Chapter 1
Exergoeconomic analysis of energy conversion systems: From fundamentals to applications

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Abstract: Exergoeconomic analysis, a simultaneous investigation of exergetic and monetary performance has attained significant attention to analyze and improve the performance of energy conversion systems. This combined analysis allows an individual audit of all the components in the system. The research is particularly useful for multi-component systems to get a better understanding of how effectively each component consumes energy and economic capital. This chapter aims to present a comprehensive theoretical framework for exergoeconomic study of thermal systems. For this purpose, the framework is initially developed for standalone heat exchangers and then extended to commercial-scale thermal desalination systems consisting of preheaters, pumps, evaporators, and compressors, etc. The exergetic and economic values of each stream in the system were evaluated using the developed framework. The sensitivity and parametric analysis of different thermodynamic and economic parameters on the system performance was conducted to study the performance variations. The presented model can be generalized for performance analysis of other systems.

Keywords: Exergoeconomic analysis; thermal systems; thermodynamic parameters, economic parameters; theoretical framework

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Nomenclature

Variables

A	area, m^2
C	cost, $/s
h	enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
P	pressure, *kpa*
$\dot{Q}$	heat transfer rate, kW
s	entropy, kJ/kg K
T	temperature, ^{o}C
$\dot{W}$	work, kW
x	specific exergy, kJ/kg
X	exergy, kW

Greek letters

Λ	operational availability
β	chevron angle ^{o}
ε	effectiveness
Δ	change in quantity
η	efficiency, %

Subscripts/superscripts

cap	capital
ch	chemical
comp	compressor
D	distillate
ele	electricity
ene	energy
eq	equivalent
G	generator
i	inlet
misc	miscellaneous

o	outlet
ren	renewable
the	thermal
y	amortization period
0	dead state
Abbreviations	
AD	adsorption
CF	conversion factor
CRF	capital recovery factor
FF	forward feed
GA	Genetic algorithm
HX	heat exchanger
MED	multi-effect desalination
MVC	mechanical vapor compression
PCF	parallel cross feed
PF	parallel feed
PHX	plate heat exchanger
PR	performance ratio
RO	reverse osmosis
STHX	shell and tube heat exchanger
UPR	universal performance ratio

1.1 Introduction

The economic efficiency of energy conversion systems is particularly focused on the last few decades because of soaring power requirements, optimal design constraints, environmental concerns, and high investments [1, 2]. Some of the major areas in this regard include power plants, air conditioning units, water desalination systems, and energy recovery heat exchangers[3–5]. This is because these areas have a direct impact on the human life cycle. For instance, power plants fulfill the energy demands [6], the air conditioning systems maintain the comfortable working and living environment [7], desalination systems supply drinking water [8], and the energy recovery sections enhance the performance efficiency of these systems through waste heat recovery [9]. Therefore, significant research is conducted in all these sectors to enhance their performance efficiencies from energy, economic and environmental standpoints. For instance, in the power plant sector, new power cycles [10], and the cooling industry sustainable technologies with low energy consumption and minimal environmental impacts [11] are being developed.

Likewise, various developments in energy recovery heat exchangers and thermal desalination systems (which are the focus of this study) have been made [12, 13]. In this regard, the commonly used heat exchangers for liquid phase energy recovery are shell-and-tube heat exchangers (STHX) and plate heat exchangers (PHX) [14, 15]. For STHX, the major interest has been the performance improvement through variation in design parameters including the number and orientation of baffles, and diameter, length, layout, and the number of tubes [16, 17]. Besides, the economic optimization of these HXs has also been conducted using different numerical techniques [18, 19]. For instance, Iyer et al. [20] achieved up to 52% cost reduction of STHX using Adaptive range and Genetic Algorithm (GA). Mirzaei et al. [21] used Constructal Theory and GA which reduced the investment cost by 32%. Tharakeshwar et al. [22] reported a 14% reduction using GA and Bat Algorithm. Segundo et al. [23], achieved a 54% reduction using the Differential Evolution algorithm. Rao and Siraj [24] attained a 33% decrement in the total cost using Elitist-Jaya Algorithm. Dhavle et al. [25], reported 52%, Hajabdollahi et al. [26] 35% and Mohanty [27] 29% using Cohort Intelligence Algorithm, sensitivity based GA and Firefly Algorithm, respectively.

While for plate heat exchangers the research focus has been on the plate features including length, width, protrusion/chevron angle (β), and enlargement factor [28, 29]. Nilpueng et al. [30] investigated the influence of surface roughness, chevron angle, and Reynolds number. They found that the heat transfer coefficient and pressure drop of 30° angle plates were 2.5 and 1.8 times greater than those of 60° angle plates, respectively. The 30° angle plates with the highest surface roughness and lowest Reynolds number had the best overall results. Turk et al. [31] used artificial neural networks to investigate the effect of mixed angle plates and found that they had no substantial effect on thermal performance. Similarly, Kumar et al. [32] reported that an increasing the chevron angle from (30°/30°) to (60°/30°) and then to (60°/60°) increased ΔP by 22.05% and 37.9%, respectively.

For desalination systems, the focus has been on energy and cost optimization particularly for thermal systems which are suitable for harsh feeds [33, 34]. The common systems in this regard include multi-effect desalination [35], multi-stage flash, mechanical/thermal vapor compression [36], electrodialysis [37], and other hybrid systems like MED hybrid with AD [38, 39]. Though, significant research has been conducted to improve the performance of desalination systems the equivalent energy consumption of conventional systems hover around 3.7-8 kWh/m^3 for RO, 14.45-21.35 kWh/m^3 for MED, and 19.58-27.25 kWh/m^3 for MSF [40, 41]. These energy consumptions are significantly higher (~5-30 times) than the minimum separation work (0.72 kWh/m^3 at 35g/kg and 25°C) [42]. Therefore, some novel systems like domestic scale units [43], hybrid systems [44], greener desalination technologies [45], integrated cooling and water production systems [46], and cogeneration plants [47] are also investigated.

It is important to mention that almost all the developments presented above either involve design modifications or the integration of new components. For the case of standalone components, the design modifications require a robust computational facility for the execution of a complex optimization algorithm. While for the multicomponent system, this approach is not viable because of being computationally expensive due to the combinatory effect of parameters. Moreover, most multi-component systems are analyzed treating the whole system as a single unit. The total expenditures, i.e., purchasing, chemical, labor, recurring, operation, and maintenance costs spent at system boundaries, are divided by the product (electricity, freshwater, cooling capacity, etc.) to calculate the unit product cost. Therefore, the approach provides a quick initial estimation of the product cost, however, it is difficult to locate the most sensitive parameters/components for performance improvement.

In this regard, the exergoeocnomic analysis method presented in this study has a significant potential for a detailed design and analysis of standalone as well as multi-component systems [48]. The method works by taking thermodynamics as well as economic parameters into account and investigating their individual as well as a combined effect on the system performance. Each component is analyzed individually to evaluate how efficiently the input thermodynamic (energy, exergy, etc.), as well as economic resources, are utilized on local as well as overall performance scale. Moreover, the approach also offers flexibility for design improvement and fault diagnosis. The current study presents a systematic procedure for exergoeconomic analysis of thermal systems with applications. Two energy recovery heat exchangers and three industrial-scale mechanical vapor compression-based desalination systems are presented as an example. Based on the discussions made in the study, the method can also be extended to analyze other systems involving energy conversion mechanisms.

The remaining chapter is organized as follows, in section 2, the exergoeconomic mathematical framework is formulated with examples of key components (pump, compressor, evaporator, etc.). Section 3 covers illustrative examples for an application of exergoeocnomic analysis on standalone (heat exchangers) and multi-component systems (desalination systems). The conclusion is presented in section 4.

1.2 Problem formulation

A comprehensive framework for exergoeconomic analysis of energy conversion systems is formulated in this study. The analysis is employed as a combined application of thermodynamic and economic analyses. The analysis proceeds by calculating the exergetic and monetary values of all the fluid streams in the systems as they pass through each component. The exergy value is calculated based on temperature, pressure, and chemical potential. While the monetary value is calculated based on the capital and operational expenses of each component individually. The product is characterized by the main function of the parts, such as high-pressure water for a pump, compressed vapor for a compressor, and evaporated vapors for evaporators. In the first step, the significance of selecting appropriate input energy calculation metrics (i.e., exergy) is presented by reviewing different available models. Then a systematic procedure for developing cost balance equations for different key components is established. Finally, the illustrative examples of heat exchangers as a standalone system and thermal desalination systems as a multi-component system analysis are presented.

1.2.1 On energy metrics

The input energy metric is very important in desalination system calculations because of being a decisive parameter for selection among different systems. The accurate calculation of energy consumption requires an equal emphasis on its quantitative, qualitative, and source characteristics. This is because the same quantity (W) of different energy grades like thermal, mechanical, or electrical, etc. correspond to different metrics and costs. Both factors must be considered for a fair comparison of unit energy usage of multiple desalination systems working with different energy forms. Therefore, to handle the potential discrepancies in performance metrics due to variations in input energy calculations, the following notable efforts have been made.

The exergy-based calculation model [49, 50] asserts that all the calculations in the thermal systems should be based on the exergy of streams (which represents the maximum theoretical work) rather than energy. Where the stream exergy was defined based on a unform dead state as given below [51].

$$X(kW) = \dot{m}\,x = \dot{m}[\{(h-h_0)-T_0(s-s_0)\}+x_{ch}] \tag{1.1}$$

Where h and S denote the stream enthalpy and entropy while, h_0, S_0 represents the dead state enthalpy and entropy ($T_{0,}\,P_0$) and x_{ch} denotes the chemical exergy.

An equivalent electricity consumption model was proposed to cumulate secondary energy inputs (electricity) with the primary energy inputs (steam) using electrical energy units [52]. It refers to the amount of electrical work that might have been produced if the desalination system had been supplied with steam. This electrical work is estimated by expanding an equivalent amount of steam in a theoretical steam turbine as given below [52].

$$\dot{W}(kW) = \dot{m}\,\eta_G\left(h_i - h_o\right) \quad (1.2)$$

Where η_G is the generator efficiency (taken 95%), steam outlet temperature 35°C, and the turbine efficiency as 85% [52]. The equivalent electricity consumption is calculated as.

$$E_{eq}(kWh/m^3) = \frac{\dot{W}}{3.6\,\dot{m}_D} \quad (1.3)$$

A universal performance ratio model was proposed to assess the desalination system performance on a common platform using primary energy [53]. The model is important for a cogeneration system that observes inappropriate distribution among energy given for electricity and desalination. Unlike the conventional performance ratio (PR) formula (based on derived energy), in the proposed UPR the derived energies are corrected with conversion factors (CF) as given below [54].

$$UPR = \frac{evaporative\ energy}{primary\ energy\ input} = \frac{h_{fg}}{3.6\left\{CF_1\left(\frac{kWh}{m^3}\right)_{ele} + CF_2\left(\frac{kWh}{m^3}\right)_{the} + CF_3\left(\frac{kWh}{m^3}\right)_{ren}\right\}} \quad (1.4)$$

According to the above discussion, exergy is the true indicator of plant input energy in the plant. Therefore, the calculation model presented below is based on the exergetic cost of fluids streams.

1.2.2 Components of exergoeconomic analysis

The economic analysis involves the calculation of capital cost, input energy cost, operation and maintenance cost, and other applicable miscellaneous costs heads as product post-treatment, storage, distribution cost, etc. Among these different components, the capital cost represents the purchasing cost obtained from the market or calculated using well-established correlations [55]. It depends upon component capacity, material, efficiency, and local market situation. While the energy cost depends upon input energy type, consumption, and unit cost. Similarly, the maintenance cost depends upon the shutdown time and parts replacement. Therefore, the total cost rate equation is given as:

$$C_{total}(\$/s) = C_{cap} + C_{ene} + C_{O\&M} + C_{ch} + C_{misc} \quad (1.5)$$

It is important to mention that all the costing terms in the above equation should correspond to same units i.e., *($/s)*. For this purpose, the capital cost ($) is multiplied with the capital recovery factor (CRF) using interest rate, and amortization period given as below [56].

$$CRF = \frac{i \times (1+i)^{y}}{(1+i)^{y} - 1} \tag{1.6}$$

$$C_{cap} = \frac{\bar{C}_{cap} \times CRF}{365 \times 24 \times 3600 \times \Lambda} \tag{1.7}$$

Similarly, the energy cost is obtained in $/s by multiplying the energy consumption (*kW*) with the unit energy cost (*$/kJ*). Likewise, the other costs i.e., labor, chemical, maintenance, etc. are also converted into *$/s* using appropriate unit rates and consumption rates.

In conventional economic analysis, the total cost calculated using Eq. 5 is finally divided by the output which is different for different systems e.g., for power plants it is electricity, for refrigeration systems it is cooling capacity, for heat exchangers, it is energy recovered, and for desalination systems, it is desalinated water.

While, in the exert economic analysis, each component is investigated individually using a cost balance equation consisting of its local inputs, outputs, and fixed cost rate as given below [57].

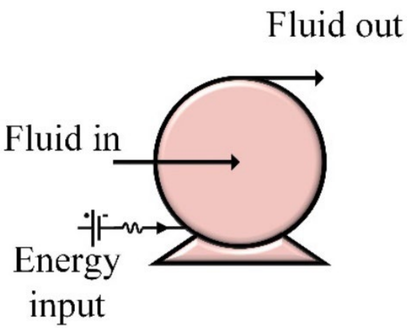
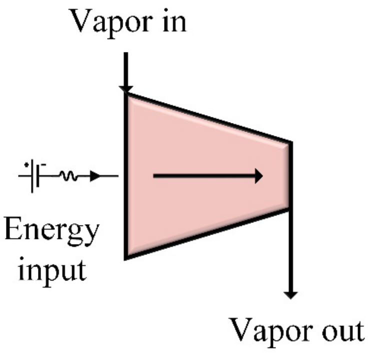
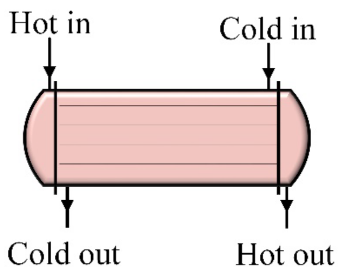
$$C_{outputs}(\$ / s) = \Sigma C_{inputs} + C_{cap} \tag{1.8}$$

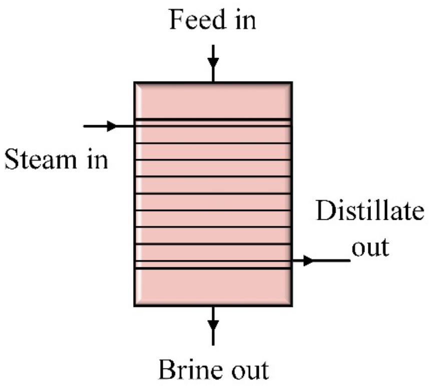
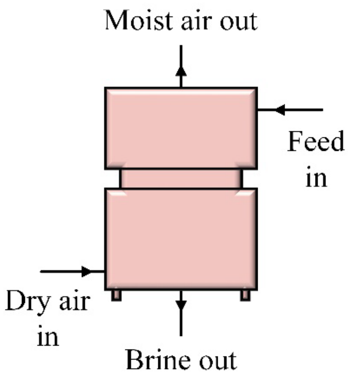
It's worth mentioning that the output cost of the equipment with a single output stream (such as compressors, pumps, and blowers) is measured as shown above. Meanwhile, additional supplementary calculations are needed to solve the cost balance equation for components with several outlet streams (e.g., evaporators, heat exchangers, etc.). For a system with “J” outlet streams, a “J-1” number of supplementary equations based on the equality of the average cost of inlet and outlet streams are needed to solve the system as given below [58].

$$\frac{C_{inlet}}{X_{inlet}} = \frac{C_{outlet}}{X_{outlet}} \tag{1.9}$$

The sample cost equations for the common system component are given in Table1.

Table 1.1. The cost balance equations for some common thermal system components [59, 60].

Sr.	Component & cost function	Cost balance equation
1	**Pump:** $\bar{C}_{cap} = f(\dot{m}, \dot{W}, \eta, P)$ 	$C_{fluid,out} = C_{fluid,in} + C_{ele}\dot{W}_{Pump} + C_{cap,pump}$
2	**Compressor:** $\bar{C}_{cap} = f(\dot{m}, \dot{W}, \eta, P)$ 	$C_{vapor,out} = C_{vapor,in} + C_{ele}\dot{W}_{comp} + C_{cap,comp}$
3	**Heat exchanger:** $\bar{C}_{cap} = f(\dot{m}, \dot{Q}, \varepsilon, A, \Delta P, \Delta T)$ 	$C_{cold,out} = C_{cold,in} + C_{hot,in} - C_{hot,out} + C_{cap,HX}$ $\frac{C_{hot,in}}{X_{hot,in}} - \frac{C_{hot,out}}{X_{hot,out}} = 0$ or $C_{hot,out} = C_{cold,in} + C_{hot,in} - C_{cold,out} + C_{cap,HX}$ $\frac{C_{cold,in}}{X_{cold,in}} - \frac{C_{cold,out}}{X_{cold,out}} = 0$

4	**Evaporator:** $\bar{C}_{cap} = f(\dot{m}, \dot{Q}, \varepsilon, A, \Delta P, \Delta T)$ 	$C_{Vapor,\,out} = C_{Feed,\,in} + C_{Steam,\,in} - C_{Brine,\,out} - C_{Distillate,\,out} + C_{cap,\,Evap}$ $\frac{C_{Steam,\,in}}{X_{Steam,\,in}} - \frac{C_{Distillate,\,out}}{X_{Distillate,\,out}} = 0$ & $\frac{C_{Feed,\,in}}{X_{Feed,\,in}} - \frac{C_{Brine,\,out}}{X_{Brine,\,out}} = 0$
5	**Humidifier:** $\bar{C}_{cap} = f(\dot{m}, \varepsilon, \Delta T, A)$ 	$C_{moist\ air,out} = C_{dry\ air,in} + C_{Feed,in} - C_{Brine,out} + C_{cap,\,Hum}$ $C_{Feed,\,in} = C_{Brine,\,out}$

A = area (m^2), $\dot{m}$ = mass flow rate (kg/s), $\dot{Q}$ = heat capacity (kW), ε = effectiveness (%), ΔP = pressure differential (kPa), ΔT = temperature differential (°C)

1.3 Illustrative examples and discussions

The exergoeconomic analysis investigates every system component (either standalone or multi-component) as a complete system with its local inputs, outputs, and capital cost. For instance, in the case of pumps, the local output is pressurized water while the local inputs are water stream and electricity. Similarly, for heat exchangers, the local inputs are cold-and-hot fluid inlet streams, while the outputs are cold-and-hot fluid outlet streams. However, the single major output of HXs is decided to depend upon their main function i.e., whether it is used as a cooler (e.g., lubricating oil coolers in power generation), or as a heater (e.g., feed heater/preheater in the desalination systems). Similarly, for multicomponent systems, besides defining local inputs and outputs, and overall production of the system is optimized. For instance, in the case of a power plant, the electricity production cost is the global output, while for a desalination system, it is the freshwater production cost. The below section presents the effect of major input parameters on the output stream cost for standalone as well as multi-component systems.

1.3.1. Standalone component (Heat exchanger analysis)

For standalone system example, two different heat exchangers i.e., a shell and tube heat exchanger (STHX) and a plate heat exchanger (PHX) are considered. These heat exchangers work as energy recovery heat exchangers with the purpose to preheat the intake water by recuperating the waste heat. The STHX is analyzed with three different methods including Kern, Bell-Delaware, and Wills-Johnston methods as presented in a recent study by Jamil et al. [61]. The operating parameters used in the analysis are presented in Table 2. In the first step, the cost flow diagram exhibiting the stream cost at the inlet and outlet of the pumps and HX is presented in Figure 1. It is important to note that, the intake cost, in this case, is negligible (taken as 0$) because the normal lake water without any pretreatment is pumped to the heat exchanger. However, it varies in the case of chemicals/chemically treated water. After that, the effect of cold-water flow rate on the stream outlet cost is studied with three methods. The analysis showed that (refer to Figure 2) an increase in the cold (shell-side) flow rate increased the cold product/stream outlet ($C_{cold,\ out}$) cost. As the mass flow rate of the cold fluid is increased from 15 to 45 kg/s, the commodity cost for the Bell-Delaware and Wills-Johnston methods increased by 6-8 percent, and the Kern method increased by about 20%. This increase in stream cost is because of an increase in the pressure drop which increased the pumping power and energy cost. Moreover, the remarkable difference in the calculations made using the Kern method gives very high-pressure drop values particularly at high flow rates because of a less accurate and very simple formulation. As a result, the other two approaches can be used to reduce resources and economic investments with a realistic design.

Table 1.2. Heat exchangers operating parameters [61, 62].

Parameter	Value	
	STHX [61]	PHX [62]
Mass flow rate (hot/cold), *kg/s*	28/69	13/13
Hot fluid temperature (inlet/outlet), *°C*	95/40	63/23
Cold fluid temperature (inlet/outlet), *°C*	25/40	21/57
Heat transfer area, m^2	279	245
Overall heat transfer coefficients, $kW/m^2\ K$	0.84	4.9
Pumping power, *kW*	1.73	1.56

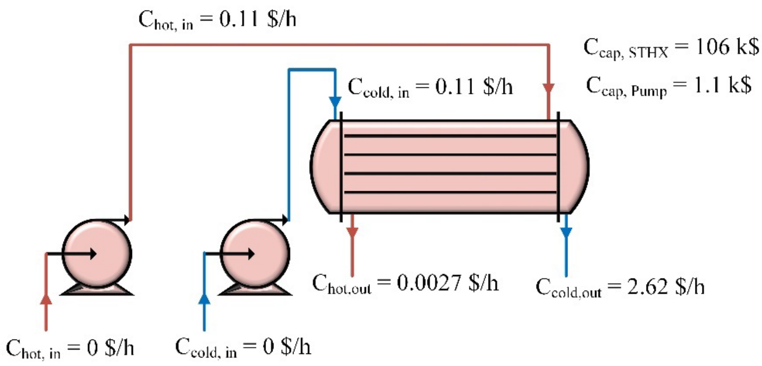


Figure 1.1 Cost flow diagram for STHX.

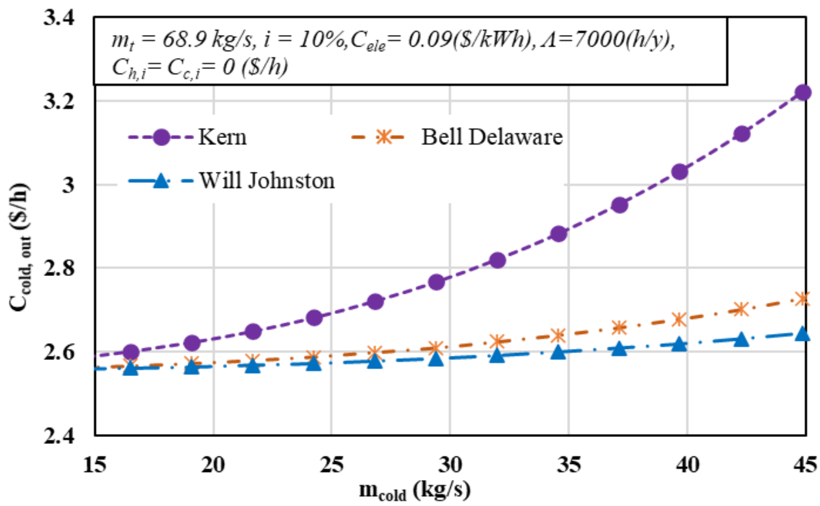


Figure 1.2 Variation in cold fluid outlet cost versus cold fluid flow rate for STHX.

Similarly, Figure 3, shows the cost flow diagram for PHX used as a preheater for the desalination system. The intake cost is taken as 4.6$/h as the chemically treated seawater is fed to pumps and heat exchangers to mitigate fouling issues. Then the variation in the product cost for a PHX with different chevron angles at varying flow rates is studied. The input data for the analysis is given in Table 2 and the design procedure used is presented in detail in a recent study by Jamil et al. [62]. The analysis showed that (refer to Figure 4) product/cold stream outlet cost $C_{cold, out}$ increased by 2-6% with increasing flow rate from 2-20 kg/s because of the increasing pressure drop that increased the pumping power. Similarly, for chevron angles, the $C_{cold, out}$, followed the following order $\beta = 30° > 45° > 50° > 60°$.

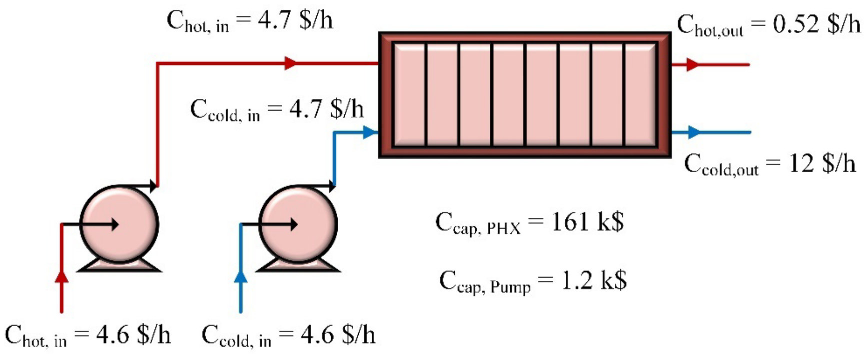


Figure 1.3 Cost flow diagram for PHX.

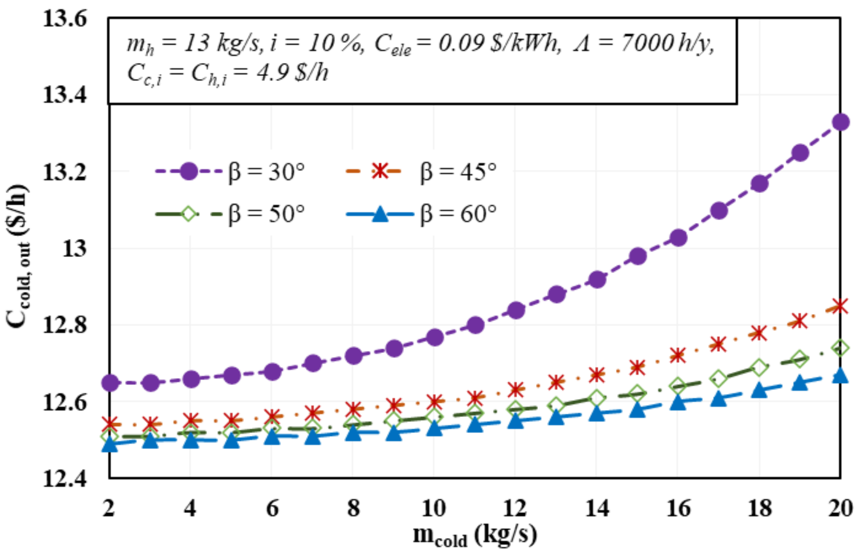


Figure 1.4 Variation in cold fluid outlet cost versus cold fluid flow rate for PHX.

1.3.2. Multi-component system (Desalination system analysis)

A mechanical vapor compression desalination device with a water output capacity of 35 kg/s is provided as an example of a multi-component system. Forward feed (FF), parallel feed (PF), and parallel crossfeed (PCF) are the three common feed flow configurations used by the system. The design specifications and operating conditions used in the analysis are adopted from a detailed study by Jamil and Zubair [63]. In the first step, the cost flow diagram representing the stream cost for all three feed configurations is developed and presented in Figure 5. After that, a detailed parametric analysis is conducted for all three systems. As an example, the impact of compressor efficiency on the cost of freshwater output is discussed. The effect of compressor efficiency η_{comp} is more dominant at a lower number of evaporators (refer to Figure 6) than at a higher number. As a result, rising η_{comp} substantially reduced the product cost C_P. As there are more evaporators, though, the capital cost governs the running cost, and the cost of producing water becomes less sensitive to compressor performance. For example, in the FF case, C_P decreased by 20% for a 2-effect system with η_{comp} ranging from 55 to 85%. While the 5-effect system showed only a 17% decrease for the same variation in η_{comp}. Similar behavior is observed for other flow arrangements with slightly different magnitudes.

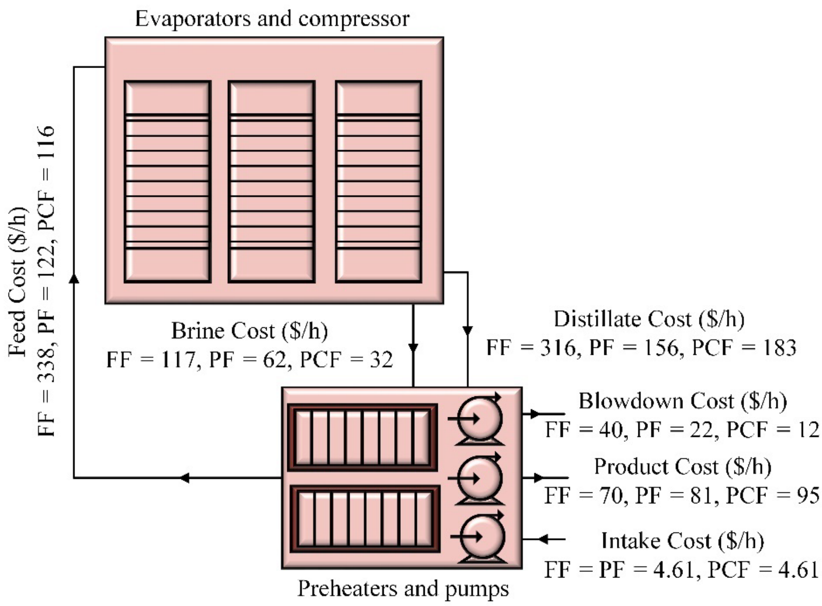


Figure 1.5 Cost flow diagram for multi-effect MVC system under forward (FF), parallel (PF), and parallel crossfeed (PCF) arrangement.

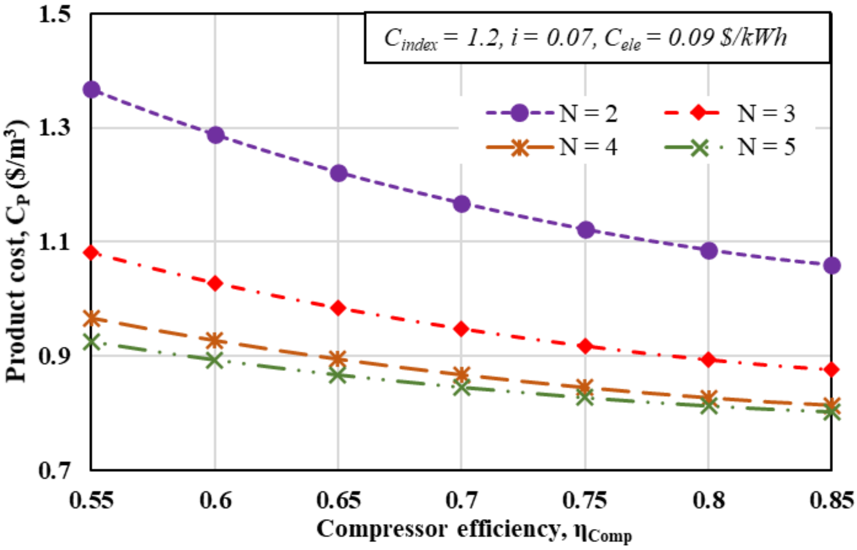


Figure 1.6 Variation in cold fluid outlet cost versus cold fluid flow rate for PHX.

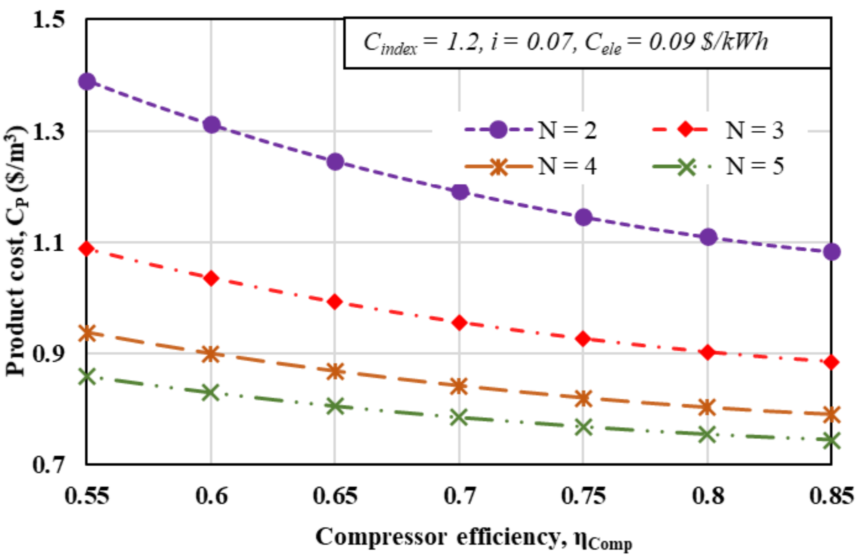


Figure 1.7 Variation in cold fluid outlet cost versus cold fluid flow rate for PHX.

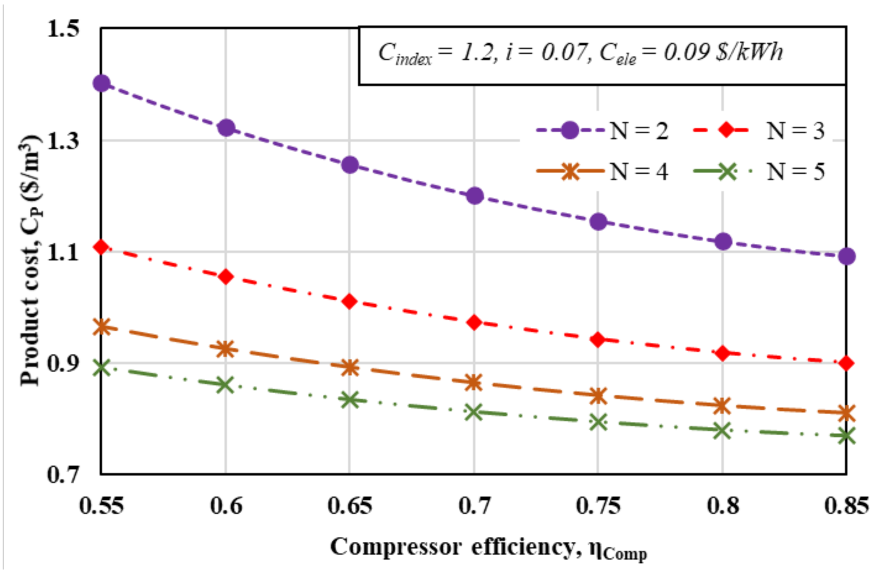


Figure 1.8 Variation in cold fluid outlet cost versus cold fluid flow rate for PHX.

1.4 Conclusion

The chapter presents a comprehensive theoretical framework for exergoeconomic analysis of standalone and multi-component systems. The presented model is equally important for investigation, malfunction detection, and simultaneous thermodynamic and economic performance optimization of energy conversion systems. Two distinct energy recovery exchangers i.e., shell-and-tube heat exchanger and plate heat exchanger are solved using the proposed method as an example of standalone system analysis. Similarly, a multi-effect mechanical vapor compression desalination system operating under three different feed flow arrangements is analyzed as a multi-component system example. In the first step, cost flow diagrams depicting stream cost ($/h) are developed for all these systems. These diagrams indicate the contribution of each component in the system (from both capital and operational cost perspectives) in achieving the final product cost. After that, a parametric analysis using output stream cost against different input parameters is conducted.

In the case of heat exchangers (both STHX and PHX), the study revealed that increasing the flow rate raised the production cost due to higher pressure drop, which increased pumping power and energy usage. Meanwhile, it is also important to note that higher flow rate results in a higher heat transfer coefficient, however, a higher flow rate is not recommended above a certain range because of an exponential rise in pressure drop and operational cost. In the case of STHX, for example, increasing the shell side flow rate from 15 to 45 kg/s raised the cold stream outlet cost by 6 to 8%. Likewise, for PHX, the increase in stream outlet cost was observed 2-6% for different chevron angles when the flow rate increased from 2-20 kg/s.

In the case of a desalination system, the effect of compressor efficiency on the water production cost is studied. For instance, for the forward feed case, the product cost sowed a 20% decrease for a 2-effect system, when compressor efficiency varied from 55-85%. While the 5-effect system, showed only a 17% decrease for the same variation in the compressor efficiency. Therefore, it is observed that that at a lower number of evaporators, the effect of compressor efficiency η_{comp} is dominant than that at the higher number because of the major contribution of operating cost.

Overall, it is concluded that in conventional thermodynamic analysis the economic part is missing while in economic analysis the effect of monetary parameters is studied only. Although the presented framework allowed for simultaneous investigation of the impact of thermodynamic parameters on the economic performance of thermal systems.

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