PROCEEDINGS OF ECOS 2015 - THE 28TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
JUNE 30-JULY 3, 2015, PAU, FRANCE

Thermodynamic Analysis of Heat and Mass Exchange Systems

J. Martinez-Patiño[a], L. Serra[b], V. Verda[c], M. Picón-Núñez[d], C. Rubio-Maya[e].

[a] Department of Electrical Engineering, University of Guanajuato, México. jesusmp23@ugto.mx.
[b] Department of Mechanical Engineering, University of Zaragoza, Spain, Spain.
[c] Department of Energy, Politecnico di Torino. Italy.
[d] Department of Chemical Engineering, University of Guanajuato, México.
[e] Department of Mechanical Engineering, UMSNH, Spain, México.

Abstract:

The direct heat exchange network (direct flow mixing network) and the indirect heat exchange network (exchanger network) are two of the elements that constitute a water network where heat and mass are transferred. When designing these systems, it is important to consider different aspects such as thermodynamics and equipment costs. This paper analyzes different design options within the framework of heuristic methodologies on a case study taken from the open literature. Two design methodologies are compared on the basis of exergy losses. It also enunciates a series of considerations in heuristic design for the heat and mass networks. A very helpful tool in relation with the considerations set out herein is the composite curve; special focus will be placed during its construction. The results shown in this article show how to incorporate the exergy component in design seeking to minimize thermal irreversibility.

Keywords:

Exergy analysis, heat and water networks.

1. Introduction

Industries are looking for ways to reduce production costs by optimizing resources and achieving maximum efficiency in its processes. As a consequence, there is a constant search for practical engineering methodologies to accomplish these goals. Water and energy are used in processes in many ways; one of them is in the case of processing water where this fluid is mainly used as a contaminant and energy carrier. Such systems are technically known as simultaneous heat and mass transfer networks. Methodologies have been developed for the design of these types of systems where the main goal is to reduce the amount of fresh water and external heating required. Among the most known approaches are the ones based on mathematical programming and the ones based on heuristic rules.

These types of methodologies integrate the use of water and thermal energy by finding the best way to mix and reuse water streams considering the unit operations present in the process. A water use and reuse network is developed in order to reduce water consumption levels taking into consideration the concentration goals of every operation within process. As for the energy recovery system, heat exchangers are employed in order to achieve the required temperature levels specified by the process operations.

This article will particularly present a heuristic methodology developed from the concepts of Thermal Pinch Analysis and Water Pinch Analysis methodologies. The study presents a comparison between methodologies focusing on the mixing points. The calculations and comparisons are based on destroyed exergy that takes place at each mixing point with the aim of determining the impact of exergy losses on the system and find ways to maximize energy recovery.

2. Simultaneous Heat and Mass Transfer Systems

2.1. Literature review

Heuristic and mathematic optimization technologies for the design of heat and mass exchange networks result in different structures where water streams at different concentrations and temperature are mixed and separated either isothermally or non-isothermally.

Design methodologies of the heuristic type have been reported by by Savulescu et al. [1], [2], Polley et al. [3] and Martinez et al. [4], [5]. On the other hand, Leewongtanawit et al. [6] proposed a methodology based on mathematical optimization. Its development takes into account two possible types of design: networks with non-separated systems, and networks with separated systems. The solution strategy decomposes the original problem in two sub-systems where mathematical programming techniques are employed, namely Mixed Integer Linear Programming (MILP) and other Non-Linear Programming (NLP).

Simultaneous Heat and Mass Transfer System are made up of three identifiable subnetworks: a network where mass transfer takes place; a network where direct heat transfer between streams is forced and a network where indirect heat transfer between the effluent stream and the fresh stream takes and where external heating utilities are employed to meet the required duties. In order to design/build the three networks, it is necessary to construct composite curves for the cold and hot streams of the process. These composite curves are subdivided in two zones: one for the mixing of streams and the other for determining the exchange networks of the process.

2.2. Features of a Simultaneous Heat and Mass Transfer Systems

The structure of a Simultaneous Heat and Mass Transfer System was first introduced by El-Halwagi and Manousiouthakis [7], who developed the concept of mass exchange networks for separation systems in isothermal applications. Sorin et al. [8] presented a methodology for the design of heat and mass exchange networks focused on minimizing the number of heat exchange equipment, introducing the concept of direct and indirect heat exchange. Meanwhile, Martinez et al. [4] showed in a more concrete way the separation of the three different networks constituting these systems (Figure 1).

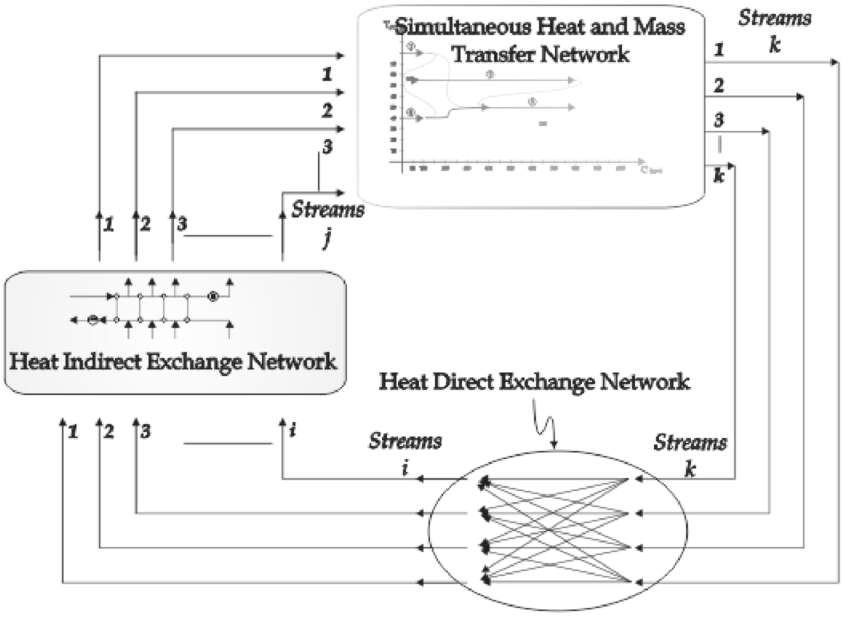
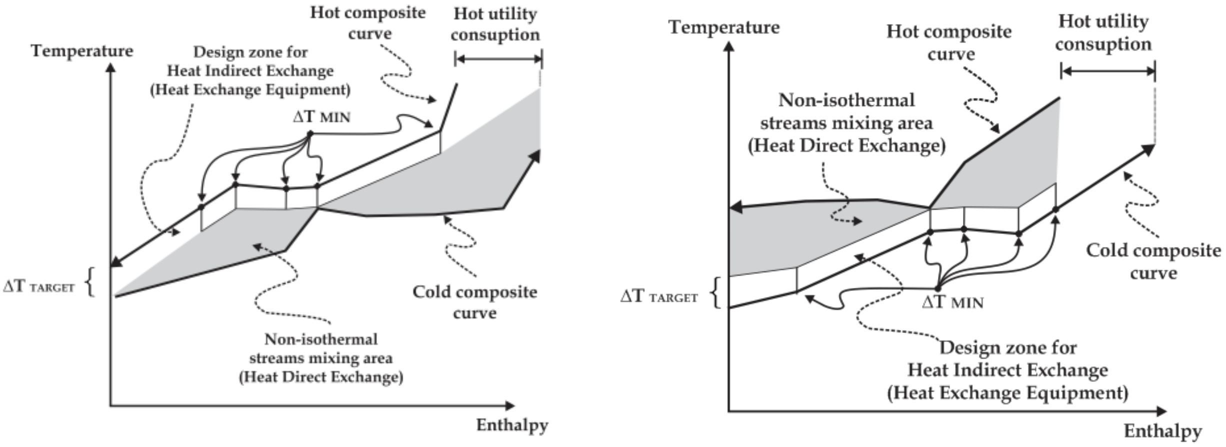


Figure 1 - Simultaneous Heat and Mass Transfer System.

A goal that is usually pursued when designing water heat and mass transfer networks is the reduction of the total operating costs. Such costs are made up of the following components: cost of heat exchange equipment, cost derived from external thermal energy consumption for heating and cooling, and cost derived from fresh water consumption. Construction methods for water Heat and Mass Transfer System are presented by Martinez et al. [5], wherein the different design options are shown.

Figure 2 is a Temperature vs. Enthalpy Flow diagram that shows the cold and hot composite curves, the external energy employed, the indirect heat transfer area (heat exchange network) and the direct heat exchange area (greyed area). This diagram also shows the values of the stream flow rates and their temperatures. Also, Figure 2(a) shows a mixing network in the cold water streams whereas Figure 2(b) shows a mixing network in the hot water streams. In order to understand the difference between both diagrams, it is necessary to note that the area that is not greyed-out represents the indirect heat transfer process that initiates with the heat exchangers network. From these curves it can be seen that the larger the direct mixing area, the lesser the temperature driving force for indirect heat transfer, giving place to an increase in the heat transfer surface area of the equipment.



(a) *(b)*

Figure 2 - Mixing network in the cold (a) and hot (b) water flow currents.

3. Problem statement

The design of a Simultaneous Heat and Mass Transfer System involves the determination o the way water streams must be divided and mixed in order to meet the process requirements that involve the specified water contaminant concentration and temperatures levels achieving both, the minimum fresh water consumption and the minimum energy consumption.

The steps for the application of the design methodology to a process are:

1. Extraction of process information,
2. Determination of the minimum fresh water flow rate,
3. Design of the heat and mass transfer network,
4. Design of the direct and indirect heat recovery networks,
5. Merging of the sub-networks of the system.

An important consideration to take into account in the construction of the system is that the profile of the composite curves will change depending on the distribution of the water streams and the temperature driving forces for heat recovery. This will bring about changes in energy consumption as shown in Figure 3.

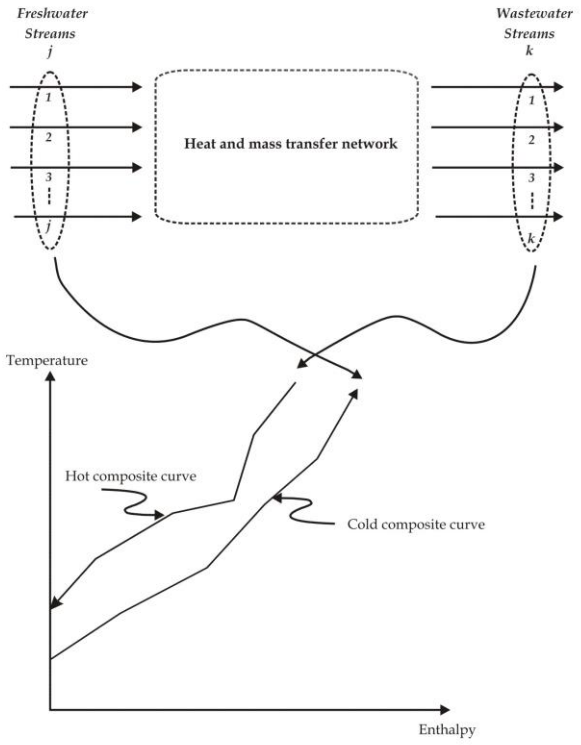


Figure 3 - Relationship between composite curve and heat and mass transfer network.

Methodologies based on mathematical optimization exhibit advantages when it comes to the design of water networks to achieve the temperature and concentration goals. This is so even if they have the main disadvantage of not permitting the designer to fully understand the interactions between the different sub-systems. This is the relation between fresh water consumption levels, heat and equipment is not thoroughly known. These dimensions are more clearly perceived by means of composite curves, thereby the importance of using them for design purposes.

4. Exergy analysis

The second law of thermodynamics states that all real processes are irreversible, hence always it will result in a loss of available energy, which means, a loss of the ability to do work. Therefore, exergy is the ideal tool for the analysis because it usually refers to the Exergy as the property of the systems that gives a quantitative description of the useful energy contained in it [9] [10].

The general exergy balance equation is given by Equation 1:

$$\left(\frac{dA}{dT}\right)_{re} = \sum_e \dot{m}_e Ex_e - \sum_s \dot{m}_s Ex_s + \dot{Q}\left(1-\frac{T_0}{T}\right) - \left(\dot{W} - P_0\frac{dv}{dt}\right) - \dot{I} \tag{1}$$

where:

$$\left(\frac{dA}{dT}\right)_{re} = 0 \tag{2}$$

$$\dot{Q}\left(1-\frac{T_0}{T}\right)=0 \tag{3}$$

$$\left(\dot{W}-P_0\frac{dv}{dT}\right)=0 \tag{4}$$

Substitution o Equation (2), (3) and (4) into (1) gives:

$$\dot{I}=\dot{m}_1Ex_1+\dot{m}_2Ex_2-\dot{m}_3Ex_3 \tag{5}$$

The physical exergy can be determined form:

$$Ex(\mathrm{T},P)=h(\mathrm{T},P)-h_0(\mathrm{T}_0,P_0)-T_0\left(s(\mathrm{T},P)-s_0(\mathrm{T}_0,P_0)\right) \tag{6}$$

In the case of temperature changes in water, the change can be determined from:

$$Ex=\dot{m}Cp(\mathrm{T}-T_o)-\left(\dot{m}T_oCp\ln\left(\frac{T}{T_0}\right)\right) \tag{7}$$

5. Case study

The case study presented here is extracted from the open literature and data is presented in Table 1. The problems consider a single contaminant. The design network structures derived by Martínez-Patiño et al. [5] and Leewongtanawit [6] are used for the analysis.

Table 1 - Process data for case study.[1]

Operation *(No.)*	**Concentration$_{in}$** *(ppm)*	**Concentration$_{out}$** *(ppm)*	**Temperature$_{in}$** *(ºC)*	**Temperature$_{out}$** *(ºC)*	**Limiting water flowrate** *(kg/s)*	**Contaminant mass load** *(g/s)*
1	50	100	100	100	100	5
2	50	800	75	75	40	30
3	400	800	50	50	10	4
4	0	100	40	40	20	2

Temperature of fresh water source: T_{in} = 20 ºC
Temperature of discharge wastewater: T_{out} = 30 ºC

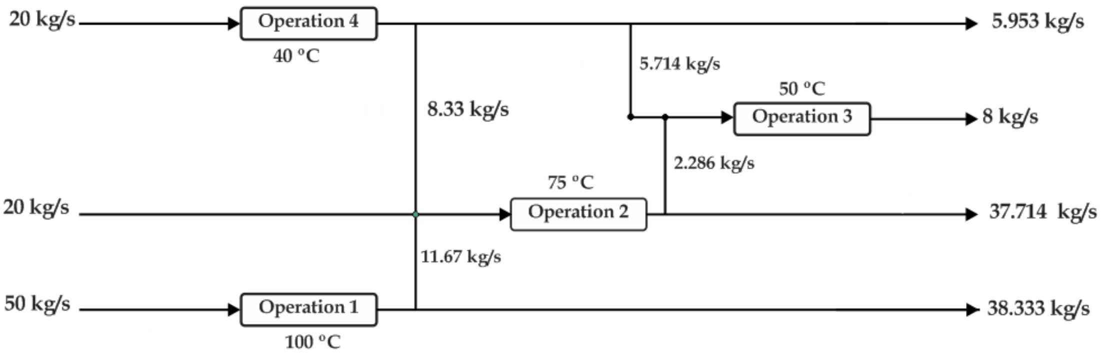


Figure 4 - Simultaneous heat and mass exchange network structure. Case 1, Martinez et al. [5].

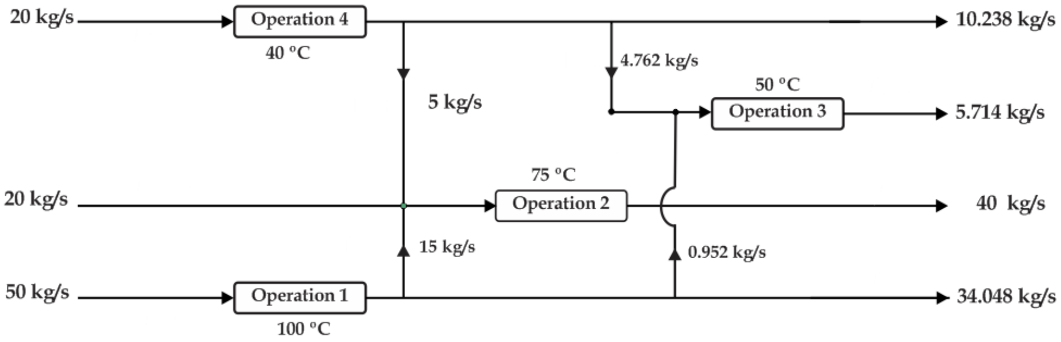


Figure 5 - Simultaneous heat and mass exchange network structure. Case 2: Leewongtanawit et al. *[6]*.

Once the simultaneous heat and mass exchange network structure is constructed (Figures 4 and 5), the different mixing points can be reviewed in relation to the exergy destroyed. To do that, the exergy balance shown in Figure 6 is established. For the two cases shown in Figures 4 and 5, the destroyed exergy is calculated for each mixing point and the results are given in Figures 6 and 7. Taking the process data and applying Equation (7) gives:

$$Ex = \dot{m}Cp(\mathrm{T}-T_o) - \left(\dot{m}T_oCp\ln\left(\frac{T}{T_0}\right)\right)$$

$$\mathrm{Ex}_{-40°C} = (5\frac{kg}{s})\bullet(4.2\frac{kJ}{kg°K})\bullet\left[(40+273)\text{-}(20+273)°K\right]\text{-}(5\frac{kg}{s})(\left[(20+273)°K\right])(4.2\frac{kJ}{kg°K})\ln(\frac{(40+273)}{(20+273)}°K)$$

$$Ex_{-40°C} = 13.71kW$$

$$Ex_{-75°C} = 263.6kW$$

$$Ex_{-100°C} = 583.9kW$$

$$Ex_{-mix75°C} = 772kW$$

Therefore, the destroyed exergy in case 1(Martinez et al., [5]) is:

$$Ex_{destroyed\_mix75°C} = Ex_{-40°C} + Ex_{-75°C} + Ex_{-100°C} - Ex_{-mix75°C} \tag{7}$$

$$Ex_{destroyed\_mix75°C} = 13.71kW + 263.6kW + 583.9kW - 772kW$$

$$Ex_{destroyed\_mix75°C} = 89.21kW$$

As can be seen in Figure 7, the destroyed exergy is higher in case 2 than in case 1; the result is equal for the first mixing point in both cases (89.21 kW), whereas for the second mixing point, case 1 shows an exergy loss of 11.46 kW and case 2 of 15.61 kW. It is important to note that in the global results for both cases, temperature and concentration requirements are perfectly met and the energy consumption is of 3789kW with a water consumption of 90 kg/s.

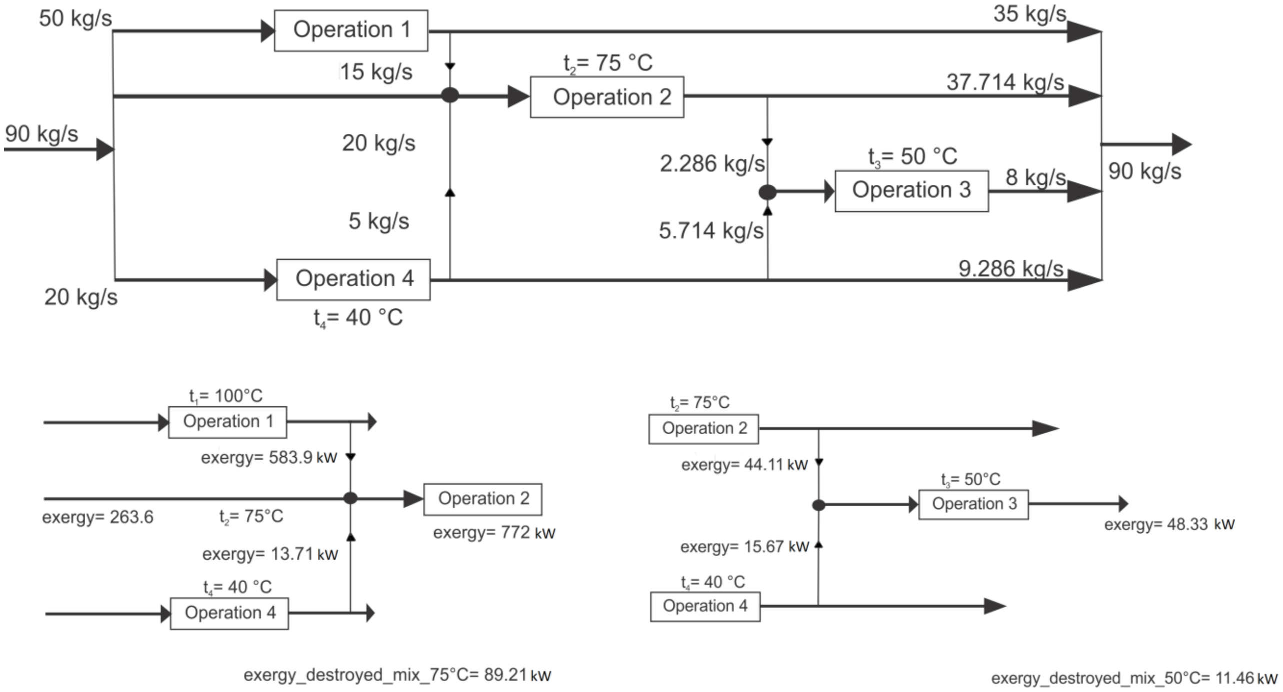


Figure 6 – Exergy of the Simultaneous Heat and Mass Exchange network (Case 1).

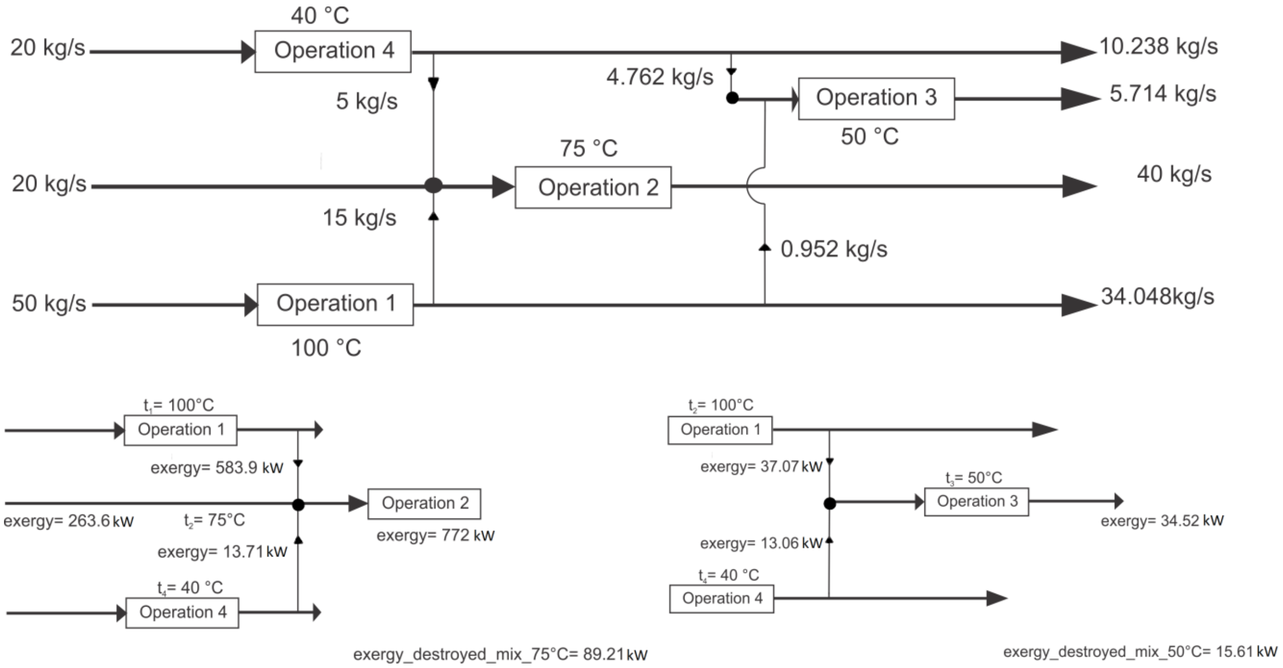


Figure 7 - Exergy of the Simultaneous Heat and Mass Exchange network (Case 2).

6. Conclusions

Most of the reported methodologies for the design of heat and mass exchange networks where the working fluid is water use non-isothermal mixing between streams. In his work two of these techniques are compared based on the exergy losses that take place at the mixing points. The case studies analyzed in this work, although exhibit different topologies, both have the same external energy consumption and the same fresh water consumption. From the structural point of view, the case studies under comparison have the same number of mixing points and from the operating stand point they both have the same operating costs. This situation might indicate that any of them could be an appropriate design option; however, from the point of view of lost potential (exergy loss) one of the systems exhibits lower losses. Exergy losses are the result of the mixing of streams at different temperatures. The greater is the temperature driving force between the mixing streams, the higher is the exergy loss. The negative impact of the exergy losses can be observed in the heat exchanger system, which, in order to transmit the specified amount of thermal energy, will require larger heat transfer surface area due to the availability of lower driving forces. A direct consequence of this is the increment of the associated capital costs.

Nomenclature

h	specific enthalpy	[kJ/kg]
s	specific entropy	[kJ/kg^{o}K]
Ex	exergy	[kW]
$Ex_{\_destroyed}$	destroyed exergy	[kW]
$\dot{m}$	mass flow rate	[kg/s]
Cp	heat capacity at constant pressure	[kJ/kg^{o}K]
$\dot{Q}$	hot utility	[kW]
$\dot{W}$	mechanic power	[kW]
T	temperature	[^{o}K]
T_o	ambient temperature	[^{o}K]
$\dot{I}$	irreversibility	[kW]
P	pressure	[Pa]
P_o	atmospheric pressure	[Pa]
v	specific volume	[m^3/kg]

References

[1]. Savulescu, L., J.-K. Kim, et al. (2005 a). Studies on simultaneous energy and water minimisation- Part I: Systems with no water re-use. Chemical Engineering Science 60: 3279 - 3290.

[2]. Savulescu, L., J.-K. Kim, et al. (2005b). Studies on simultaneous energy and water minimisation- Part II: Systems with maximum re-use of water.Chemical Engineering Science 60: 3291 - 3308.

[3]. Polley, G. T., Picón-Núñez, M., & de Jesús López-Maciel, J. (2010). Design of water and heat recovery networks for the simultaneous minimisation of water and energy consumption. Applied thermal engineering, 30(16), 2290-2299.

[4]. Martínez-Patiño, J., Picón-Núñez, M., Serra, L. M., & Verda, V. (2012). Systematic approach for the synthesis of water and energy networks. Applied Thermal Engineering, 48, 458-464.

[5]. Martínez-Patiño, J., Picón-Núñez, M., Serra, L. M., & Verda, V. (2011). Design of water and energy networks using temperature–concentration diagrams. Energy, 36(6), 3888-3896.

[6]. Leewongtanawit, B., & Kim, J. K. (2009). Improving energy recovery for water minimisation. Energy, 34(7), 880-893.

[7]. El‐Halwagi, M. M., & Manousiouthakis, V. (1989). Synthesis of mass exchange networks. AIChE Journal, 35(8), 1233-1244.

[8]. Sorin, M. and L. Savulescu (2004). On minimization of the number of heat exchangers in water networks. Heat Transfer Engineering 25(5): 30 - 38.

[9]. Bejan A. Entropy Generation Through Heat and Fluid Flow. New York. Wiley. 1982.

[10]. Moran, M.J; Shapiro, H.N. Fundamental of Engineering Thermodynamics. 5 Edition. Chichester: Jhon Wiley& Sons Ltd, 2006.