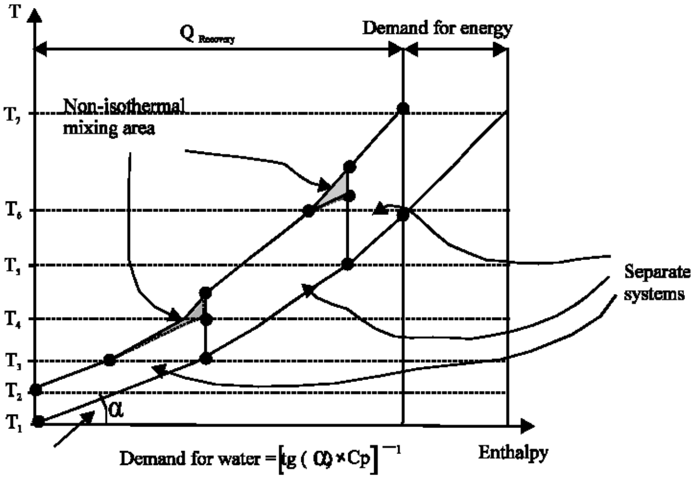

Fig. 2: Non-isothermal mixing area and separate systems in the composite curves

The new design method comprises two new design aspects; new method for non-isothermal mixing point identification to design a water network with the minimum freshwater and energy requirements and new separate system generation for designing a heat exchanger network with minimum number of heat exchanger units and optimum heat transfer area. Moreover, in the proposed method, the optimum detail design of the heat changers related to each separate system can be achieved. Figure 2 shows the non-isothermal mixing area and separate systems in the cold and hot composite curves

New Method for Non-Isothermal Mixing Point Identification

Non-isothermal mixing enables direct heat recovery between water streams and therefore allows the reduction of the number of heat transfer units. However, non-isothermal mixing can cause the degradation of temperature driving forces and also reduces the number of possibilities of indirect heat transfer matching between hot and cold streams. Thus, in the introduction of non-isothermal mixing, a water network without utility penalty should be considered.

In this study, an NLP model is formulated to identify feasible non-isothermal mixing points, which satisfy not only the inlet requirements (temperature and contaminant concentration levels) of the operations but also achieve the minimum freshwater and utility requirements and create an overall water network with fewer number of heat exchanger units. By using this mathematical model, the water network design with small number of heat exchangers and minimum operating cost can be obtained without utility penalty.

Figure 3 shows a general water-using operation I and a regeneration process with a fixed outlet concentration C_0. Here, we define the operation with a fixed mass load of contaminant to be transferred $\Delta m_{i,tot}$ and with maximum allowable concentrations of contaminant at the inlet $C_{i,in}^{max}$ and outlet, $C^{max}_{i,out}$ of the operation. We include inlet streams from the freshwater source at temperature T_0 and heated to T_{fi} with a flow rate, $f_i(I = 1,2,3,...,n_{operations})$, as well as streams reused from other operations j $(j = 1,2,3,...,n_{operations})$, at a flow rate, $X_{i,j}$, temperature of $T_{j,out}$ and a contaminant concentration $C_{j,out}$. Likewise, we consider an outlet stream to wastewater treatment at a flow rate, W_i, temperature of $T_{i,out}$ and a contaminant concentration $C_{i,out}$ and outlet streams for reuse in other operations j $(j = 1,2,3,...,n_{operations})$, at flow rates, $X_{j,i}$, temperature of $T_{i,out}$ and concentration $C_{i,out}$. The figure also includes streams to (at a flow rate, $X_{r,i}$, temperature of T_r and a contaminant concentration $C_{i,out}$) and from (at a flow rate, $X_{i,r}$, temperature of T_r and a contaminant concentration, C_0) a regeneration process.

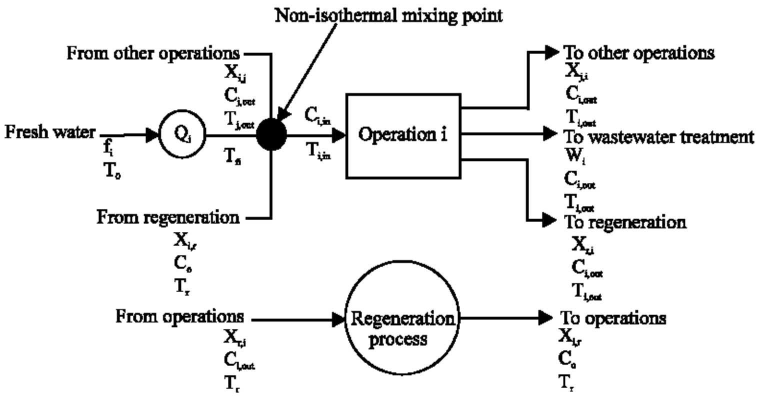

Fig. 3: NLP model for non-isothermal mixing point identification

The total operating cost, as the objective function, is expressed in Eq. 1:

$$\text{Min OPCOST} = C_w \sum_{i=1}^{n_{\text{operations}}} f_i + C_{reg} \sum_{i=1}^{n_{\text{operations}}} X_{r,i} + C_e \sum_{i=1}^{n_{\text{operations}}} Q_i \tag{1}$$

A mass balance on water for the regeneration process, depicted in Fig. 3, is expressed by Eq. 2:

$$\sum_i X_{i,r} = \sum_i X_{r,i} \tag{2}$$

A mass balance on water for the operation I is given by Eq. 3:

$$f_i + \sum_{j \neq i} X_{i,j} + X_{i,r} - W_i - \sum_{j \neq i} X_{j,i} - X_{r,i} = 0 \tag{3}$$

We formulate the constraints governing regeneration of wastewater from the maximum inlet and outlet concentrations as well as the fixed mass load contaminant transferred in each operation. We calculate the average inlet concentration,$C_{i,in}$ by the flow rate-weighted average of the concentrations provided by the fresh water source, regeneration process and reused from other operations.

This average inlet concentration should be smaller than or equal to the maximum allowed concentration at the inlet $C_{i,in}^{max}$.

$$C_{i,in} = \frac{\sum_{j \neq i} C_{j,out} X_{i,j} + C_o X_{i,r}}{\sum_{j \neq i} X_{i,j} + f_i + X_{i,r}} \leq C_{i,in}^{max} \tag{4}$$

The outlet concentration is the sum of the average inlet concentration, $C_{i,in}$ and the change in concentration due to the fixed mass load of contaminant transferred, $\Delta m_{i,tot}$:

$$C_{i,out} = C_{i,in} + \frac{\Delta m_{i,tot} \times 10^3}{\sum_{j \neq i} X_{i,j} + f_i + X_{i,r}} \leq C_{i,out}^{max} \tag{5}$$

By rearranging Eq. 4 and 5, a set of more linear constraints can be formed as follows:

$$\sum_{j\neq i}\left[C_{i,in}^{max}-C_{j,out}\right]X_{i,j}+C_{i,in}^{max}f_i+\left[C_{i,in}^{max}-C_0\right]X_{i,r}\geq 0 \tag{6}$$

$$\sum_{j\neq i}\left[C_{i,out}^{max}-C_{j,out}\right]X_{i,j}+C_{i,out}^{max}f_i+\left[C_{i,out}^{max}-C_0\right]X_{i,r}\geq \Delta m_{i,tot}\times 10^3 \tag{7}$$

The temperature of inlet water stream to the operation i,$T_{i,in}$ and the temperature of outlet water stream from the operation I, $T_{i,out}$ are fixed and known parameters. The constraint related to the fixed and known amount of inlet water temperature can be expressed as Eq. 8:

$$T_{i,in}\left[\left(\sum_{j\neq i}X_{i,j}\right)+X_{i,r}+f_i\right]=\left[\left(\sum_{j\neq i}T_{j,out}X_{i,j}\right)+T_r X_{i,r}+T_{fi}f_i\right] \tag{8}$$

The average temperature of streams to and from the regeneration process can be calculated by Eq. 9:

$$T_r\sum_i X_{r,i}=\sum_i T_{i,out}X_{r,i} \tag{9}$$

The energy requirement for heating of the inlet freshwater to the operation I from temperature T_0 to T_{fi} is given in Eq. 10:

$$Q_i=Kf_iC_p\left(T_{fi}-T_o\right) \tag{10}$$

The nonlinear program to optimize the water-using network, including a regeneration process, is to minimize the total operating cost, OPCOST, expressed in Eq. 1, subject to Eq. 2, 3, 6, 7, 8, 9 and 10. The presented NLP model can be a useful tool to determine water and energy targets and specify the distribution of water among the water-using operations.

After the connections between operations are established by using the above mentioned model, heat exchanger network design is considered to complete the overall network configuration.

New Method for Separate System Generation

Once the non-isothermal mixing for the water re-use streams is completed, the remaining design is to identify the matching of water streams by generating separate systems and appropriate location of separate systems. The remaining problem of heat recovery involves only fresh water streams as cold streams and wastewater streams as hot streams, which enables a simple HEN design with fewer heat transfer units (Kim *et al*., 2000; Savulescu *et al*., 2002). To design a cost-efficient heat exchanger network for the water system, new separate system generation has been developed. As each separate system represents a heat transfer unit between hot and cold streams (Kim *et al*., 2000), the number of separate systems should be minimized in order to achieve the minimum number of heat exchanger units. Besides, the temperature driving forces should be maximized to reduce heat transfer area. Moreover, the optimum heat transfer area in each separate system should be explored by introducing a trade-off between the capital cost of heat exchanger and the cost related to compensation of pressure drops in tube and shell sides, for achieving the minimum total annual cost. Therefore, the concept of new separate system approach intends to create minimum number of separate systems and optimum heat transfer area in each separate system. The procedure of the new separate system approach is based on the five steps as follows:

- **Step 1: Construct the Energy Composite Curves:** The initial energy composite curves are generated based on individual thermal stream data extracted from the water network. As shown in Fig. 2, the minimum demand for fresh water can be targeted by the slope of the fresh water supply line from the cold composite curve. The energy target obtained from the analysis of these composite curves is the same as the value of energy consumption estimated in the stage of non-isothermal mixing point identification

- **Step 2: Minimize the Number of Separate Systems:** In order to achieve the minimum number of separate systems and consequently fewer heat transfer units, separate systems should be generated following kink points on the composite curve with fewer kink points. Then, the boundaries of separate systems can be defined at kink points from the selected curve
- **Step 3: Maximize Temperature Driving Force in Each Separate System:** The creation of separate systems involves non-isothermal stream mixing in order to achieve the temperatures required by the water-using operations. Through non-isothermal mixing of hot wastewater streams, the hot composite curve should be modified to maintain maximum driving force in each separate system for reducing the heat transfer area
- **Step 4: Determine Water Distribution Between Separate Systems and Operations:** Since some modifications have been made to the composite curves, water distribution between the separate systems and the operations should be determined. The water distribution involving non-isothermal mixing of wastewater streams can be carried out by solving a simple series of mass and heat balance equations
- **Step 5: Optimize Heat Transfer Area in Each Separate System:** After determination of cold and hot streams in each separate system in step 4, the optimum heat transfer area in each separate system should be explored by introducing a trade-off between the capital cost of heat exchanger and the cost related to compensation of pressure drops in the tube side and shell side, for achieving the minimum total annual cost

Here, we examine a procedure for optimizing the heat transfer area in each separate system. We assume the heat exchanger, which represented by each separate system, is a baffled shell- and -tube, single-pass, counter flow heat exchanger (Fig. 4), in which the tube fluid is in turbulent flow but no change of phase of fluids takes place in the shell or tubes. It should be noted that the inlet and outlet flow rates and temperatures to and from the tube side and shell side of the heat exchanger in each separate system are known in this stage. Also, the tube spacing and tube inside and outside diameters should be specified a priori by the designer.

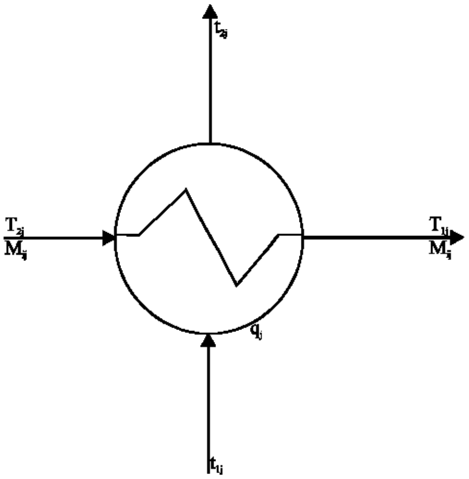

Fig. 4: NLP model for optimization of the heat transfer area in a general separate system j. (Key: $\Delta t_{1j} = T_{1j}-t_{1j}$ cold-end temperature difference; $\Delta t_{2j} = T_{2j}-t_{2j}$ warm-end temperature difference)

Note, that the presented optimization procedure is specified for a general separate system j. Thus, this procedure should be carried out for each of separate systems individually.

The total cost of the heat exchanger in the separate system j, as the objective function in dollars per year, is formulated as follows:

$$\text{Min}\,TC_j = A_{oj}\left(C_{Aj} + C_{ij}E_{ij} + C_{oj}E_{oj}\right) \tag{11}$$

The rate of indirect heat transfer in the separate system j is given in Eq. 12 (Edgar *et al*., 2001):

$$q_j = F_{tj}U_{oj}A_{oj}\frac{\Delta t_{2j} - \Delta t_{1j}}{\text{Ln}\left(\frac{\Delta t_{2j}}{\Delta t_{1j}}\right)} \tag{12}$$

where, F_{tj} is unity for a single-pass exchanger for the separate system j. U_{oj} is given by the values of h_{oj}, h_{ij} and the fouling coefficient h_{tj} in the separate system j, as follows (Edgar *et al*., 2001):

$$\frac{1}{U_{oj}} = \frac{1}{f_{Aj}h_{ij}} + \frac{1}{h_{oj}} + \frac{1}{h_{tj}} \tag{13}$$

where, h_{tj} is a combined coefficient for tube wall and dirt films, based on tube outside area. This parameter is expressed in Eq. 14:

$$\frac{1}{h_{tj}} = \frac{l_j' A_{oj}}{k_{wj}A_{lmj}} + \frac{A_{oj}}{h_{fij}A_{ij}} + \frac{1}{h_{foj}} \tag{14}$$

The annual pumping loss terms in Eq. 11 could be related to h_{ij} and h_{oj} by using friction factors for tube flow and shell flow (Serna and Jiménez, 2005):

$$E_{ij} = \varphi_{ij}h_{ij}^{3.5} \tag{15}$$

$$E_{oj} = \varphi_{oj}h_{oj}^{4.75} \tag{16}$$

The coefficients φ_{ij} and φ_{oj} depend on fluid specific heat, thermal conductivity, density and viscosity as well as the tube diameters in the separate system j. φ_{oj} is based on either in-line or staggered tube arrangements.

If we substitute in Eq. 11, the resulting objective function can be expressed in Eq. 17:

$$\text{Min}\,TC_j = C_{Aj}A_{oj} + C_{ij}\varphi_{ij}h_{ij}^{3.5}A_{oj} + C_{oj}\varphi_{oj}h_{oj}^{4.75}A_{oj} \tag{17}$$

To accommodate the constraint on the fixed and known indirect heat transfer rate in the separate system j, a Lagrangian function L_j is formed by augmenting TC_j with Eq. 12, using a Lagrange multiplieras ω_j follows:

$$L_j = TC_j + \omega_j\left[\frac{F_{tj}\left(\Delta t_{2j} - \Delta t_{1j}\right)}{Q_j \ln\left(\frac{\Delta t_{2j}}{\Delta t_{1j}}\right)} - \frac{1}{U_{oj}A_{oj}}\right] \tag{18}$$

Equation 18 can be differentiated with respect to four variables (h_{ij}, h_{oj}, Δt_{2j} and A_{oj}). After some rearrangement, a relationship between the optimum h_{oj} and h_{ij} can be obtained as follows:

$$h_{oj} = \left[\frac{0.74 C_{ij} \varphi_{ij} f_{Aj}}{C_{oj} \varphi_{oj}} \right]^{0.17} h_{ij}{}^{0.78} \tag{19}$$

The value of h_{ij} in the separate system j can be obtained by solving the following equation:

$$C_{Aj} - 2.5 C_{ij} \varphi_{ij} h_{ij}^{3.5} - 2.91 (C_{oj} \varphi_{oj})^{0.17} (C_{ij} \varphi_{ij} f_{Aj})^{0.83} h_{ij}^{3.72} - \frac{3.5 C_{ij} \varphi_{ij} f_{Aj} h_{ij}^{4.5}}{h_{tj}} = 0 \tag{20}$$

Accordingly, the following algorithm can be used to obtain the optimal values of heat transfer coefficients, power loss inside and outside tubes because of pressure drops and heat transfer area in the separate system j without the explicit calculation of ω_j:

- **I:** Solve for h_{ij} from Eq. 20
- **II:** Obtain h_{oj} from Eq. 19
- **III:** Calculate U_{oj} from Eq. 13
- **IV:** Determine E_{ij} and E_{oj} from h_{ij} and h_{oj} using Eq. 15 and 16
- **V:** Calculate A_{oj} from Eq. 12

Note that steps I to V require that several nonlinear equations be solved one at a time.

Optimal Detail Design of the Heat Exchangers Related to Each Separate System

Once the optimal four variables (h_{ij}, h_{oj}, Δt_{2j} and A_{oj}) were calculated in the previous stage, the physical dimensions of the heat exchanger can be determined.

Accordingly, the following algorithm can be used to obtain the optimal detail design of the heat exchangers related to each separate system:

- **I:** Determine the optimal v_{ij} and v_{oj} from h_{ij} and h_{oj} using the appropriate heat transfer correlations (McAdams, 1954); recall that the inside and outside tube diameters are specified a priori
- **II:** The number of tubes can be found from a mass balance as follows:

$$V_{ij} N_{tj} \frac{\pi D_{ij}{}^2}{4} = K M_{ij} \tag{21}$$

- **III:** The length of the tube L_{tj} can be found from Eq. 22:

$$A_{oj} = N_{tj} \pi D_{oj} L_{tj} \tag{22}$$

- **IV:** The number of clearances N_{cj} can be found from N_{tj} based on either square pitch or equilateral pitch. The flow area S_{oj} is obtained from v_{oj} (flow normal to a tube bundle). Finally, baffle spacing (or the number of baffles) is computed from S_{oj}, A_{oj}, N_{tj} and N_{cj}

Application of the new systematic design methodology is presented through a case study to specify the distribution of water among the water-using operations as well as the allocation of heat exchangers between these water streams in order to complete the cost-effective configuration of overall network. This study was conducted from Jan. 2007 to Aug. 2008 in Mazandaran Wood and Paper Industries Company (MWPI) as the case study.

The result of the recently introduced design methodology is compared with the conventional design method.

RESULTS AND DISCUSSION

Case Study

The new simultaneous energy and water minimization technique is examined by using a case study. The limiting water-using operations data of the case study are given in Table 1. Design specifications of the case study have been given in Table 2. The conventional network configuration for this case study is presented in Fig. 5.

For the case study, a regeneration process capable of an outlet contaminant concentration of 20 ppm is considered. The cost and another needed data related to the regeneration of wastewater are presented in Table 2.

Table 1: The operating data of the case study

Operations	Limiting water flowrate (t h^{-1})	Contaminant mass load (kg h^{-1})	C_{in}^{max} (ppm)	C_{out}^{max} (ppm)	Inlet temperature (°C)	Outlet temperature (°C)
1	30	3.00	0	100	80	70
2	70	1.75	75	100	60	40
3	30	3.00	50	150	60	50

Table 2: Design specifications of the case study

Process specifications and economical data	Values
Fresh water supply temperature (°C)	20
Environmental temperature discharge limit (°C)	30
Specific heat capacity for water and wastewater streams (kJ/kg °C)	4.2
Cost of fresh water ($ t^{-1})	0.26
Cost of wastewater regeneration ($ t^{-1})	0.013
Cost of hot utility ($/kW h)	0.005
Cost of cold utility ($/kW h)	0.000625
Cost of supplying 1 (kW) electricity to pump shell side fluid ($/kW h)	0.05
Cost of supplying 1 (kW) electricity to pump tube side fluid ($/kW h)	0.05
Annual cost of heat exchanger per unit outside tube surface area ($/m^2 year)	385
Payback time (year)	4
Hours operation per year (h year^{-1})	8000
Interest rate (%)	15
Design specifications for heat exchangers	
Fouling resistance is shell and tube sides (m^2°C W^{-1})	0.00018
Tube material	Carbon steel
Type of tube layout	Triangular
Construction type	Fixed tube sheet
Maximum allowable shell diameter (mm)	1000
Number of tube passes	1
Tube outside diameter (mm)	19.05
Tube thickness (mm)	2.11

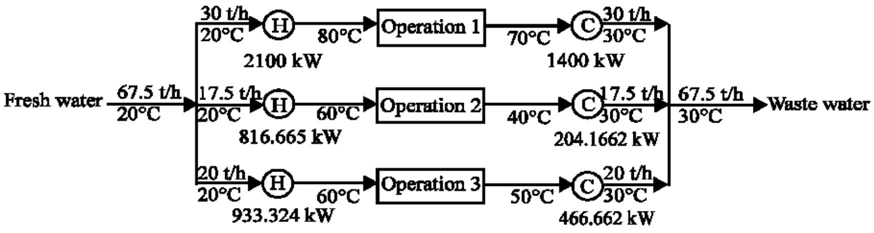

Fig. 5: Conventional network configuration

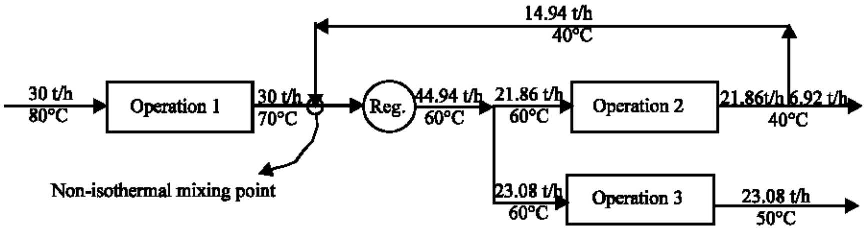

Fig. 6: An optimum water network

Table 3: The targeting results for the case study

Targeted requirements	Values
Fresh water (t h^{-1})	30
Wastewater regeneration (t h^{-1})	44.94
Hot utility (kW)	1480.5
Cold utility (kW)	0
Annual cost of fresh water (\$ $year^{-1}$)	62400
Annual cost of wastewater regeneration (\$ $year^{-1}$)	4674
Annual cost of hot utility (\$ $year^{-1}$)	59220
Annual cost of cold utility (\$ $year^{-1}$)	0
Total annual cost of operating (\$ $year^{-1}$)	126294

Table 4: Thermal steam data from the water network of Fig. 6

Streams	Inlet temperature (°C)	Outlet temperature (°C)	Heat flow capacity (kW/°C)	Enthalpy (kW)
Freshwater to operation 1	20	80	35.0000	2100.000
Wastewater from operation 2	40	30	8.0733	80.733
Wastewater from operation 3	50	30	26.9267	538.533

As seen, the regeneration of wastewater as well as heat losses inside unit operations shall be incorporated in this system. Therefore, this network can not be designed by the methodology which was developed by Savulescu *et al.* (2005). To implement such a design, in addition to the conventional design method, the recently introduced design methodology can be considered.

As presented in Table 2, the temperature of the fresh water supply in the case study is assumed to be fixed, 20°C and the effluent discharge temperature is assumed to be 30°C. Therefore, heat can be recovered from the effluent until ΔT_{min}, 10°C, is achieved.

Applying the new NLP model to the case study, through the commercial mathematical optimization software package GAMS, optimum water network, which can achieve both minimum freshwater, 30 t h^{-1} and hot utility 1480.5 kW consumption, is identified in Fig. 6.

As shown in Fig 6, the network includes one non-isothermal mixing point (direct heat transfer) as the mixing of two reuse streams sent to the same regenerator. This mixing can reduce the number of heat exchanger units required in the design without non-isothermal mixing. The targeting results for the case study are given in Table 3.

After the connections between operations regarding a regeneration process are created, design of heat exchanger network through the new separate system approach is considered to complete the optimal overall network configuration. The thermal data of streams referred to the optimum water network (Fig. 6) are given in Table 4.

The initial energy composite curves based on the thermal stream data and a minimum temperature approach, 10°C, which indicate the minimum water and energy requirements in the new water network are shown in Fig. 7. As represented in Fig. 7, these composite curves assure that the energy requirements in the new water network achieve the utility target to 1480.5 kW hot utility and 0 kW cold utility.

Table 5: Optimum design of the heat exchanger

Number of shell in series	1	Tube counts	108
Number of shell in parallel	1	Number of tube passes	1
Shell diameter (mm)	337	Tube layout	30
Tube thickness (mm)	2.11	Baffle cut (%)	45
Tube outside diameter (mm)	19.05	Baffle spacing (mm)	336.6
Tube pitch (mm)	23.81	Baffle type	Single segmental
Tube length (m)	1.463	Area (m^2)	9.5

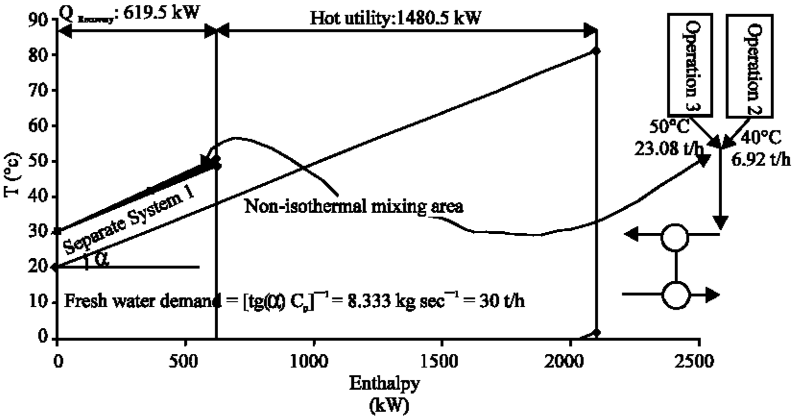

Fig. 7: New separate system approach

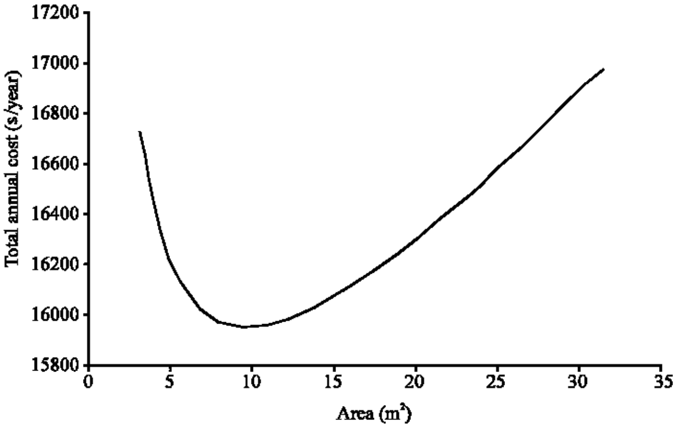

Fig. 8: Total annual cost of the heat exchanger related to the represented separate system

To achieve the minimum number of separate systems in the case study, separate systems are created following kink points on the cold composite curve. Then, the boundaries of separate systems can be defined at kink points from the cold composite curve as shown in Fig. 7.

In addition, the hot composite curve is modified to maintain maximum driving force in each separate system. Heat loads exchanged between wastewater and freshwater streams in the separate systems are vertically transferred and the shaded area between the original and the modified hot composite curves represents the non-isothermal mixing of hot wastewater streams from the operation 2 and 3.

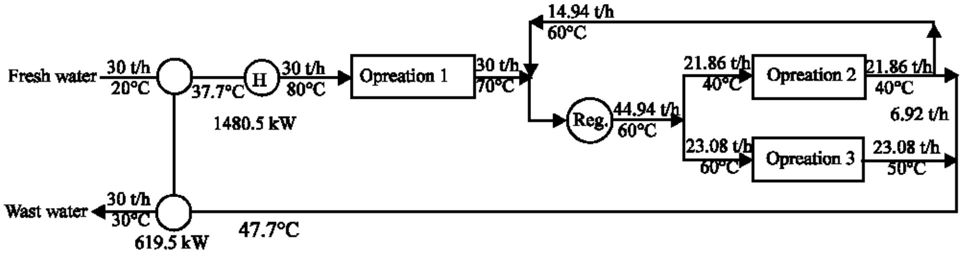

Fig. 9: New network configuration

Table 6: The result comparison

Requirements	New design	Conventional design	Saving (%)
Fresh water (t h^{-1})	30	67.5	56
Hot utility (kW)	1480.5	3850	62
Cold utility (kW)	0	2070.8	100
Number of heat transfer units	2	6	67
Total annual cost (\$ $year^{-1}$)	142241	352595	60

According to Fig. 7, by applying the new separate system generation method to the case study, only one separate system can be enough to complete overall network configuration.

The optimum heat transfer area and detail design of the heat exchanger related to the represented separate system is found by the introduced trade-off between the capital cost of heat exchanger and the cost related to compensation of pressure drops in the tube side and shell side. Figure 8 shows the effect of the heat transfer area on the total annual cost of the heat exchanger related to the represented separate system. The optimum heat transfer area achieves the minimum total annual cost. The optimum design of the heat exchanger has been given in Table 5.

The total number of heat transfer units is two, as there is one heat exchanger (separate system) plus one heater. The new network configuration is presented in Fig. 9.

As seen, the simultaneous energy and water minimization in this case study could not be implemented by the design method which was presented by Savulescu *et al*. (2005) due to its limitations. In other words, the results of the new design methodology on the case study can be compared only with the conventional design method. This comparison is made in Table 6.

As presented in Table 6, the new approach provides a better design with less utility usage, fewer heat transfer units and smaller total annual cost.

CONCLUSIONS

In this study, process integration has been highlighted to develop a novel systematic design methodology for the simultaneous management of energy and water systems that also feature optimum regeneration of wastewater with considering heat losses inside unit operations. The method relies on two sequential design aspects to achieve the water and energy targets; new method for non-isothermal mixing points identification and new separate system generation. In the new method for non-isothermal mixing points identification, recycle option of regenerated wastewater within the water-using systems are exploited not only from the point of view of contaminant concentration, but also considering energy. An NLP model is proposed to identify feasible non-isothermal mixing points, which create an overall water network with minimum freshwater and utility consumption. Then, new separate system generation is developed to design a simplified heat exchanger network. The new approach provides a heat exchanger network with fewer heat transfer units and optimal heat transfer area.

The presented simultaneous water and energy minimization technique has been tested through a case study. The results showed that the total cost of the new design method resulted in the total cost of 142241 (\$/year) as compared to 352595 (\$/year) for the conventional design. Optimization was made using the commercial mathematical optimization software package GAMS. The results of the analysis for a three-operation illustrative case demonstrated 56% of fresh water, 62% of hot utility, 100% of cold utility, 67% of number of heat transfer units and 60% of total cost saving relevant to the conventional design method. Consequently, applying the presented methodology to the industrial large-scale problems can provide more water and energy conservational opportunities.

NOMENCLATURE

A_{ij}	Inside tube surface area in separate system j (m^2)
A_{lmj}	Log mean of inside and outside tube surface areas in separate system j (m^2)
A_{oj}	Outside tube surface area in separate system j (m^2)
C	Cooler
C_o	Contaminant concentration of outlet stream from the regeneration process (ppm)
C_{Aj}	Annual cost of heat exchanger per unit outside tube surface area in separate system j (\$/m^2 year)
C_e	Annual cost of energy (\$/k W year)
$C_{i,in}$	Average concentration of inlet stream to operation I (ppm)
C_{ij}	Cost of supplying 1 (kW) electricity to pump tube side fluid in separate system j (\$/k W year)
$C_{i,out}$	Average concentration of outlet stream from operation I (ppm)
$C_{j,out}$	Average concentration of outlet stream from operation j (ppm)
C_{oj}	Cost of supplying 1 kW electricity to pump shell side fluid in separate system j (\$/k W year)
C_p	Specific heat capacity (kJ/kg °C)
C_{reg}	Annual cost of wastewater regeneration (\$.h/t.year)
C_w	Annual cost of fresh water (\$.h/t. year)
D_{ij}	Tube inside diameter in separate system j (m)
D_{oj}	Tube outside diameter in separate system j (m)
E_{ij}	Power loss inside tubes per unit outside tube area in separate system j (kW/m^2)
E_{oj}	Power loss outside tubes per unit outside tube area in separate system j (kW/m^2)
f_{Aj}	A_{ij}/A_{oj}
f_i	Inlet fresh water flowrate to operation I (t/h)
F_{tj}	Multipass exchanger factor in separate system j
H	Heater
h_{fij}	Fouling coefficient of inside tubes in separate system j (W/m^2 °C)
h_{foj}	Fouling coefficient of outside tubes in separate system j (W/m^2 °C)
h_{ij}	Coefficient of heat transfer inside (W/m^2°C) tubes in separate system j
h_{oj}	Coefficient of heat transfer outside tubes in separate system j (W/m^2 °C)
h_{tj}	Combined coefficient for tube wall and dirt films in separate system j (W/m^2 °C)
K	Unit conversion factor, 0.2778
k_{wj}	Thermal conductivity of tube wall in separate system j (W/m °C)
L_j	Lagrangian function for separate system j (\$/year)
L_{tj}	Length of tubes in separate system j (m)
l'_j	Thickness of tube wall in separate system j (m)
$X_{r,i}$	Flowrate of stream from operation I to regeneration process (t/h)
M_{ij}	Flowrate of fluid inside tubes in separate system j (t/h)
Min	Minimization
N_{cj}	Number of clearances for flow between tubes across shell axis in separate system j
NLP	Non-linear programming
$n_{opreations}$	Number of operations
N_{tj}	Number of tubes in exchanger in separate system j
OPCOST	Total anuual cost of operating (\$/year)
OP1, OP2, OP3,OP4	Water-using operations
Q_i	Energy requirement for heating of inlet freshwater stream to operation I (kW)
$Q_{Recovery}$	Heat recovery, (kW)
q_j	Rate of indirect heat transfer in separate system j (kW)
Reg.	Regeneration process
S_{oj}	Minimum cross-sectional area for flow cross tubes in separate system j (m^2)
T	Temperature (°C)
T_0	Temperature of freshwater source (°C)
t_{1j}	Shell side inlet temperature in separate system j (°C)
t_{2j}	Shell side outlet temperature in separate system j (°C)
T_{1j}	Tube side outlet temperature in separate system j (°C)
T_{2j}	Tube side inlet temperature in separate system j (°C)
Tc_j	Total annual cost of the heat exchanger in separate system j (\$/year)
T_{fi}	Temperature of inlet fresh water stream to operation I (°C)
$T_{i,in}$	Average temperature of inlet stream to operation I (°C)
$T_{i,out}$	Average temperature of outlet stream from operation I (°C)
$T_{j,out}$	Average temperature of outlet stream from operation j (°C)
T_r	Average temperature of streams to and from the regeneration process (°C)
U_{oj}	Overall coefficient of heat transfer based on outside tube area in separate system j (W/m^2°C)
W_i	Flowrate of steam from operation I to wastewater treatment (t/h)
$X_{i,j}$	Flowrate of stream from operation j to operation I (t/h)
$X_{i,r}$	Flowrate of stream from regeneration process to operation I (t/h)
$X_{j,i}$	Flowrate of stream from operation I to operation j (t/h)
ω_j	Lagrange multiplier for separate system j (\$W/year °C)

Greek Letters

$\Delta m_{i,tot}$	Total mass transfer load of contaminant in operation I (kg/h)
V_{ij}	Average velocity of fluid inside tubes in separate system j (m/sec)
V_{oj}	Average velocity of fluid outside tubes at shell axis in separate system j (m/sec)
φ_{ij}	Factor relating friction loss to h_{ij}
φ_{oj}	Factor relating friction loss to h_{oj}

Superscripts

Max. Maximum

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