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New Method for Industrial Water Reuse and Energy Minimization

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ABSTRACT: Water and energy are key commodities utilized in the process industries. Water minimization and energy minimization have been studied separately. In this paper, a new systematic design methodology has been developed for the simultaneous management of energy and water systems that also feature maximum re-use of water. In addition to allowing re-use of water, issues about heat losses inside unit operations have also been incorporated in this new design method. 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 an example.

Key word: Heat loss, Non-isothermal mixing, Separate system, Heat recovery, Heat exchanger network

INTRODUCTION

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 (Kim and Smith, 2002; Panjeshahi and Ataei, 2008). There are conceptual and automated approaches as two traditional methods to design water networks with re-use of water (Mann and Liu, 1999). The former analysis exploits graphical tools to explore the possibilities of water reuse, whilst the latter employs mathematical optimization models to obtain a cost-effective solution (Alva-Argaez, 1999; Bagajewicz *et al.*, 2002; Smith, 2005). The analysis of water management generally involves water distribution among water-using operations with the criteria of contaminant concentration levels (Mann and Liu, 1999). 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. Therefore,

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the problem has become a combined analysis of water and energy systems (see Fig.1).

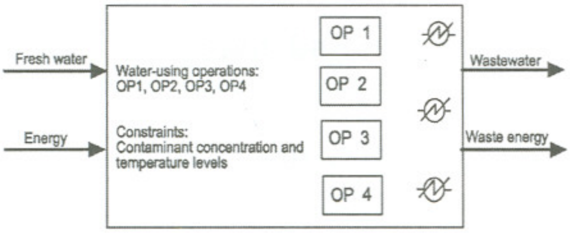

Fig. 1. Simultaneous water and energy management

The simultaneous energy and water minimization was first addressed by Savulescu (1999). This methodology assumes that each water-using operation has a fixed temperature and runs isothermally. It should be noted that for particular operations, temperature of water changes and hence isothermally running assumption for practical water-using operations cannot be correct.Two main stages are suggested for simultaneous water and energy minimization through Savulescu (1999) methodology:

Stage 1. Two 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, which suggested in this method, 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.In this study, a new simultaneous management of energy and water systems with maximum re-use of water is introduced to overcome the aforementioned problems and the limitations of Savulescu methodology (1999). The new simultaneous water and energy minimization technique has been tested through an illustrative example. Related coding in GAMS optimization package was used for the illustrative example to get optimal values in the proposed design method computations.

MATERIALS & METHODS

The new systematic design methodology has been developed for the simultaneous management of energy and water systems that also feature maximum re-use of water. In addition to allowing re-use of water, 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 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.

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. 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.

(Fig.2). depicts a general water-using operation i. 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, $C_{i,out}^{\max}$, of the operation. We include inlet streams from the freshwater source at temperature$T_0$and heated to T_{fi} with a flowrate, $f_i(i = 1,2,3,...n_{operations})$, 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 total operating cost, as the objective function, is expressed in Eq. (1);

$$MinOPCOST = C_w \sum_{i=1}^{n_{operations}} f_i + C_e \sum_{i=1}^{n_{operations}} Q_i \tag{1}$$

A mass balance on water for the operation i is given by Eq.(2) (Prakash and Shenoy, 2005);

$$f_i + \sum_{j\neq i} X_{i,j} - W_i - \sum_{j\neq i} X_{j,i} = 0 \tag{2}$$

We formulate the constraints governing water reuse 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 and reused other operations.

$$C_{i,in} = \frac{\sum_{j\neq i} X_{i,j} C_{j,out}}{\sum_{j\neq i} X_{i,j} + f_i} \leq C_{i,in}^{\max} \tag{3}$$

This average inlet concentration should be smaller than or equal to the maximum allowed concentration at the inlet$C_{i,in}^{\max}$. 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, $\Delta m_{i,tot}$. To maximum water reuse, we force the outlet concentration to equal the limiting outlet concentration (Prakash and Shenoy, 2005);

$$C_{i,out} = C_{i,in} + \frac{\Delta m_{i,tot} \times 10^3}{\sum_{j\neq i} X_{i,j} + f_i} = C_{i,out}^{\max} \tag{4}$$

Substituting for $C_{i,in}$ from Eq. (3) into Eq. (4) gives;

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

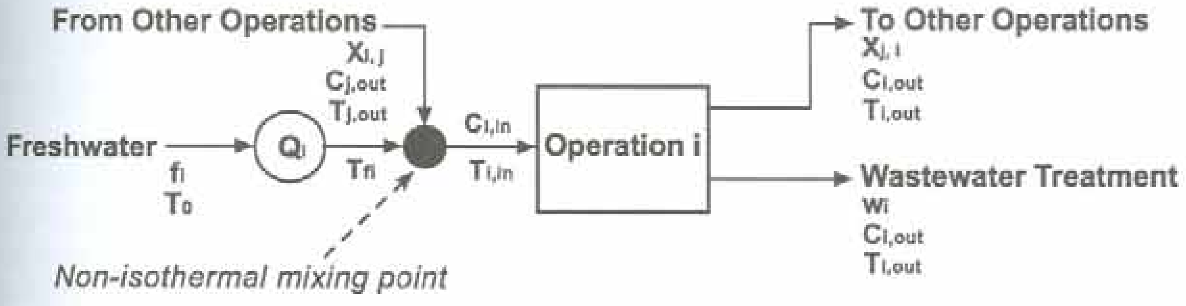

Fig. 2. Illustration of the NLP model for non-isothermal mixing point identification

By rearranging Eqs. (4) and (5), a set of more linear constraints can be formed as follows;

$$\sum_{j\neq i}[C_{i,in}^{\max}-C_{j,out}]X_{i,j}+C_{i,in}^{\max}f_i\geq 0 \quad (6)$$

$$\sum_{j\neq i}[C_{i,out}^{\max}-C_{j,out}]X_{i,j}+C_{i,out}^{\max} f_i\geq \Delta m_{i,tot}\times 10^3 \quad (7)$$

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);

$$T_{i,in}\,[(\sum_{j\neq i}X_{i,j})+f_i]=[(\sum_{j\neq i}T_{j,out}\,X_{i,j})+T_{fi}\,f_i] \quad (8)$$

The energy requirement for heating of the inlet freshwater to the operation i from temperature T_0 to T_{fi} is given in Eq.(9);

$$Q_i=Kf_iC_p(T_{fi}-T_o) \quad (9)$$

We specify that all concentrations and flow rates be positive;

$$C_{i,out}\geq 0;\ f_i\geq 0;\ X_{i,j}\geq 0;\ W_i\geq 0 \quad (10)$$

The nonlinear program to optimize the water-using network is to minimize the total operating cost, *OPCOST* expressed in Eq.(1), subject to Eqs. (2), (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. In the next section, a new separate system approach will be introduced to design the heat exchanger network.

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 heat exchanger network design with fewer heat transfer units (Kim *et al.*, 2001; Savulescu *et al.*, 2002). To design a cost-effective 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.*, 2001), the number of separate systems should be minimized in order to achieve the minimum number of heat exchanger units. Besides, the temperature driving forces in each separate system 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. 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. 3). 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. 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;

$$MinTC_j = A_{oj}(C_{Aj} + C_{ij}E_{ij} + C_{oj}E_{oj}) \quad (11)$$

The rate of indirect heat transfer in the separate system *j* is given in Eq.(12) (Edgar *et al.*, 2001; Polley *et al.*, 1990);

$$q_j = F_{ij}U_{oj}A_{oj}\frac{\Delta t_{2j} - \Delta t_{1j}}{ln(\frac{\Delta t_{2j}}{\Delta t_{1j}})} \quad (12)$$

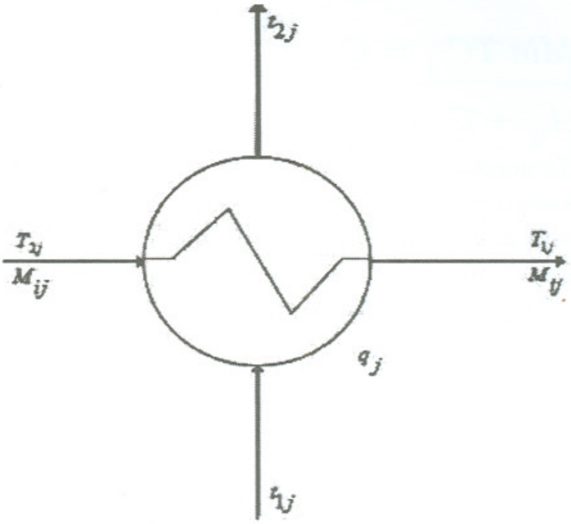

Fig. 3. Illustration of the NLP model for optimization of the heat transfer area in a general separate system *j*. (Key: $\Delta t_{1j} = T_{1j} - t_{1j}$ cold-end temperature difference; $\Delta t_{2j} = T_{2j} - t_{2j}$ warm-end temperature difference.)

F_{ij} 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; Polley and Panjeshahi, 1991);

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

h_{tj} is a combined coefficient for tube wall and dirt films, based on tube outside area. This parameter is expressed in Eq.(14) (Polley and Panjeshahi, 1991);

$$\frac{1}{h_{tj}} = \frac{l'_j A_{oj}}{K_{wj}A_{lmj}} + \frac{A_{oj}}{h_{fij}A_{ij}} + \frac{1}{h_{foj}} \quad (14)$$

Cichelli and Brinn (1956) showed that 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;

$$E_{ij} = \varphi_{ij}h_{ij}^{3.5} \quad (15)$$

$$E_{oj} = \varphi_{oj}h_{oj}^{4.75} \quad (16)$$

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 for E_{ij}, E_{oj} in Eq.(11), the resulting objective function can be expressed in Eq.(17);

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

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 multiplier ω_j as follows;

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

Eq.(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;

$$h_{oj} = (\frac{0.74 C_{ij} \varphi_{ij} f_{Aj}}{C_{oj} \varphi_{oj}})^{0.17} h_{ij}^{\ 0.78} \tag{19}$$

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

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

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 and using Eqs. (15) and (16).

V.Calculate from Eq.(12).

Note that steps I to V require that several nonlinear equations be solved one at a time. Application of the new systematic design methodology is presented through an illustrative example 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. The result of the recently introduced design methodology is compared with the conventional design method.

RESULTS & DISCUSSION

The new simultaneous energy and water minimization technique is examined by using an example. The limiting water-using operations data of the example are given in (Table 1). Design specifications of the illustrative example have been given in (Table 2).As presented in Table 2, the temperature of the fresh water supply in the example 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 illustrative example, through the commercial mathematical optimization software package GAMS, optimum water network, which can achieve both minimum freshwater (324 t/h) and hot utility (7344 kW) consumption, is identified in (Fig. 4).

As shown in Fig. 4. the network includes two non-isothermal mixing points (direct heat transfer). One is the mixing of a freshwater stream and two reuse streams at the inlet of operation 3. The other is the mixing of two reuse streams sent to the same operation 4. These mixings can reduce the number of heat exchanger units required in the design without non-isothermal mixing. The targeting results for the example are given in (Table 3).

Table 1. The operating data of the illustrative example

Operation	Limiting Water Flow rate (t/h)	Contaminant Mass Load (kg/h)	C_{IN}^{MAX} (ppm)	C_{OUT}^{MAX} (ppm)	Inlet temperature (°C)	Outlet temperature (°C)
Operation 1	72	7.2	0	100	50	44
Operation 2	360	18	50	100	90	80
Operation 3	144	108	50	800	70	65
Operation 4	36	14.4	400	800	50	44

Table 2. Design specifications of the illustrative example

Process specifications and economical data	
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	0.26
Cost of hot utility, $/kWh	0.005
Cost of cold utility, $/kWh	0.000625
Cost of supplying 1 kW electricity to pump shell side fluid, $/kWh	0.05
Cost of supplying 1 kW electricity to pump tube side fluid, $/kWh	0.05
Annual cost of heat exchanger per unit outside tube surface area, $/m^{2}yr	385
Payback time, yr	4
Hours operation per year, h/yr	8000
Interest rate, %	15
Cold utility type	Cooling water
Hot utility type	Low-pressure steam
Design specifications for heat exchangers	
Fouling resistance is shell and tube sides, $m^{2\circ}C/W$	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

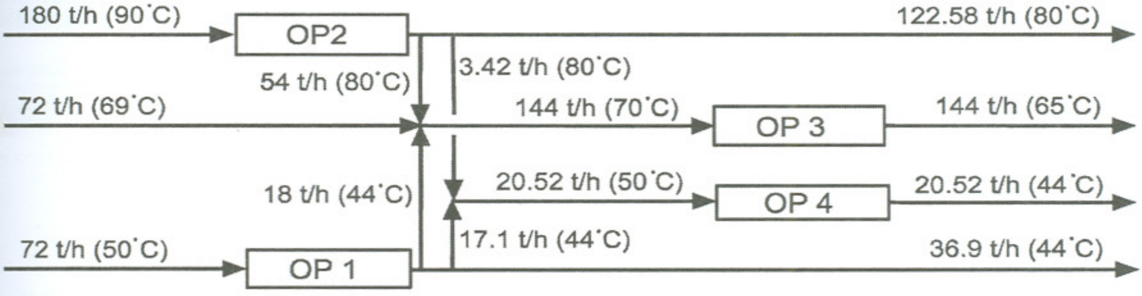

Fig. 4. An optimum water network

Table 3. The targeting results for the illustrative example

Targeted requirements	
Fresh water, t/h	324
Hot utility, kW	7344
Cold utility, kW	0
Annual cost of fresh water, $/yr	673920
Annual cost of hot utility, $/yr	293760
Annual cost of cold utility, $/yr	0
Total annual cost of operating , $/yr	967680

After the connections between operations 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. 4). are given in (Table 4).

The initial energy composite curves based on the thermal stream data and a minimum temperature approach ($10^{\circ}C$) which indicate the

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

Streams	T_{in} (°C)	T_{out} (°C)	Heat flow capacity (kW/°C)	Enthalpy (kW)
Freshwater to operation 1	20	50	84	+2520
Freshwater to operation 2	20	90	210	+14700
Freshwater to operation 3	20	69	84	+4116
Wastewater from operation 1	44	30	43	-602
Wastewater from operation 2	80	30	143	-7150
Wastewater from operation 3	65	30	168	-5880
Wastewater from operation 4	44	30	24	-336

minimum water and energy requirements in the new water network are shown in Figure 5. As represented in Fig. 5. these composite curves assure that the energy requirements in the new water network achieve the utility target to 7344 kW hot utility and 0 kW cold utility. To achieve the minimum number of separate systems in the illustrative example, 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. 5).

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 areas between the original and the modified hot composite curves represents the non-isothermal mixing of hot wastewater streams from the operations. According to (Fig. 5), by applying the new separate system generation method to the example, only two separate systems can be enough to complete overall network configuration.

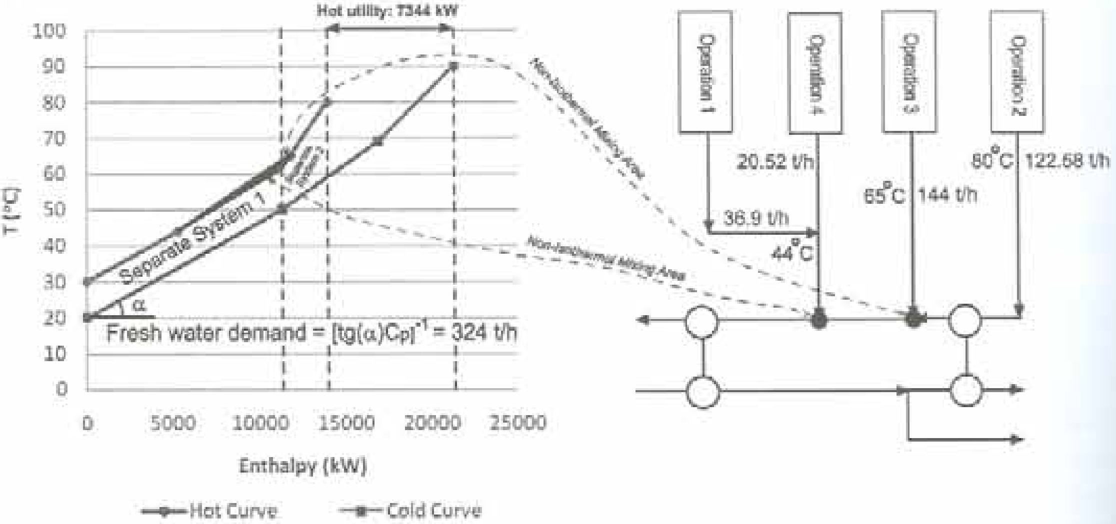

Fig. 5. New separate system approach

The optimum heat transfer area in each 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.(Fig. 6). illustrates the effect of the heat transfer area on the total annual cost of heat exchangers 1, 2 related to the represented separate systems in the example. The optimum heat transfer area achieves the minimum total annual cost.

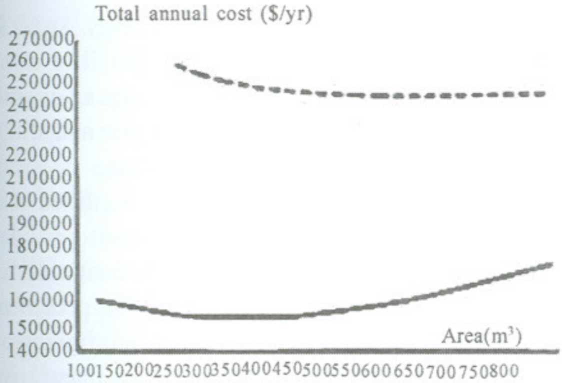

Fig. 6. Total annual cost of heat exchangers 1, 2 related to the represented separate systems in the example

The total number of heat transfer units is four, as there are two heat exchangers (separate systems) plus two steam heaters. The new and conventional network configurations are presented in (Fig. 7 & 8). respectively.In energy saving projects, environment costs of fossil fuels and water as well as electricity must be assessed. However, internalization of externalities needs further research (Karbassi *et al.,* 2008; Shafie-Pour Motlagh and Farsiabi, 2007).A comparison of designs from the conventional and new approaches is made in (Table 5). As presented in Table 5, the new approach provides a better design with less utility usage, fewer heat transfer units and smaller total annual cost.

According to Table 5, applying the new process design method to this example can provide more than 18.38 MW, 71.45%, energy saving, which is supplied by low-pressure steam as the hot utility, for heating of the process streams in heaters. By reducing energy consumption in process plants, considerable amount of air pollutants as well as greenhouse gases will be

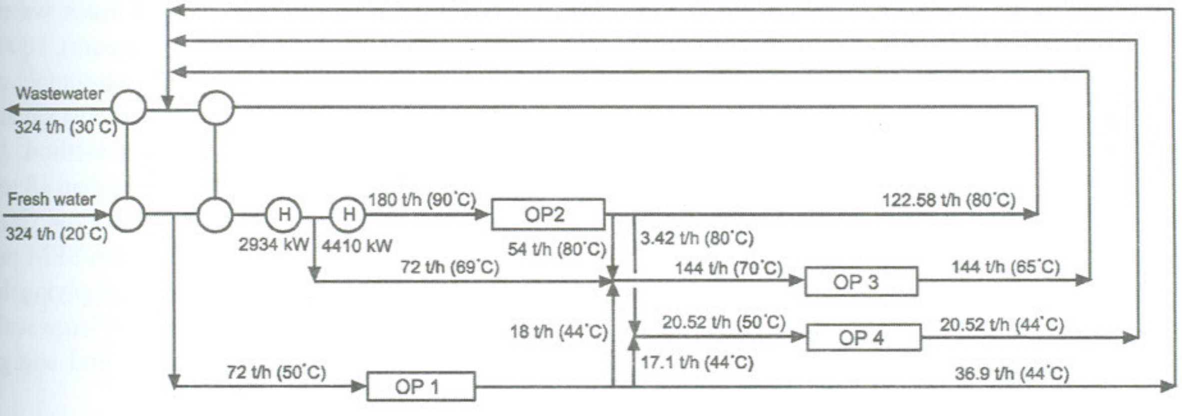

Fig. 7. New network configuration

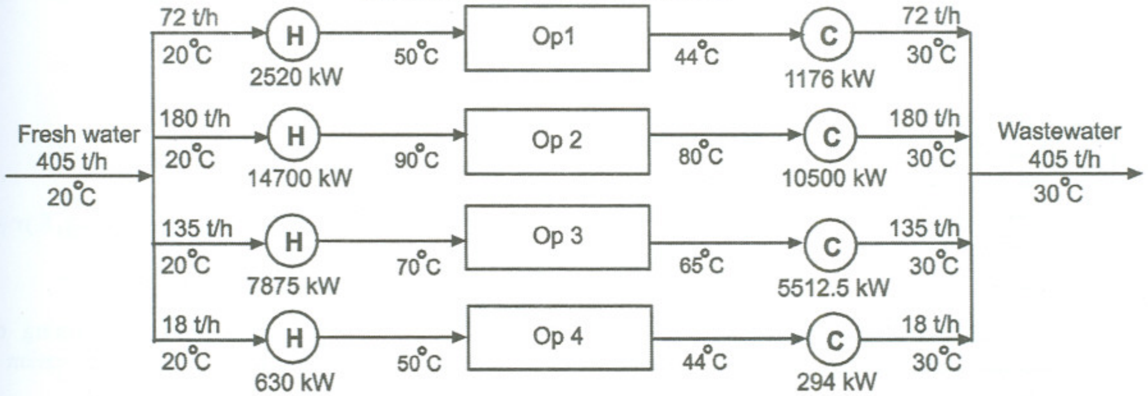

Fig. 8. Conventional network configuration

Table 5. Comparison of the results

Requirements	New design	Conventional design	Saving, %
Fresh water, t/h	324	405	20
Hot utility, kW	7344	25725	71.45
Cold utility, kW	0	17482.5	100
Number of heat transfer units	4	8	50
Total annual cost, $/yr	1377800	2559900	46.2

reduced (Karbassi *et al.*, 2008). The reduction of air pollutants emission for this example is given in (Table 6).

Table 6. Reduction of air pollutants emission for the illustrative example (t/yr)

NO_x	SO_2	SO_3	CO_2	CO	CH	SPM
48.28	38.29	0.592	8399	0.074	1.44	5.14

CONCLUSION

Process integration has been highlighted in this paper to provide a new systematic design methodology for the problem of simultaneous energy and water minimization with considering heat losses inside unit operations. A new design procedure has been developed to achieve both water and energy targets for systems using water at different temperatures and maximum re-use of water. 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, reuse options of water 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 an illustrative example. Optimization was made using the commercial mathematical optimization software package GAMS. The results of the analysis for the example demonstrated 20% of fresh water, 71.45% of hot utility (low-pressure steam), 100% of cold utility (cooling water), 50% of number of heat transfer units and 46.2% of total cost saving relevant to the conventional design method. In addition, the results showed that more than 48 ton NO_x, 38 ton SO_2, 0.59 ton SO_3, 8399 ton CO_2, 0.07 ton CO, 1.44 ton CH and 5.14 ton SPM per year could be reduced. 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
	Cooler
C_{Aj}	Annual cost of heat exchanger per unit outside tube surface area in separate system *j*, $\$/m^2yr$
NLP	Non-linear programming
$n_{operations}$	Number of operations
OPCOST	Total anuual cost of operating, *$/yr*
OP1, OP2, OP3, OP4	Water-using operations
Q_i	Energy requirement for heating of inlet freshwater stream to operation *i*, *kW*

C_e	Annual cost of energy, *$\$/kWyr$*
$C_{i,in}$	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, $\$/kWyr$*
$C_{i,out}$	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, $\$/kWyr$*
C_p	Specific heat capacity, *kJ/kg^oC*
C_w	Annual cost of fresh water, *$\$.h/t.yr$*
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*
	Heater
h_{fij}	Fouling coefficient of inside tubes in separate system *j, $W/m^{2o}C$*
h_{foj}	Fouling coefficient of outside tubes in separate system *j, $W/m^{2o}C$*
h_{ij}	Coefficient of heat transfer inside tubes in separate system *j, $W/m^{2o}C$*
h_{oj}	Coefficient of heat transfer outside tubes in separate system *j, $W/m^{2o}C$*
h_{tj}	Combined coefficient for tube wall and dirt films in separate system *j, $W/m^{2o}C$*
K	Unit conversion factor, *0.2778*
k_{wj}	Thermal conductivity of tube wall in separate system *j, W/m^oC*
L_j	Lagrangian function for separate system *j, $\$/yr$*
l'_j	Thickness of tube wall in separate system *j, m*
Min	*Minimization*

$Q_{Recovery}$	Heat recovery, *kW*
q_j	Rate of indirect heat transfer in separate system *j, kW*
T	Temperature, *^oC*
T_0	Temperature of freshwater source, *^oC*
t_{1j}	Shell side inlet temperature in separate system *j, ^oC*
t_{2j}	Shell side outlet temperature in separate system *j, ^oC*
T_{1j}	Tube side outlet temperature in separate system *j, ^oC*
T_{2j}	Tube side inlet temperature in separate system *j, ^oC*
TC_j	Total annual cost of the heat exchanger in separate system *j, $\$/yr$*
T_{fi}	Temperature of inlet fresh water stream to operation *i, ^oC*
$T_{i,in}$	Average temperature of inlet stream to operation *i, ^oC*
$T_{i,out}$	Average temperature of outlet stream from operation *i, ^oC*
$T_{j,out}$	Average temperature of outlet stream from operation *j, ^oC*
U_{oj}	Overall coefficient of heat transfer based on outside tube area in separate system *j, $W/m^{2o}C$*
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*
$X_{j,i}$	Flowrate of stream from operation *i* to operation *j, t/h*

Greek Letters

$\Delta m_{i,tot}$	Total mass transfer load of contaminant in operation *i, kg/h*
ω_j	Lagrange multiplier for separate system *j, $\$W/yr^oC$*
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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