

Chapter 2

Thermodynamic Analysis

2.1 Introduction

The use of thermodynamic analysis plays a pivotal role in performance assessment and evaluation of any system under study. Thermodynamic analysis branches into two concepts, the first-law of thermodynamics and the second-law of thermodynamics, which are recognized as energy and exergy analyses. These are essentially applicable to all the engineering and science problems at large. The present chapter sheds light on the important aspects of energy and exergy analyses for absorption refrigeration systems. Also, presented are the general energy and exergy analyses of individual components of absorption refrigeration systems. The chapter also discusses the modeling of the absorption refrigeration systems from exergoeconomic and exergoenvironment perspectives, which are helpful in determining the overall effect of using absorption refrigeration systems on society. A brief introduction to optimization is also provided to show how an absorption refrigeration system can be optimized by considering energy, exergy, exergoenvironmental and exergoeconomic parameters.

2.2 Energy and Exergy Analyses

Thermodynamics can be defined as the science of energy (from the first-law of thermodynamics) and exergy (from the second-law of thermodynamics). Energy is the branch of thermodynamics that is derived from the law of conservation of energy according to which energy can be neither created nor destroyed but can transfer from one form to another. Performing energy analysis of a system is the first step in determining the overall performance of the system, as it is based on the basic conservation law. Energy analysis is important, but not sufficient since it does not account for irreversibility, inefficiency and exergy destruction. It is necessary to

proceed one more step to focus on exergy analysis which can further be enhanced for cost accounting and environmental impact assessment under exergoeconomic and exergoenvironmental analyses.

The drawback to using only energy analysis is that it only provides the quantity of energy and does not specify the quality of it. On the other hand, exergy analysis takes the concept of energy analysis forward by specifying the quality of energy carried by the system. Any process that is not in equilibrium with the surrounding is capable of doing work in one direction or another. Exergy analysis states that it is impossible to have a system that can work at 100% efficiency because no matter what every system has losses occurring. For example, it is known that heat transfer takes place from a hot body to a cold body but what if heat transfer is to take place from a cold body to a hot body?. Based on energy analysis it is possible to transfer heat from a cold body to a hot body without supplying any external work but it is known that this cannot happen in reality. This is when exergy comes into play to provide quality to the quantity obtained from energy analysis. Exergy analysis can also be viewed as an inequality in thermodynamic analysis as it says that if a process is taking place, the total energy at the termination of a process will either be greater than or equal to the starting point of the process. The equality holds only for hypothetical reversible processes. The following subsections present energy and exergy formulations of each component of the ARS. Also presented, is an example for each component of the ARS.

2.2.1 Pump

The mass balance equation across the pump as shown in Table 2.1 can be written as

$$\dot{m}_{in} = \dot{m}_{out} = \dot{m}_p \quad (2.1)$$

where \dot{m} represents mass flow rate.

The specific power consumed by the pump can be calculated using

$$w_p = \frac{v(P_{out} - P_{in})}{\eta_p} \quad (2.2)$$

where w , v , P and η represent specific power, specific volume, pressure and efficiency, respectively.

The total power consumed by the pump is defined as

$$\dot{W}_p = \dot{m}_p w_p \quad (2.3)$$

where \dot{W} represents total power consumed by the pump.

Table 2.1 Name and schematic of essential components of ARS

Name	Schematic
Pump	
Generator	
Condenser	
Evaporator	

(continued)

Table 2.1 (continued)

Name	Schematic
Absorber	
Expansion valve (weak solution)	
Expansion valve (refrigerant)	

The overall energy balance equation of the pump is given as

$$\sum (\dot{m}h)_{\text{in}} + \sum \dot{W}_p = \sum (\dot{m}h)_{\text{out}} \quad (2.4)$$

where h represents specific enthalpy of the state.

The specific exergy at any state is defined as

$$\text{ex}_i = (h_i - h_0) - T_0(s_i - s_0) \quad (2.5)$$

where ex , T and s represent specific exergy, temperature, and specific entropy. The same equations can be written at every state of the cycle.

The overall exergy balance equation of the pump is given as

$$\sum (\dot{m} \times \text{ex})_{\text{in}} + \dot{W}_{\text{pump}} = \sum (\dot{m} \times \text{ex})_{\text{out}} + \dot{\text{Ex}}_{\text{dest,p}} \quad (2.6)$$

where $\dot{\text{Ex}}_{\text{dest,p}}$ represents exergy destruction rate in the pump.

Example 2.1 Let us consider an ARS, a solution pump in which is a strong solution of an ammonia–water mixture with a concentration of 0.6 is supplied at 250 kPa with a mass flow rate of 1 kg/s. The pump is used to raise the pressure of the strong solution to 400 kPa. Consider the isentropic efficiency of the pump to be 85 % and ambient temperature and pressure to be 25 °C and 100 kPa, respectively. Calculate the power consumed by the pump and the total exergy rate destruction inside the pump.

- Solution

$$\left. \begin{array}{l} P_1 = 250 \text{ kPa} \\ x_1 = 0.6 \\ Qu_1 = 0.00 \end{array} \right\} \begin{array}{l} h_1 = 199.5 \text{ kJ/kg} \\ s_1 = 0.06834 \text{ kJ/kg K} \\ v_1 = 0.001247 \text{ m}^3/\text{kg} \end{array}$$

$$w_p = \frac{0.001247(400 - 250)}{0.85} = 0.002201 \text{ kW/kg}$$

$$h_2 = h_1 + w_p = 199.5 + 0.002201 = 199.5002201 \text{ kJ/kg}$$

$$\left. \begin{array}{l} P_2 = 400 \text{ kPa} \\ x_2 = 0.6 \\ h_2 = 199.5002201 \end{array} \right\} s_2 = 0.06945 \text{ kJ/kg K}$$

$$\dot{W}_p = 1 \cdot (0.002201) = 0.002201 \text{ kW}$$

$$\left. \begin{array}{l} P_0 = 100 \text{ kPa} \\ T_0 = 298.15 \text{ K} \end{array} \right\} \begin{array}{l} h_0 = 524.3 \text{ kJ/kg} \\ s_0 = 2.554 \text{ kJ/kg K} \end{array}$$

$$\dot{E}x_1 = 1(|(199.5 - 524.3) - 298.15(0.06834 - 2.554)|) = 457 \text{ kW}$$

$$\dot{E}x_2 = 1(|(199.5002201 - 524.3) - 298.15(0.06945 - 2.554)|) = 457.3 \text{ kW}$$

$$457 + 0.002201 = 457.3 + \dot{E}x_{\text{dest,p}}$$

$$\dot{E}x_{\text{dest,p}} = 0.327 \text{ kW}$$

2.2.2 Generator

The mass balance equations of the generator as displayed in Table 2.1 can be written as

$$\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}} \quad (2.7)$$

and

$$\sum (\dot{m}x)_{\text{in}} = \sum (\dot{m}x)_{\text{out}} \quad (2.8)$$

where x represents concentration of the solution.

The energy balance equation of the generator is given as

$$\sum (\dot{m}h)_{\text{in}} + \sum \dot{Q}_g = \sum (\dot{m}h)_{\text{out}} \quad (2.9)$$

where \dot{Q}_g represents rate of heat required by the generator.

The thermal exergy rate supplied to the generator is defined as

$$\dot{E}x_{th,g} = \left(1 - \frac{T_0}{T_g}\right) \dot{Q}_g \quad (2.10)$$

where $\dot{E}x_{th,g}$ represents thermal exergy rate of generator.

The exergy balance equation of the generator is given as

$$\sum (\dot{m} \times ex)_{in} + \dot{E}x_{th,g} = \sum (\dot{m} \times ex)_{out} + \dot{E}x_{dest,g} \quad (2.11)$$

where $\dot{E}x_{dest,g}$ represents rate of exergy destruction in the generator.

Example 2.2 A strong solution of an ammonia–water mixture at 400 K and 400 kPa with a concentration of 0.6 enters the ARS generator. In the generator, 250 kW of heat is supplied to vaporize the ammonia refrigerant from the strong solution. The weak solution and ammonia refrigerant leaves the generator with a mass concentration of 0.4 and 0.999, respectively. The temperature of the weak solution leaving the generator is taken to be 15 °C higher than the strong solution temperature. Calculate the exit temperature of the refrigerant vapor, mass flow rate of the refrigerant and strong solution and total destroyed exergy rate in the generator. Assume ambient temperature and pressure to be 25 °C and 100 kPa, respectively.

- Solution

$$\left. \begin{array}{l} P_1 = 400 \text{ kPa} \\ x_1 = 0.6 \\ T_1 = 400 \text{ K} \end{array} \right\} \begin{array}{l} h_1 = 2022 \text{ kJ/kg} \\ s_1 = 6.387 \text{ kJ/kg K} \end{array}$$

$$\left. \begin{array}{l} P_2 = 400 \text{ kPa} \\ x_2 = 0.4 \\ T_2 = 415 \text{ K} \end{array} \right\} \begin{array}{l} h_2 = 2282 \text{ kJ/kg} \\ s_2 = 6.718 \text{ kJ/kg K} \end{array}$$

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3$$

$$\dot{m}_1 x_1 = \dot{m}_2 x_2 + \dot{m}_3 x_3$$

$$1 = \dot{m}_2 + \dot{m}_3$$

$$1(0.6) = \dot{m}_2(0.4) + \dot{m}_3(0.999)$$

Solving two equations simultaneously will give us

$$\dot{m}_2 = 0.6661 \text{ and } \dot{m}_3 = 0.3339 \text{ kg}$$

$$\dot{m}_1 h_1 + \dot{Q}_g = \dot{m}_2 h_2 + \dot{m}_3 h_3$$

$$1(2022) + 250 = 0.6661(2282) + 0.3339 h_3$$

$$h_3 = 2252 \text{ kJ/kg}$$

$$\left. \begin{array}{l} P_3 = 400 \text{ kPa} \\ x_3 = 0.999 \\ h_3 = 2252 \text{ kJ/kg} \end{array} \right\} \begin{array}{l} T_3 = 662.7 \text{ K} \\ s_3 = 6.877 \text{ kJ/kg K} \end{array}$$

$$\dot{E}x_1 = 1[(2022 - 524.3) - 298.15(6.387 - 2.554)] = 355.2 \text{ kW}$$

$$\dot{E}x_2 = 0.6661[(2282 - 80.87) - 298.15(6.718 - 0.9197)] = 314.9 \text{ kW}$$

$$\dot{E}x_3 = 0.3339[(2252 - 1353) - 298.15(6.877 - 5.621)] = 175.1 \text{ kW}$$

$$\dot{E}x_{th,g} = \left(1 - \frac{298.15}{662.7}\right) 250 = 137.5 \text{ kW}$$

$$355.2 + 137.5 = 314.9 + 175.1 + \dot{E}x_{dest,g}$$

$$\dot{E}x_{dest,g} = 2.77 \text{ kW}$$

2.2.3 Condenser

The mass balance equation for the condenser as portrayed in Table 2.1 is defined as

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (2.12)$$

The overall energy balance equation of the condenser is given as

$$\sum (\dot{m}h)_{in} = \sum (\dot{m}h)_{out} + \sum \dot{Q}_c \quad (2.13)$$

where \dot{Q}_c represents the rate of heat rejected by the refrigerant flowing through the condenser.

The thermal exergy rate rejected by the condenser is defined as

$$\dot{E}x_{th,c} = \left(1 - \frac{T_0}{T_c}\right) \dot{Q}_c \quad (2.14)$$

where $\dot{E}x_{th,c}$ represents thermal exergy rate of condenser.

The overall exergy balance equation of the condenser is given as

$$\sum (\dot{m} \times ex)_{in} = \sum (\dot{m} \times ex)_{out} + \dot{E}x_{th,c} + \dot{E}x_{dest,c} \quad (2.15)$$

where $\dot{E}x_{dest,c}$ represents rate of exergy destruction in the condenser.

Example 2.3 In a condenser, ammonia vapor enters at 400 kPa, 400 K with a concentration of 0.999. The ammonia vapor leaves the condenser at 313.5 K with a mass flow rate of 1 kg/s. Calculate the rate of heat rejected by the condenser and total destroyed exergy rate in the condenser. Take ambient temperature and pressure to be 25 °C and 100 kPa, respectively.

- Solution

$$\left. \begin{array}{l} P_1 = 400 \text{ kPa} \\ x_1 = 0.999 \\ T_1 = 400 \text{ K} \end{array} \right\} \begin{array}{l} h_1 = 1571 \text{ kJ/kg} \\ s_1 = 5.58 \text{ kJ/kg K} \end{array}$$

$$\left. \begin{array}{l} P_2 = 400 \text{ kPa} \\ x_2 = 0.999 \\ T_2 = 313.5 \text{ K} \end{array} \right\} \begin{array}{l} h_2 = 1369 \text{ kJ/kg} \\ s_2 = 5.011 \text{ kJ/kg K} \end{array}$$

$$\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{Q}_c$$

$$1(1571) = 1(1369) + \dot{Q}_c$$

$$\dot{Q}_c = \mathbf{202.2 \text{ kW}}$$

$$\dot{E}x_1 = 1[(1571 - 1353) - 298.15(5.58 - 5.621)] = 230.1 \text{ kW}$$

$$\dot{E}x_2 = 1[(1369 - 1353) - 298.15(5.011 - 5.621)] = 197.7 \text{ kW}$$

$$\dot{E}x_{th,c} = \left(1 - \frac{298.15}{313.2}\right) 202.2 = \mathbf{9.684 \text{ kW}}$$

$$230.1 = 197.7 + 9.684 + \dot{E}x_{dest,c}$$

$$\dot{E}x_{dest,c} = \mathbf{22.66 \text{ kW}}$$

2.2.4 Evaporator

The mass balance equation for the evaporator as shown in Table 2.1 is written as

$$\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}} \quad (2.16)$$

The overall energy balance equation of the evaporator is given as

$$\sum (\dot{m}h)_{\text{in}} + \sum \dot{Q}_e = \sum (\dot{m}h)_{\text{out}} \quad (2.17)$$

where \dot{Q}_e represents rate of heat gained by the refrigerant flowing through the evaporator.

The thermal exergy rate gained by the evaporator is defined as

$$\dot{E}x_{\text{th,e}} = \left(1 - \frac{T_0}{T_e}\right) \dot{Q}_e \quad (2.18)$$

where $\dot{E}x_{\text{th,e}}$ represents thermal exergy rate of evaporator.

The overall exergy balance equation of the evaporator is given as

$$\sum (\dot{m} \times \text{ex})_{\text{in}} + \dot{E}x_{\text{th,e}} = \sum (\dot{m} \times \text{ex})_{\text{out}} + \dot{E}x_{\text{dest,e}} \quad (2.19)$$

where $\dot{E}x_{\text{dest,e}}$ represents rate of exergy destruction in the evaporator.

Example 2.4 An ammonia refrigerant enters the evaporator at 250 kPa, 259.6 K with a concentration of 0.999. The refrigerant leaves the evaporator at 259.7 K with a mass flow rate of 1 kg/s. Calculate the cooling rate and total destroyed exergy rate in the evaporator. Assume ambient temperature and pressure to be 25 °C and 100 kPa, respectively.

• Solution

$$\left. \begin{array}{l} P_1 = 250 \text{ kPa} \\ x_1 = 0.999 \\ T_1 = 259.6 \text{ K} \end{array} \right\} \begin{array}{l} h_1 = 965.2 \text{ kJ/kg} \\ s_1 = 3.724 \text{ kJ/kg K} \end{array}$$

$$\left. \begin{array}{l} P_2 = 250 \text{ kPa} \\ x_2 = 0.999 \\ T_2 = 259.7 \text{ K} \end{array} \right\} \begin{array}{l} h_2 = 1058 \text{ kJ/kg} \\ s_2 = 4.0891 \text{ kJ/kg K} \end{array}$$

$$\dot{m}_1 h_1 + \dot{Q}_e = \dot{m}_2 h_2$$

$$1(965.2) + \dot{Q}_e = 1(1058)$$

$$\dot{Q}_e = \mathbf{93.14 \text{ kW}}$$

$$\dot{E}x_1 = 1[(965.2 - 1353) - 298.15(3.724 - 5.621)] = 177.7 \text{ kW}$$

$$\dot{E}x_2 = 1[(1058 - 1353) - 298.15(4.081 - 5.621)] = 164.4 \text{ kW}$$

$$\dot{E}x_{th,e} = \left| \left(1 - \frac{298.15}{259.6} \right) 93.14 \right| = 13.83 \text{ kW}$$

$$177.7 + 13.83 = 164.4 + \dot{E}x_{dest,e}$$

$$\dot{E}x_{dest,e} = 27.16 \text{ kW}$$

2.2.5 Absorber

The mass balance equation for the absorber as displayed in Table 2.1 is written as

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (2.20)$$

The overall energy balance equation of the absorber is given as

$$\sum (\dot{m}h)_{in} = \sum (\dot{m}h)_{out} + \sum \dot{Q}_a \quad (2.21)$$

where \dot{Q}_a represents rate of heat rejected by the refrigerant and the weak solution when they mix together in the absorber.

The thermal exergy rate rejected by the absorber is calculated as

$$\dot{E}x_{th,a} = \left(1 - \frac{T_0}{T_a} \right) \dot{Q}_a \quad (2.22)$$

where $\dot{E}x_{th,a}$ represents thermal exergy rate of absorber.

The overall exergy balance equation of the absorber is given as

$$\sum (\dot{m} \times ex)_{in} = \sum (\dot{m} \times ex)_{out} + \dot{E}x_{th,a} + \dot{E}x_{dest,a} \quad (2.23)$$

where $\dot{E}x_{dest,a}$ represents rate of exergy destruction in the absorber.

Example 2.5 In an absorber of the absorption refrigeration system, ammonia refrigerant enters at 250 kPa and 259.7 K with a mass flow rate and concentration of 0.5 kg/s and 0.999, respectively. The weak solution enters the absorber at 250 kPa and 314 K with a concentration and mass flow rate of 0.25 and 0.5 kg/s, respectively. The weak solution leaves the absorber as a saturated liquid with a concentration of 0.35. Calculate the heat rate rejected by the absorber and total destroyed exergy rate in the absorber. Assume ambient temperature and pressure to be 25 °C and 100 kPa, respectively.

- Solution

$$\left. \begin{array}{l} P_1 = 250 \text{ kPa} \\ x_1 = 0.35 \\ Q_1 = 0 \end{array} \right\} \begin{array}{l} h_1 = -16.77 \text{ kJ/kg} \\ s_1 = 0.5451 \text{ kJ/kg K} \end{array}$$

$$\left. \begin{array}{l} P_2 = 250 \text{ kPa} \\ x_2 = 0.999 \\ T_2 = 259.7 \text{ K} \end{array} \right\} \begin{array}{l} h_2 = 1058 \text{ kJ/kg} \\ s_2 = 4.081 \text{ kJ/kg K} \end{array}$$

$$\left. \begin{array}{l} P_3 = 250 \text{ kPa} \\ x_3 = 0.25 \\ T_3 = 314 \text{ K} \end{array} \right\} \begin{array}{l} h_3 = 10.58 \text{ kJ/kg} \\ s_3 = 0.5496 \text{ kJ/kg K} \end{array}$$

$$\dot{m}_1 h_1 + \dot{Q}_a = \dot{m}_2 h_2 + \dot{m}_3 h_3$$

$$1(-16.77) + \dot{Q}_a = 0.5(1058) + 0.5(10.58)$$

$$\dot{Q}_a = \mathbf{551.2 \text{ kW}}$$

$$\dot{E}_{x1} = 1[(-16.77 - (-29.98)) - 298.15(0.5451 - 5.112)] = 36.64 \text{ kW}$$

$$\dot{E}_{x2} = 1[(1058 - 1353) - 298.15(4.081 - 5.621)] = 82.18 \text{ kW}$$

$$\dot{E}_{x3} = 1[(10.58 - (-57.23)) - 298.15(0.5496 - 0.3285)] = 0.9507 \text{ kW}$$

$$\dot{E}_{x_{th,a}} = \left| \left(1 - \frac{298.15}{314} \right) 551.2 \right| = \mathbf{27.83 \text{ kW}}$$

$$36.64 + 27.83 = 82.18 + 0.9507 + \dot{E}_{x_{dest,a}}$$

$$\dot{E}_{x_{dest,a}} = \mathbf{18.67 \text{ kW}}$$

2.2.6 Expansion Valve

The mass balance equation for the expansion valve as shown in Table 2.1 is written as

$$\dot{m}_{in} = \dot{m}_{out} \quad (2.24)$$

The overall energy balance equation of the expansion valve is defined as

$$(\dot{m}h)_{in} = (\dot{m}h)_{out} \quad (2.25)$$

The overall exergy balance equation of the expansion valve is defined as

$$\sum (\dot{m} \times ex)_{in} = \sum (\dot{m} \times ex)_{out} + \dot{E}x_{dest,ev} \quad (2.26)$$

where $\dot{E}x_{dest,ev}$ represents rate of exergy destruction in the expansion valve.

Example 2.6 In an expansion valve, a weak solution with a concentration of 0.113 enters at 443.2 K and 1548 kPa. The weak solution leaves at 478.4 kPa with a mass flow rate of 1 kg/s. Calculate the exit temperature of the expansion valve and total destructed exergy rate. Assume ambient temperature and pressure to be 25 °C and 100 kPa, respectively.

- Solution

$$\left. \begin{array}{l} P_1 = 1548 \text{ kPa} \\ x_1 = 0.4 \\ T_1 = 443.2 \text{ K} \end{array} \right\} \begin{array}{l} h_1 = 654.2 \text{ kJ/kg} \\ s_1 = 2.103 \text{ kJ/kg K} \end{array}$$

$$\left. \begin{array}{l} P_2 = 478.4 \text{ kPa} \\ x_2 = x_1 \\ h_2 = h_1 \end{array} \right\} \begin{array}{l} T_2 = 402.2 \text{ K} \\ s_2 = 2.132 \text{ kJ/kg K} \end{array}$$

$$\dot{E}x_1 = 1[(654.2 - 28.46) - 298.15(2.103 - 0.4027)] = 118.7 \text{ kW}$$

$$\dot{E}x_2 = 1[(654.2 - 28.46) - 298.15(2.132 - 0.4027)] = 110.1 \text{ kW}$$

$$118.7 = 110.1 + \dot{E}x_{dest,ev}$$

$$\dot{E}x_{dest,ev} = \mathbf{8.578 \text{ kW}}$$

2.2.7 Coefficient of Performance

The performance of an absorption refrigeration system is measured using the coefficient of performance. The energetic coefficient of performance of is defined as

$$COP_{en} = \frac{\dot{Q}_c}{\sum \dot{Q}_{in} + \dot{W}_p} \quad (2.27)$$

The exergetic COP is defined as

$$COP_{ex} = \frac{\dot{E}x_{th,e}}{\sum \dot{E}x_{th,in} + \dot{W}_p} \quad (2.28)$$

Example 2.7 An absorption refrigeration system is capable of producing 220 kW of cooling while consuming 150 kW of heat in the generator. The solution pump consumes 1 kW of power to pump the solution from 250 to 400 kPa. Calculate the energy and exergy coefficients of performance for this absorption refrigeration system. Assume evaporator, generator and ambient temperatures to be 260, 520, and 298 K, respectively.

- Solution

$$\text{COP}_{\text{en}} = \frac{220}{150 + 1} = 1.46$$

$$\text{COP}_{\text{ex}} = \frac{\left|1 - \frac{298}{260}\right| 220}{\left(1 - \frac{298}{520}\right) 150 + 1} = 0.49$$

2.3 Exergoeconomic Analysis

Exergoeconomic analysis opens a new front in cost analysis of the energy systems by bridging the gap between the exergy and the cost of the system. Exergoeconomic analysis takes into consideration the cost of the equipment, operational costs, the cost of working fluid, and costs related to the exergy destruction of the system.

The exergoeconomic equation of the absorption refrigeration system is written as

$$\dot{Z}_{\text{eq}} + \dot{C}_{\text{OPM}} = \dot{C}_{\text{Cool}} \quad (2.29)$$

where \dot{Z}_{eq} , \dot{C}_{OPM} , and \dot{C}_{Cool} represent cost associated with equipments, operation and maintenance, and cooling, respectively.

The cost linked with the equipment is calculated as

$$\dot{Z}_{\text{eq}} = \dot{C}_a + \dot{C}_g + \dot{C}_c + \dot{C}_e + \dot{C}_p + \dot{C}_{\text{ev}} \quad (2.30)$$

where \dot{C}_a , \dot{C}_g , \dot{C}_c , \dot{C}_e , \dot{C}_p and \dot{C}_{ev} represent the cost of the absorber, generator, condenser, evaporator, pump and expansion valve, respectively.

The cost associated with the operation and maintenance is defined as

$$\dot{C}_{\text{OPM}} = c_{\text{OPM}} \times \dot{E}x_{\text{OPM}} \quad (2.31)$$

where c_{OPM} and $\dot{E}x_{\text{OPM}}$ represent operation and maintenance cost and exergy carried by the heat and power, respectively.

The cost related to the cooling produced is defined as

$$\dot{C}_{\text{Cool}} = c_{\text{Cool}} \times \dot{E}x_{\text{Cool}} \quad (2.32)$$

where c_{Cool} and $\dot{E}x_{\text{Cool}}$ represent cost of cooling produced and the exergy related to the cooling produced, respectively.

Thus the above equation can be written as

$$(c \times \dot{E}x)_{\text{OPM}} + \dot{Z}_{\text{eq}} = (c \times \dot{E}x)_{\text{Cool}} \quad (2.33)$$

The cost of cooling can then be calculated by rearranging the above mentioned equation and rewriting it as

$$c_{\text{Cool}} = \frac{(c \times \dot{E}x)_{\text{OPM}} + \dot{Z}_{\text{eq}}}{\dot{E}x_{\text{cool}}} \quad (2.34)$$

The problems, which have more unknowns than equations can be simplified by replacing exergy terms with mass flow rate terms. Figure 2.1 displays a flowchart for exergoeconomic analysis.

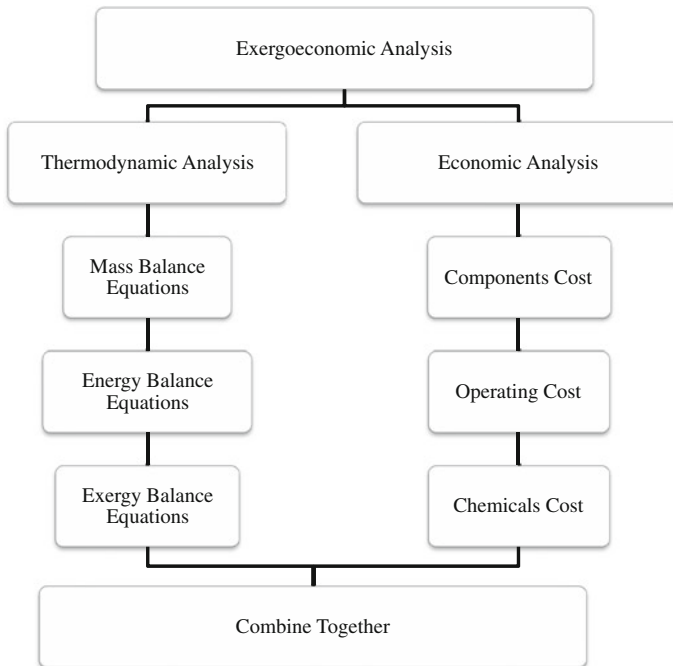


Fig. 2.1 Flowchart of exergoeconomic analysis

Example 2.8 An absorption refrigeration system is capable of producing 220 kW of cooling. The solution pump consumes 1 kW of power to pump the solution from 250 to 400 kPa. Calculate the cooling cost of this absorption refrigeration system. Assume evaporator and ambient temperatures to be 260 and 298 K, respectively. Note: the equipment cost of absorption refrigeration system can be estimated using $\dot{Z}_{eq}(\$) = 1144.3(\dot{Q}_{cool})^{0.67}$ and consider operation and maintenance cost to be 3 % of the total investment cost.

- Solution

$$\begin{aligned}\dot{Z}_{eq} &= 1144.3(220)^{0.67} = \$42458 \\ \dot{C}_{OPM} &= 0.03 * 42458 = \$1274 \\ \dot{E}x_{Cool} &= \left(1 - \frac{298}{260}\right) 220 = 32.15 \text{ kW} \\ c_{Cool} &= \frac{1274 + 42458}{32.15} = 1360 \$/\text{kW}\end{aligned}$$

2.4 Exergoenvironmental Analysis

In the present era, it is necessary to conduct an environmental analysis of a system under investigation to ensure that it has a minimal or no effect on the environment. This section of the chapter combines exergy and environmental analyses to present a new type of study namely exergoenvironmental analysis. Exergoenvironmental analysis is based on exergy analysis and it takes into account exergy destruction and efficiency to provide a measure of its impact on the environment. Exergoenvironmental analysis consists of six parameters which are an impact factor, impact coefficient, impact index impact improvement, exergetic stability factor, and exergetic sustainability index.

2.4.1 Exergoenvironmental Impact Factor

The exergoenvironmental impact factor determines the positive effect of the investigated system on the environment. The purpose of studying this parameter is that it helps to reduce the environmental impact of the system by decreasing the irreversibility in the system.

The reference value of this factor is “zero” which shows that the system has no irreversibility. The exergoenvironmental impact factor is defined as

$$f_{ei} = \frac{\dot{E}x_{dest,tot}}{\sum \dot{E}x_{in}} \quad (2.35)$$

where f_{ei} , $\dot{E}x_{dest,tot}$ and $\dot{E}x_{in}$ represent exergoenvironmental impact factor, total exergy destruction rate in the system and total exergy rate supplied to the system, respectively.

2.4.2 Exergoenvironmental Impact Coefficient

The exergoenvironmental impact coefficient is related to the exergetic efficiency of the system. In the ideal case, its value should be one, indicating that the system is working under an ideal condition with no exergy destruction. This coefficient is defined as

$$C_{ei} = \frac{1}{\eta_{ex}/100} \quad (2.36)$$

where C_{ei} and η_{ex} represent exergoenvironmental impact coefficient and exergetic efficiency, respectively.

2.4.3 Exergoenvironmental Impact Index

The exergoenvironmental impact index is an important parameter to study as it indicates whether or not the system under investigation damages the environment due to its unusable waste exergy output and exergy destruction. The desired value of the exergoenvironmental impact index should be as small as possible. The exergoenvironmental impact index is calculated by multiplying exergoenvironmental impact factor with exergoenvironmental impact coefficient and is defined as

$$\theta_{ei} = f_{ei} \times C_{ei} \quad (2.37)$$

where θ_{ei} represents exergoenvironmental impact index.

2.4.4 Exergoenvironmental Impact Improvement

The exergoenvironmental impact improvement parameter helps in finding the environmental appropriateness of the investigated system. In order to improve the environmental appropriateness of the system, its exergoenvironmental impact index should be minimized. A high value of exergoenvironmental

impact improvement means system is more useful for the environment and it is defined as

$$\theta_{\text{eii}} = \frac{1}{\theta_{\text{ei}}} \quad (2.38)$$

where θ_{eii} represents exergoenvironmental impact improvement.

2.4.5 Exergetic Stability Factor

The exergetic stability factor is a function of the desired output exergy, total exergy destruction, and exergy carried by unused fuel. The desired value of this factor should be as close to “one” as possible. This factor is defined as

$$f_{\text{es}} = \frac{\dot{E}x_{\text{tot,out}}}{\dot{E}x_{\text{tot,out}} + \dot{E}x_{\text{dest,tot}} + \dot{E}x_{\text{uu}}} \quad (2.39)$$

where f_{es} and $\dot{E}x_{\text{uu}}$ represent exergetic stability factor and exergy rate carried by unused fuel.

2.4.6 Exergetic Sustainability Index

The exergetic sustainability index is the multiplication of exergetic stability factor and exergoenvironmental impact improvement of the system. This desired value of the exergetic sustainability index should be as high as possible. This index is defined as

$$\theta_{\text{est}} = f_{\text{es}} \times \theta_{\text{eii}} \quad (2.40)$$

where θ_{est} represents exergetic sustainability index.

Example 2.9 The rate of exergy supplied to the absorption refrigeration system through the generator, evaporator and pump are 48.39, 16.42, and 1.971 kW, respectively. The rate of exergy released by the condenser and absorber are 3.595 and 16.27 kW, respectively. Calculate all the exergoenvironmental parameters defined in the above section. The exergetic COP of absorption refrigeration system is 0.326.

- Solution

$$\dot{E}x_{in} = 48.39 + 16.42 + 1.971 = 66.78 \text{ kW}$$

$$\dot{E}x_{out} = 16.27 + 3.595 = 19.86 \text{ kW}$$

$$\dot{E}x_{dest,tot} = 66.78 - 19.86 = 46.92 \text{ kW}$$

$$f_{ei} = \frac{46.92}{66.78} = 0.70$$

$$C_{ei} = \frac{1}{0.326} = 3.07$$

$$\theta_{ei} = 0.70 \times 3.07 = 2.16$$

$$\theta_{eii} = \frac{1}{2.16} = 0.46$$

$$f_{es} = \frac{19.86}{19.86 + 46.92} = 0.29$$

$$\theta_{est} = 0.29 \times 0.46 = 0.13$$

2.5 Optimization

In designing any system, it is important to perform an optimization study in order to attain the best possible operating parameters. The optimization carried out using multi-objective optimization theory help to find the best possible set of design values needed to attain the preset objectives. There are many multi-objective optimization techniques available in the literature, but the most robust one is the genetic algorithm technique as shown in Fig. 2.2. The genetic algorithm technique can provide the best possible result for any desired output based on several inputs. The genetic method is a vigorous optimization algorithm that is designed to reliably locate a global optimum even in the presence of local minima/maxima. The genetic method intends to mimic the processes occurring in biological evolution. Initially, sample points are chosen at random from the range specified by the bounds of the independent variables. The sample points are then surveyed to determine the values of the objective function as quantified by the value of the variable that is to be minimized or maximized. A new generation of sample points is then generated in a stochastic manner by combining selected points of the current sample points. The characteristics of a point that are passed on to the next generation are represented by encoded values of its independent variables. The probability that a point out of the current sample point will be selected for breeding the next generation is an increasing function of its value. This process continues untill the best points are recorded.

There is much software available that can perform optimization studies but the most prominent are Matlab developed by Moler (2014) and Engineering Equation

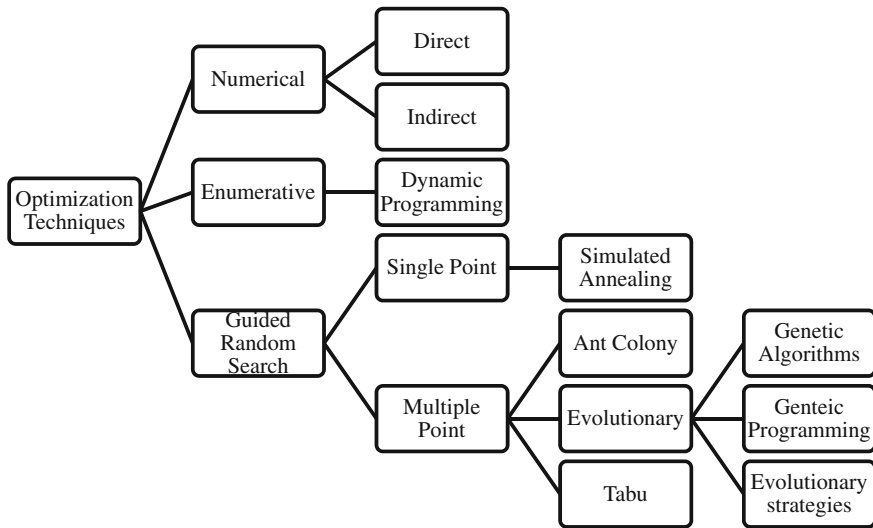


Fig. 2.2 Flowchart of optimization techniques

Solver developed by Klein (2014). While performing multi-objective optimization, first define the objective functions. The objective functions are those that should either maximized or minimized based on the requirement. An example for objective functions in absorption refrigeration systems is exergy COP (to be maximized) and cost of cooling (to be minimized). The second step in performing optimization study is to define the independent variables also known as constraints. Independent variables are variables that the designer wishes to use to optimize the desired objective functions. Examples of independent variables in optimization study of an absorption refrigeration system are the concentration of weak and strong solutions and evaporator temperature. While selecting the independent variables, the designer should ensure that they are within the acceptable range or else the optimized results obtained will be hypothetical.

Example 2.10 Reconsider Example 2.2 in order to optimize the performance of the generator by minimizing the exergy destruction rate. The constraints to this problem are the concentration of the strong solution, the concentration of the weak solution and inlet temperature to the generator which varies between 0.45–0.6, 0.35–0.45, and 350–400 K, respectively. Use Nelder–Mead Simplex method optimization routine in an engineering equation solver to carry out this optimization.

Table 2.2 Constraints and best values for the optimization study

Name	Constraints	Best value
Strong solution concentration	0.45–0.6	0.5518
Weak solution concentration	0.35–0.45	0.4042
Inlet temperature	350–400 K	378 K

- Solution

The objective function for this problem is written as

$$\dot{E}x_1 + \dot{E}x_{th,g} = \dot{E}x_2 + \dot{E}x_3 + \dot{E}x_{dest,g}$$

The optimized exergy destruction rate obtained for the present analysis is 0.001251 kW. The parameters at which this exergy destruction rate is achieved are presented in Table 2.2.

2.6 Closing Remarks

The use of absorption refrigeration systems, instead of the conventional vapor-compression refrigeration systems, to provide cooling offers a potential solution when process/waste heat or renewable heat is available. This helps to reduce environmental impact and increasing sustainability. Studying such systems energetically and exergetically is essential for their design, analysis, assessment, evaluation, and improvement. In this regard, this chapter presents comprehensive energy and exergy analyses of ARSs and their components with numerous illustrative examples. It also covers the use of exergoeconomic and exergoenvironmental analyses, instead of conventional economic and environmental studies, in terms of effect on cost and the environment because exergy provides more realistic results as compared to energy. Furthermore, it presents an optimization study before commissioning any system. The optimization study based on genetic algorithm provides best possible results, as this optimization technique can easily locate the global optimum even in the presence of local maximum and minimum. An example for each section is also provided to enhance the understanding of the material.

References

- Klein, S. A. (2014). Engineering equation solver (EES): Academic commercial. F-Chart Software. www.fChart.com
- Moler, C. (2014). Matlab: Acadmic. Mathworks. www.mathworks.com

Integrated Absorption Refrigeration Systems

Comparative Energy and Exergy Analyses

Dincer, I.; Ratlamwala, T.A.H.

2016, XVII, 270 p. 108 illus., 34 illus. in color.,

Hardcover

ISBN: 978-3-319-33656-5