1 Introduction

1.1 What Is Desalination?

Desalination is a process of separating and removing unwanted dissolved salts and minerals from feedwater sources such as seawater, brackish water, or wastewater.

The aim of desalination process is to produce a stream of fresh water (potable) with high quality (purity) according to the standards of World Health Organization (WHO), which state that the accepted maximum limit of total dissolved salts (TDS) in fresh water is 500 ppm (500 mg/l); if we take seawater (called feed or saline) as an example with a salinity of 35 000 ppm, feed can be desalted through two main industrial processes: (i) thermal desalination technologies where feed phase changes through evaporation and condensation processes and (ii) membrane desalination technologies where separation of salts achieved through using semipermeable membrane without feed phase change. In either process, potable water is produced, and salty water (called brine or concentrate) is rejected from desalination system; the rejected brine salinity varies in concentration based on technology, and it can reach up to 90 000 ppm.

Today, desalination industry plays a vital role in society development and economic growth, and worldwide freshwater consumption rate is approximately doubled every 20 years, where the availability of natural water sources is depleted. According to UN report and in the light of global population growth, statistics showed that one-third of world's population lives under a state of insufficient potable water resources and in communities that suffer from scarcity and water stress. As prehuman body, water is essentially needed for building tissues, blood circulation, and maintaining stable blood temperature, and based on human weight it is recommended that a human drinks 8–14 glasses of water every day. Today desalination industries tend to provide safe drinking water to achieve and maintain sustainable human life and minimize negative environmental impacts. As per industry, there are eight major water-consuming industrial sectors: power generation, food, pharmaceutical, mining, oil, petrochemical, electronics, and paper.

There are several types of "well-proven" industrial desalination technologies that have been used in the last seven decades. Note that the major parameters that affect desalination technology performance are feed type and its thermal-physical characteristics, in addition to the required desalted water quality (purity).

Introduction to Desalination: Systems, Processes and Environmental Impacts,
First Edition. Fuad Nesf Alasfour.

Companion website: www.wiley.com/go/Alasfour/Introductiontodesalination_1e

Figure 1.1 shows the classification of desalination systems based on separation processes. Note that such processes can be operated by conventional energy type such as fossil fuel (thermal and electrical) or by renewable energy types such as solar, wind, and geothermal (Chapter 9).

Statistics by IDA for year 2015 shows that there are 18 426 desalination plants worldwide, producing 86.8×10^6 m^3/d and serving more than 300×10^6 in 150 countries per day, and such production can provide potable water for municipal, industrial, and agriculture sectors. Today Gulf countries produce around 57% of world desalination capacity [2].

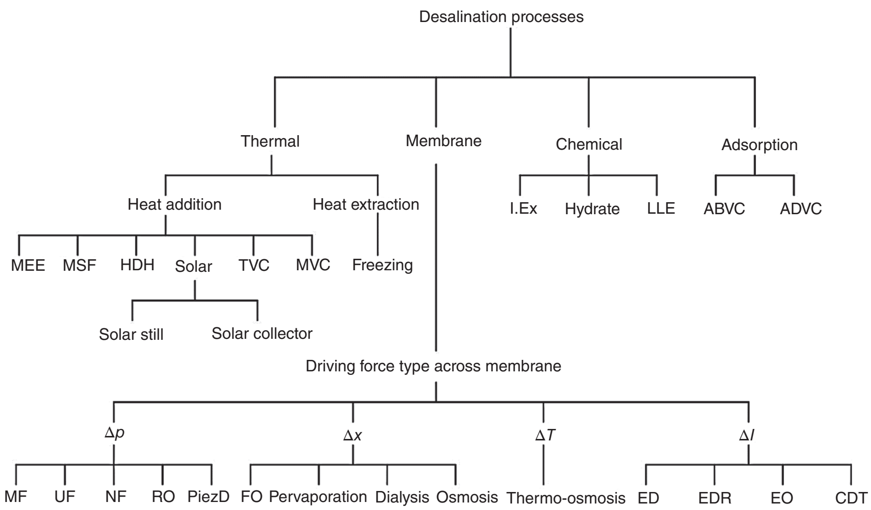


Figure 1.1 Desalination processes based on separation type.

1.2 Aims of Desalination Processes

Several desalination technologies have been invented, developed, and employed during the last seven decades, and the potentials behind such industrial developments are:

1. Satisfy the global increase in freshwater demand for drinking, and in industrial and agriculture sectors, in addition to hygiene requirements.
2. Compensate the capacity of limited natural freshwater resources specially in arid and remote areas.
3. Reduce the values of elevated intensive energy cost of freshwater production.
4. Reduce the potential levels of emissions and minimize negative environmental impacts on human and climate in terms of greenhouse effect and acid rain.
5. Provide efficient large size desalination system with the ability of integration with other conventional or renewable energy types.
6. Achieve water quality based on WHO rules and regulations or other specific industrial standards.
7. Manage wastewater processes that are associated with municipal and industrial sectors.

1.3 Desalination Processes

There are four main industrial desalination processes that exist today to separate freshwater from feedwater, and separation processes can be achieved via:

a. Thermal processes
b. Membrane processes
c. Chemical processes
d. Adsorption processes

Figure 1.2 shows the basic principles of general industrial desalination processes.

Feed can be in the form of seawater with high salinity that can reach a value of 45 000 ppm, or it can be in the form of brackish water or even wastewater that has been taken from industry or municipal.

The example of disposal fluid from desalination system can be in the following forms:

1. Brine fluid (salty water): Which have very high value of salinity that can reach 90 000 ppm in case of thermal desalination system.
2. Concentrate: Which is a fluid with very high value of salinity in case of membrane desalination system.
3. Waste: Which is a product in the form of industrial concentrated fluids.
4. Thick liquor: Product that is produced under specific purposes and applications.

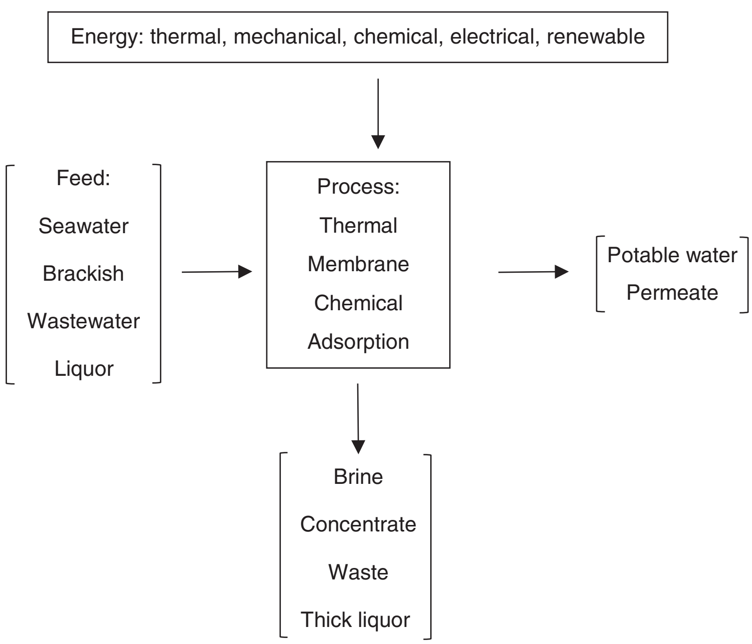


Figure 1.2 Basic principles of desalination processes.

The products from desalination system can be in the following forms:

(a) Drinkable water with salinity less than 500 ppm.
(b) Fresh water.
(c) Fluid with specific required salinity or concentration.

Choosing the proper desalination system (technology) is always a challenge for engineers, because each desalination technology can provide different levels of performance under different circumstances (design and operational conditions). To ensure the performance level for any industrial desalination system, it must be examined in terms of 4E's – energy analysis, exergy analysis, economic analysis, and environmental analysis, in addition to sustainability tendency. Student should remember that selecting desalination system must fulfill the following criteria: low energy consumption, ability to use renewable energy, low cost of water production with high value of quality, and minimum negative environmental impacts, and it must be durable and reliable in operation with minimum required maintenance. Today reverse osmosis (RO) desalination systems present about 65% of worldwide installed capacity, while multi-stage flashing (MSF) and multi-effect evaporator (MEE) systems present about 21% and 7%, respectively.

As mentioned before, selecting desalination technology is a great challenge for engineers, and such selection process depends on the evaluation of the following four parameters:

1. Feed concentration: The first parameter that must be considered during desalination technology selection is feed salinity (concentration); the selected system must be able to handle the required salinity and to produce the required water or fluid quality. Figure 1.3 shows the capability of different industrial desalination systems as per feed salinity and produced water purity.
2. Energy consumption: The second parameter that needs to be considered during selection is the value of specific energy consumption (SEC) that is required to desalt feedwater when electrical and/or thermal energies are used. Figure 1.4 predicts the amount of SEC (kWh/m^3) per desalination system.

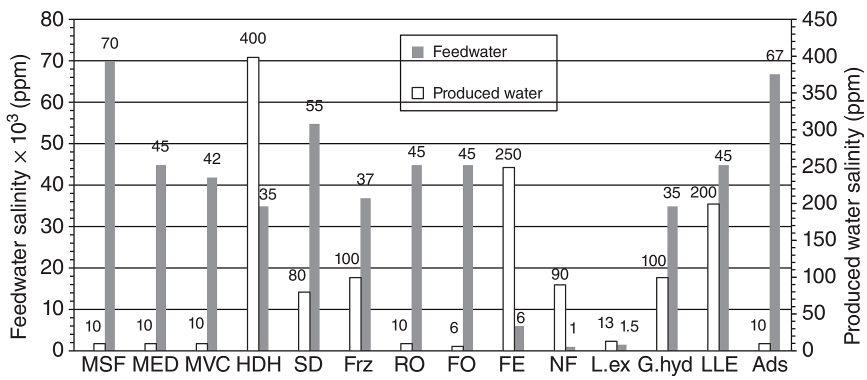


Figure 1.3 Different desalination systems' capabilities based on feed salinity and produced water purity. Source: Youssef et al. 2014 [3]. Reproduced with permission of Elsevier.

3. Cost: The third parameter that must be considered during desalination selection is the cost of freshwater production (Figure 1.5).
4. Emission: The fourth parameter is the level of emitted emissions of CO_2 from desalination that affect the formation of greenhouse phenomenon (Figure 1.6).

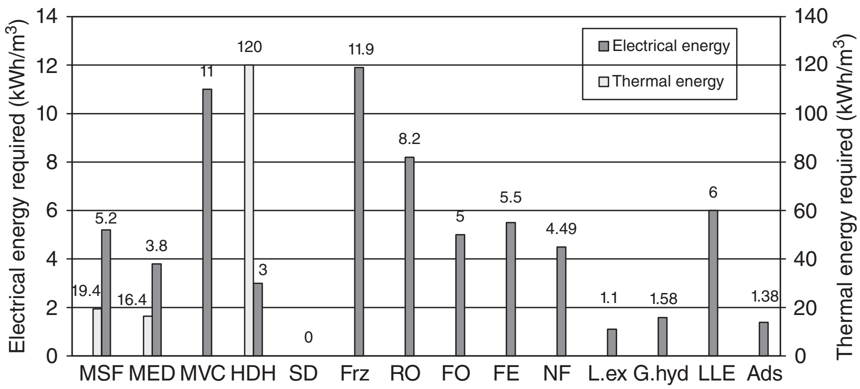


Figure 1.4 Specific energy consumption using different desalination technologies. Source: Youssef et al. 2014 [3]. Reproduced with permission of Elsevier.

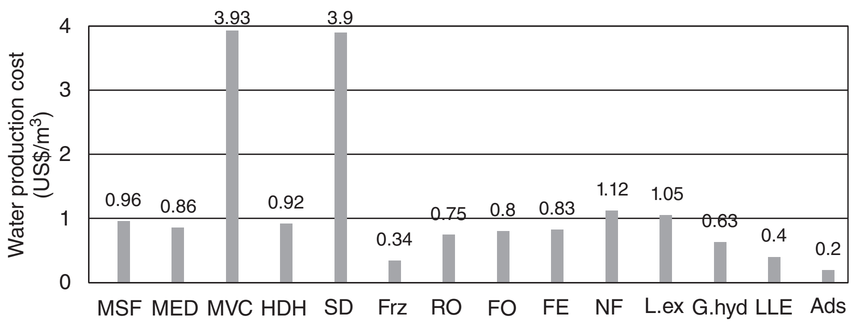


Figure 1.5 Cost of potable water production using different desalination technologies. Source: Youssef et al. 2014 [3]. Reproduced with permission of Elsevier.

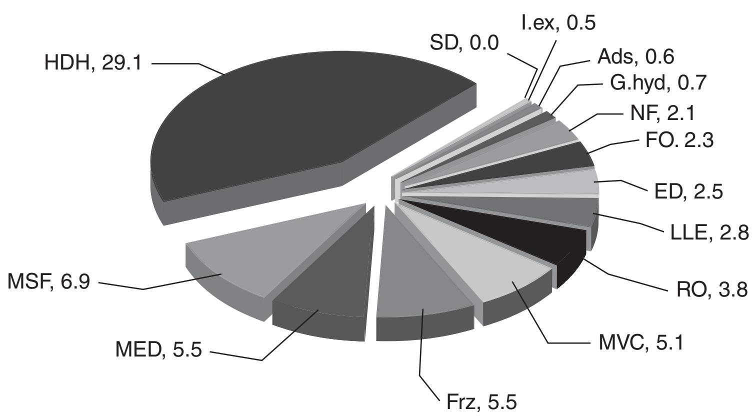


Figure 1.6 CO_2 released from different desalination technologies measured in kg/m^3. Source: Youssef et al. 2014 [3]. Reproduced with permission of Elsevier.

1.4 Desalination Technologies

We will present and explain in this section the two most applied commercial types of desalination technologies: thermal and membrane systems.

1.4.1 Thermal Desalination System

There are several mature and reliable thermal desalination systems that are used today, and the two most conventional thermal (distillation) ones are:

1. MEE, where feed is heated, thus it evaporates via boiling process, then vapor is condensed after been screened through screen (demister) as potable water.
2. MSF, where feed is evaporated via flashing process due to sudden drop in pressure, then vapor is condensed after been screened through screen (demister) as potable water.

In addition to MEE and MSF, there are several types of thermal desalination systems that are used under specific conditions such as thermal vapor compression (TVC), mechanical vapor compression (MVC), and mechanical vapor recompression (MVR).

In general, thermal desalination systems are considered as an "old conventional" types, and they are characterized with simplicity in design and operation and even in maintenance. They have the ability to operate with feed salinity ranges from 20 000 to 100 000 ppm, the SEC varies from 4 to 6 kWh/m^3 in addition to steam cost, and at the same time thermal desalination can produce high capacity of desalted water with high water purity (low TDS). As per processes, feedwater in thermal system desalination was subjected to their main progressive processes:

1. Heating: Where feed is heated via steam (thermal load) in first stage or by other type of energy source using its latent heat (h_{fg}).
2. Evaporation: Feed is evaporated through feed phase change from liquid to vapor within the stages via boiling in case of MEE or via flashing in case of MSF.
3. Condensation: Freshwater vapor is condensed as potable water via heat exchanger (condenser).

The advantages and disadvantages of thermal system are presented.

Advantages of thermal distillation processes:

1. Suitable to treat high salinity feedwater such as seawaters.
2. Reliable and rigid system.
3. Require minimal conventional pretreatment for feedwater.
4. Capacity to use low waste thermal heat (low grade) from power plants to save energy.
5. Economical system if a heat source is available.
6. Easy in maintenance.

Disadvantages of thermal distillation:

1. The amount of water production depends on feed thermo-physical properties (T_f, x_f, …).

2. Tube scaling ($CaSO_4$).
3. High value of SEC specially at elevated values of thermal performance.

Example 1.1 ***Boiling Phenomenon***
Steam flows in a nonadiabatic horizontal pipe (control volume) with an inlet conditions of $\dot{m}_1$, T_1, P_1, and exits at $\dot{m}_2$, T_2, where $T_1 > T_2$, if pipe outer surface is surrounded by water droplets:

a. Explain heat transfer phenomenon.
b. Identify the process type.

Solution

a. Since $T_1 > T_2$, it is clear that steam is subjected to heat loss.

$$\text{Mass balance}: \dot{m}_1 = \dot{m}_2; \text{steady flow}$$

$$\text{Energy balance}: \dot{Q} - \dot{W} = \dot{m}\Delta h$$

Since $\dot{W} = 0$, then $\dot{Q} = \dot{m}(h_2 - h_1) = \dot{m}c_p\, \Delta T$. Since $T_1 > T_2$, then $h_2 - h_1$ is negative, which indicate that heat transfer sign is negative, implying that heat is lost from the system (steam) to the surrounding.
b. Isobaric process.

Extra activity:

Student can perform the following:

a. Describe boiling phenomenon in MEE system.
b. Why kinetic and potential energy terms have been neglected from energy balance (first law of thermodynamics)? Explain.
c. Explain the process associated with change of water droplet phase that surrounds the exterior pipe wall. What is the type of evaporation process?
d. Based on real numbers, compare the value of h_1 against h_2. Explain the physical meaning of such difference.
e. Sketch $T–v$, $P–v$, and $T–s$ diagrams showing boiling process.

Example 1.2 ***Flashing Phenomenon***
Adiabatic rigid tank (control mass) is divided into two nonequal volumes: *A* and *B* by a flexible membrane. Part *A* contains H_2O liquid at 7 kg, 220 kPa, $\forall_A$, and at 25 °C, and part *B* is at sub-atmospheric pressure under vacuum state condition with no mass and has a volume of $2\,\forall_A$.

If membrane is ruptured by making a hole such that two systems reach a final equilibrium state at 25 °C:

Find:

a. What is the type of water evaporation process?
b. Final specific volume.

c. Final pressure.
d. Equations that represent exergy destruction (irreversibility).

Solution

a. Flashing process, where sudden drop in pressure causes water to evaporate via flashing, it is always associated with lightning and heat release.
b. $\cancel{V}_1 = m_1 v_1$

$$= (7 \text{ kg})\,(0.001 \text{ m}^3/\text{kg}) = 0.007 \text{ m}^3$$

Hence
$v_2 = \frac{\cancel{V}_2}{m} = \frac{3 \times 0.007 \ \ \text{m}^3}{7 \ \ \text{kg}} = 0.003 \ \ \text{m}^3/\text{kg}$
c. $P_2 = 3.17$ kPa
d. Entropy generation

$$S_{\text{gen}} = \Delta S_{\text{sys}} + \overset{\text{0: adiabatic}}{\cancel{\Delta S_{\text{surr}}}}$$
$$= m\,(s_2 - s_1)$$

Exergy destruction

$$\text{Ex}_{\text{d}} = I = T_0 S_{\text{gen}}$$

Extra activity:

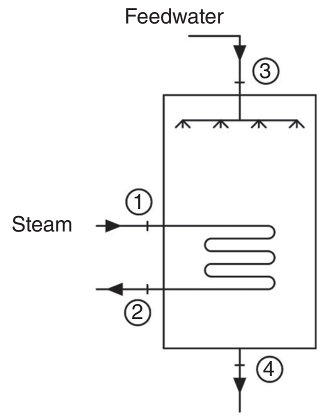
Student can perform the following:

a. Describe the flashing process in MSF system.
b. Sketch T–v, P–v, and T–s diagrams showing flashing process.
c. Perform a parametric study to investigate the effect of initial water temperature on final phase. Sketch and explain.
d. Perform a parametric study to investigate the effect of V_{B} on final phase. Sketch and explain.
e. Calculate the amount of heat release from flashing process, and explain physically what is the source and cause of such heat.
f. Perform a parametric study to investigate the effect of $\frac{\cancel{V}_2}{\cancel{V}_1}$ ratio on irreversibility.

Example 1.3 ***Feedwater Heat Exchanger***
An adiabatic heat exchanger is used to heat feedwater (H_2O) from 40 to 120 °C.

Steam: inlet state : 1MPa, 200°C (state 1)
Outlet state : 1MPa, saturated liquid (state 2)

Feedwater: inletstate : 2.5MPa, 40°C (state 3)
Outlet state : 2.5MPa, 120°C (state 4)



Find:

a. $\dfrac{\dot{m}_{\text{steam}}}{\dot{m}_{\text{feed}}}$ ratio.
b. Heat transfer rate from thermal load (steam) to feedwater.
c. Exergy destruction (irreversibility) per kg of feedwater.

Solution

a. Mass balance: $\dot{m}_1 = \dot{m}_2$

$$\dot{m}_3 = \dot{m}_4$$

Energy balance (first law of thermodynamics):

$$\cancelto{0}{\dot{Q}} - \cancelto{0}{\dot{W}} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i + \cancelto{0}{\Delta k} \cdot e + \cancelto{0}{\Delta p} \cdot e$$

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4$$

or $\dot{m}_{\text{steam}}(h_2 - h_1) = \dot{m}_{\text{feed}}(h_3 - h_4)$.

$$h_1 = 2828\ \frac{\text{kJ}}{\text{kg}},\ h_2 = 762.5\ \frac{\text{kJ}}{\text{kg}},\ h_3 = 176.5\ \frac{\text{kJ}}{\text{kg}},\ h_4 = 503\ \frac{\text{kJ}}{\text{kg}}$$

$$\frac{\dot{m}_{\text{steam}}}{\dot{m}_{\text{feed}}} = \frac{h_3 - h_4}{h_2 - h_1} = \frac{176.5 - 503}{762.5 - 2828} = 0.158\ \frac{\text{kg}_{\text{steam}}}{\text{kg}_{\text{feedwater}}}$$

b. $\dot{Q} = \dot{m} c_p (T_{\text{out}} - T_{\text{in}})$

$$\dot{Q} = \dot{m} c_p (T_4 - T_3)$$

$$\dot{Q} = (4.18)\frac{\text{kJ}}{\text{kg°C}}(120 - 40)\text{°C, use } \dot{m} = 1\ \text{kg/s}$$

$$= 334.4\ \text{kW}$$

c. $\dot{\mathrm{E}}\mathrm{x}_{\mathrm{des}} = \dot{I} = T_0\dot{S}_{\mathrm{gen}}$

$$\dot{S}_{\mathrm{gen}} = \Delta\dot{S}_{\mathrm{system}} + \underbrace{\cancel{\Delta\dot{S}_{\mathrm{surroundings}}}}_{\text{0: adiabatic}}$$

$$= (\dot{m}_1 s_1 - \dot{m}_2 s_2) + (\dot{m}_3 s_3 - \dot{m}_4 s_4)$$

$$s_1 = 6.69\ \frac{\mathrm{kJ}}{\mathrm{kg\ K}}, s_2 = 2.13\ \frac{\mathrm{kJ}}{\mathrm{kg\ K}}, s_3 = 0.5724\ \frac{\mathrm{kJ}}{\mathrm{kg\ K}}, s_4 = 1.5279\ \frac{\mathrm{kJ}}{\mathrm{kg\ K}}$$

$$\frac{\dot{S}_{\mathrm{gen}}}{\dot{m}_{\mathrm{feed}}} = \frac{\dot{m}_{\mathrm{steam}}}{\dot{m}_{\mathrm{feed}}} \cdot (s_2 - s_1) + (s_4 - s_3)$$

$$= (0.158)(2.13 - 6.69) + (1.5279 - 0.5724) = 0.235\ \mathrm{kJ/(K\ kg_{feed\ flow})}$$

Hence $\mathrm{Ex}_{\mathrm{des}} = \dot{I} = T_0\dot{S}_{\mathrm{gen}} = (298\ \mathrm{K})\left(0.235\frac{\mathrm{kg}}{\mathrm{K\ kg_{feed}}}\right) = 70\ \mathrm{kJ/kg_{feedwater\ flow}}$.

Extra activity:

Student can perform the following:

a. Perform parametric study to investigate the effect of varying T_{feed} during summer to winter seasons on heat transfer performance. Plot and explain. Take $T_{\mathrm{summer}} = 35\,°\mathrm{C}$.
b. Calculate exergy flow rate at all four states. Explain.
c. Resolve example using feedwater as seawater with salinity of 40 000 ppm. Refer to Appendix A for thermo-physical properties.

1.4.2 Membrane Desalination System

There are several types of membrane technologies that are used today in the market, and the most predominant one is RO; the separation process using RO depends on the process of pressurizing feed fluid against semipermeable membrane, and such pressure causes only water molecules to cross (pass, migrate) through membrane, where salts and unwanted constituents such as minerals are rejected in a form of brine or concentrate. In RO process there is no heat addition during desalination process, hence no feed phase change occurred during separation process; besides RO technology, there are other membrane desalination systems used at small and limited scale such as nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF).

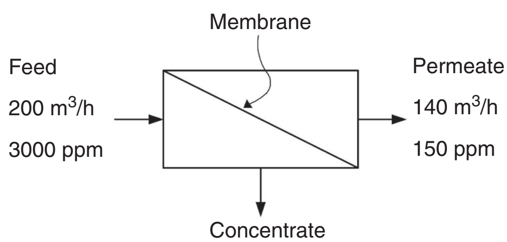
The RO desalination system is characterized with low amount of energy consumption compared with conventional thermal types and with high water recovery, but membrane lifetime is short due to fouling and scaling; unlike thermal system RO can only treat feed salinity from 50 to 46 000 ppm, and the value of SEC varies from 1 to 6 kWh/m^3. As per electrical demand an example of 50 mG/d capacity RO plant requires 20–35 MW in case of using feed seawater (sea water reverse osmosis [SWRO] system) and 8–20 MW in case of using brackish feedwater (brackish water reverse osmosis [BWRO] system).

The following are advantages and disadvantages of RO system:

Advantages of RO:
1. Low energy consumption compared with thermal desalination system.
2. Small in size and compact.
3. Low value in investment.

Disadvantages of RO:
1. Membrane has certain thermal stability limit.
2. Life of a membrane is limited and short.
3. Low feedwater can treat only salinity compared with thermal system.
4. Costly in pretreatment.
5. Use electrical power to drive system.
6. Costly in maintenance.

Example 1.4 ***Reverse Osmosis***
A simple one-stage RO desalination system operates under steady flow; brackish water with feed capacity of 200 m^3/h and 3000 ppm salinity needs to be desalted to 150 ppm as a potable water.



Find:

a. Concentrate flowrate
b. Concentrate salinity
c. Recovery ratio

Solution

a. Mass balance: $\dot{m}_f = \dot{m}_c + \dot{m}_p$
Assume constant density (incompressible)
Then $\dot{V}_c = 60\ m^3/h$

b. Salinity balance: $\dot{m}_f \cdot x_f = \dot{m}_c \cdot x_c + \dot{m}_p \cdot x_p$

$$x_c = 9650\ \text{ppm}$$

c. Recovery ratio: $\text{RR} = \frac{\dot{m}_p}{\dot{m}_f}$

$$= 70\%$$

Extra activity:

Student can perform the following:

a. Derive RR relation as a function of three stream salinities.

$$\text{RR} = \frac{x_c - x_f}{x_c - x_p}$$

b. Select one practical operational parameter and examine its effect on RR. Plot and explain.
c. Calculate salt rejection (SR), where SR is defined as
   $\text{SR} = 100 - \text{SP}$
   SP is salt passage across membrane $\text{SP} = x_p/x_f$, then perform a proper parametric study. Plot and explain.
d. Perform parametric study to investigate the effect of feed salinity on concentrate salinity. Plot and explain.

1.5 Which Desalination System Is the Best?

Recall that feed type, characteristics, and quality play a major role in selecting desalination system. In addition potable water purity, type of energy consumption, water production cost, and emissions are also factors that play a role during desalination technology selecting; engineers must evaluate all the mentioned parameters to optimize his or her selection process.

For example, if we take a case of 45 000 ppm feed seawater, thermal system can be used, while in other cases such as brackish water with 8000 ppm salinity, membrane system is recommended. In certain applications using two different combined desalination system, thermal and membrane, which is called hybrid (Chapter 10), is another option of selection.

Table 1.1 shows the range operational energy requirement for main desalination systems.

Table 1.1 Energy requirement for main desalination systems.

	MEE	MSF	MEE-TVC	MVC	RO	ED
Typical unit size (m^3/d)	5000–15 000	50 000–70 000	10 000–35 000	100–2500	24 000	–145 000
Steam pressure (atm)	0.2–0.4	2.5–3.5	0.2–0.4	—	—	—
Electrical energy consumption (kWh/m^3)	1.5–2.5	4–6	1.5–2.5	7–12	3–7	2.6–5.5
Thermal energy consumption (kJ/kg)	230–390	190–390	145–390	None	None	None
Electrical equivalent for thermal energy (kWh/m^3)	5–8.5	9.5–19.5	9.5–25.5	None	None	None
Total equivalent energy consumption (kWh/m^3)	6.5–11	13.5–25.5	11–28	7–12	3–7	26–5.5

Source: Alkaisi et al. 2017 [4]. Reproduced with permission of Elsevier.

1.6 Thermo-Physical Properties of Water

1.6.1 Potable Water

Potable water (freshwater) is characterized with salinity less than 500 ppm.

Table 1.2 shows water classification based on salinity, and the standards of WHO for freshwater limit is 500 ppm (0.05 mg/kg).

The chemical concentration in fresh water with 500 ppm are shown in Table 1.3.

Tables 1.3 and 1.4 show the 2018 Drinking Water Standards and Health Advisories, Secondary Drinking Water Regulations.

1.6.2 Seawater

Table 1.5 shows thermo-physical properties of standard seawater at 40 000 ppm and 25 °C.

Note that the comprehensive thermo-physical properties of seawater as a function of temperature and salinity are presented in Appendix A.

Table 1.2 Water classification based on salinity content.

Type	Total dissolved salts (TDS)
Freshwater	<1500
Brackish water	1500–10 000
Salt water	>10 000
Seawater	10 000–45 000
Standard seawater	35 000

Table 1.3 Secondary drinking water regulation [5].

Chemicals	SDWR
Aluminum	0.05–0.2 mg/l
Chloride	250 mg/l
Color	15 color units
Copper	1.0 mg/l
Corrosivity	Non-corrosive
Fluoride	2.0 mg/l
Foaming agents	0.5 mg/l
Iron	0.3 mg/l
Manganese	0.05 mg/l
Odor	Three threshold odor numbers
pH	6.5–8.5
Silver	0.1 mg/l
Sulfate	250 mg/l
Total dissolved solids (TDS)	500 mg/l
Zinc	5 mg/l

Table 1.4 WHO standards for potable water [5].

Constitutes	Concentration (ppm)	
	Limited values	Max allowed values
Total dissolved salts (TDS)	500	1500
Cl	200	600
SO_4^{2+}	200	400
Ca^{2+}	75	100
Mg^{2+}	30	150
F^-	0.7	1.7
NO^{3-}	<50	100
Cu^{2+}	0.05	1.5
Fe^{3+}	0.10	1.0
NaCl	250	—
pH	7–8	6.5–9

Table 1.5 Thermo-physical properties of typical seawater at 40 000 ppm and 20 °C.

Density	1.0288 kg/m^3
Specific heat capacity	3.973 kJ/(kg °C)
Boiling point elevation, at 20 °C	0.344 K
Boiling point elevation, at 90 °C	0.565 K
Thermal conductivity	0.601 W/(m K)
Dynamic viscosity	1.089×10^{-3} kg/(m^2 s)
Kinematic viscosity	10.58×10^{-7} m^2/s
Latent heat of vaporization	2355.4 kJ/kg

Table 1.6 Standard seawater composition at salinity equal to ≈35 000 ppm.

Chemical ion	Concentration (ppm)	Valence	Total salt content (%)	mmol/kg	Molecular weight
Chlorine Cl^-	19 345	−1	55.03	546	35.453
Sodium Na^+	10 752	+1	30.59	468	22.990
Sulfate SO_4^{2-}	2701	−2	7.68	28.1	96.062
Magnesium Mg^{2+}	1295	+2	3.68	53.3	24.305
Calcium Ca^{2+}	416	+2	1.18	10.4	40.078
Potassium K^+	390	+1	1.11	9.97	39.098
Bicarbonate HCO_3^-	145	−1	0.41	2.34	61.016
Bromide Br^-	66	−1	0.19	0.83	79.904
Borate BO_3^{3-}	27	−3	0.08	0.46	58.808
Strontium Sr^{2+}	13	+2	0.04	0.091	87.620
Fluoride F^-	1	−1	0.003	0.068	18.998
$\Sigma x_i = 35\,151$ ppm					

The major six elements that comprise about 99% of seawater are chlorine (Cl^-), sodium (Na^+), sulfate (SO_4^{2-}), magnesium (Mg^{+2}), calcium (Ca^{+2}), and potassium (K^+), and standard seawater composition at 35 000 ppm are presented in Table 1.6.

Note that Cl makes up to 55% of salt in seawater and NaCl makes up to 86% of salt in seawater.

Example 1.5 ***Heat Exchanger with Feed Seawater***

An adiabatic heat exchanger provides thermal load to feed seawater, such that feed seawater can be supplied to MEE desalination system at 70 °C.

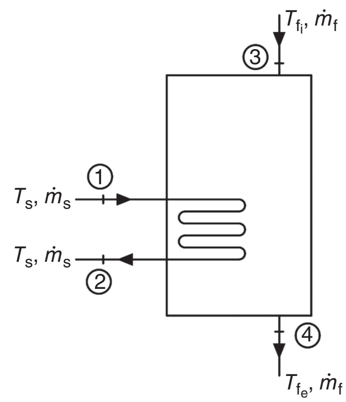
Steam stream: 1 kg/s, 120 °C

State 1: saturated vapor
State 2: saturated liquid

Feed seawater stream:

State 3: 20 °C
State 4: 70 °C

$x_f = 40\,000$ ppm



Find:

a. Feed seawater flow rate.
b. Assume feed is fresh water, find feed flow rate.
c. If steam (thermal load) is generated by conventional boiler using natural gas as a fuel, find fuel flow rate and emitted amount of CO_2.
d. Provide emission table for three types of fuels to generate steam (thermal load).

Solution

a. Energy balance (first law):

$$\text{Steam: } \dot{Q}_s - \cancelto{0}{\dot{W}} = \dot{m}_s \Delta h$$

$$\dot{Q}_s = \dot{m}_s h_{fg}$$

$$\dot{Q}_s = 1\ \frac{\text{kg}}{\text{s}} \left(2229.7\ \frac{\text{kJ}}{\text{kg}}\right)$$

$$= 2229.7\ \text{kW (thermal load by steam)}$$

$$\text{Feed water : } \dot{Q}_f - \cancelto{0}{\dot{W}} = \dot{m}_f \Delta h$$

$$2229.7\ \text{kW} = \dot{m}_f (278.5 - 79.2)\ \text{kJ/kg}$$

$\dot{m}_f = 11.187\ ^{\text{kg}}/_{(\text{s kg})}$ of thermal load (≈11 time of steam flow rate).

Alternative solution

$$\dot{Q}_f = \dot{m}_f \cdot h_{fg}$$

$$= \dot{m}_f c_p\ (\Delta T)$$

c_p is calculated at $\frac{T_3+T_4}{2} = 3.9846\ \frac{\text{kJ}}{\text{kg K}}$ then

$$\dot{m} = \frac{2.2297\ \text{kJ/kg}}{3.9846\ \frac{\text{kJ}}{\text{kg K}} \times 50\ \text{K}}$$

$\dot{m} = 11.19$ kg/(s kg) of thermal load.

b. If feed is fresh water $\dot{Q}_f = \dot{m}_f h_{fg}$

$$2229.7\ \text{kW} = \dot{m}_f [314.03 - 83.915]\ \text{kJ/kg}$$

$$\dot{m}_f = 9.7\ \text{kg/s}$$

c. $\dot{Q}_{load} = \dot{m}_{fuel} \cdot \text{LHV}$

$$2229.7\ \text{kW} = \dot{m}_{fuel} \cdot (55\ \text{MJ/kg})$$

The $\dot{m}_{fuel} = 40.54\ \text{kg/s}$ of natural gas fuel.

For CO_2 emission

$$[CO_2] = \left[2.75\ \text{kg}_{CO_2}/1\ \text{kg}_{\text{natural gas}}\right][40.54\ \text{kg/s}] = 111.4\ \text{kg}_{co_2}/\text{s}$$

d. Environmental impact of burning fossil fuels.

Fuel	Calorific value (MJ/kg)	CO_2 (kg/kg$_{fuel}$)	CO_2/energy (kg/MJ)	SO_2 (kg/kg$_{fuel}$)
Coal	26	2.361	0.091	0.018
Fuel oil	42	3.153	0.075	0.040
Natural gas	55	2.750	0.050	0

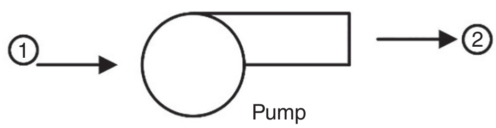
Extra activity:

Student can perform the following:

a. Perform parametric study to investigate the effect of T_{f_2} on $\dot{m}_f$. Plot and explain.
b. Perform parametric study to investigate the effect of x_f on $\dot{m}_f$. Plot and explain.
c. Find the values of the following thermo-physical parameters at T_{f_1} and T_{f_2} (x_f= 40 000 ppm); boiling point elevation (BPE), μ, v, k, h_{fg}, c_p, u, s, ρ. Explain the reason behind the differences.
d. Find the values of the following thermo-physical parameters at T_{f_2} under two salinities; x_f = 20 000 and 40 000 ppm for; BPE, μ, v, k, h_{fg}, c_p, u, s, ρ. Explain the reason behind the differences.
e. Calculate entropy generation and irreversibility per mass of feedwater flow rate.

Example 1.6 ***Performance of Feed Pump***

Feedwater is pumped from 100 kPa, 30 °C, 1.5 kg/s to 3 MPa, if pump efficiency is 75%:



Find:

a. Actual work input
b. Reversible work

c. Exergy destruction (irreversibility)
d. Second law efficiency

Solution

a. Working fluid water:
State 1

$$\left.\begin{array}{l} T_1 = 30\ ^\circ\mathrm{C} \\ X_1 = 0.0 \end{array}\right\} \Longrightarrow \begin{array}{l} v_1 = 0.001\,004\ \mathrm{m^3/kg} \\ h_1 = 125\ \mathrm{kJ/kg} \\ s_1 = 0.4367\ \mathrm{kJ/(kg\ K)} \end{array}$$

$$\dot{W}_s = \dot{m}v(P_2 - P_1)$$

$$= 1.35\ \frac{\mathrm{kg}}{\mathrm{s}} \cdot 0.001\,004\ \frac{\mathrm{m^3}}{\mathrm{kg}}(4000 - 100)\ \mathrm{kPa}$$

$$= 5.28\ \mathrm{kW}\ \text{(isentropic work)}$$

$$\dot{W}_a = \frac{\dot{W}_s}{\eta_s} = 7.55\ \mathrm{kW} > \dot{W}_s$$

$$\text{First law } \cancelto{0}{\dot{Q}} - \dot{W}_a = \dot{m}\Delta h$$

then $h_2 = 131.4$ kJ/kg and $s_2 = 0.4423$ kJ/(kg K).

b. $W_{\mathrm{rev}} = \Psi_2 - \Psi_1$

$$= \dot{m}[(h_2 - h_1) - T_o(s_2 - s_1)]$$

$$= 5.362\ \mathrm{kW}\ \text{(reversible work)}$$

c. Exergy destruction (irreversibility):

$\dot{I} = \dot{W}_a - \dot{W}_{\mathrm{rev}}$

$= 2.193\ \ \mathrm{kW}$

d. Exergetic efficiency:

$\eta_{\mathrm{II}} = \frac{\dot{W}_{\mathrm{rev}}}{\dot{W}_a}$

$= \frac{2.362}{7.55} = 71\%$

or $\eta_{II} = 1 - \frac{\dot{I}}{\Delta h}$

$= 72\%$

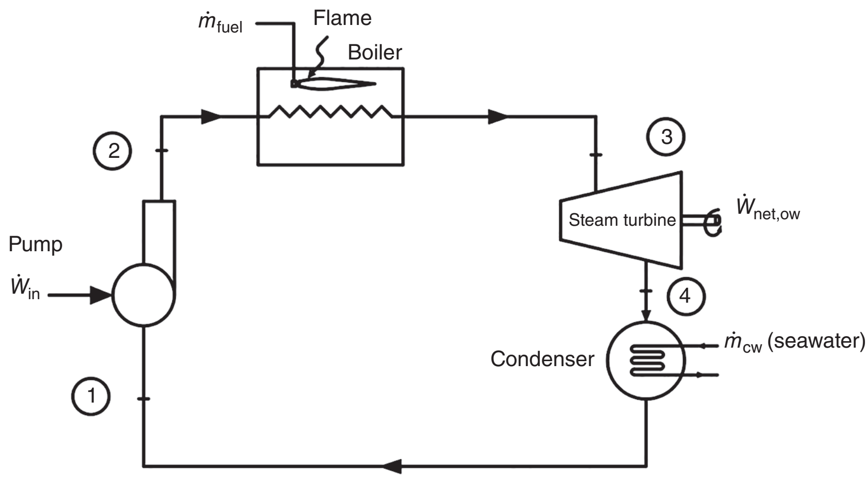
Extra activity:

Student can perform the following:

a. Sketch T–v, P–v, and T–s diagram for actual and isentropic processes.
b. Resolve example using seawater ($x = 40\,000$ ppm) as feed. Refer to Appendix A.
c. Compare results of feed seawater against water. Explain and comment.

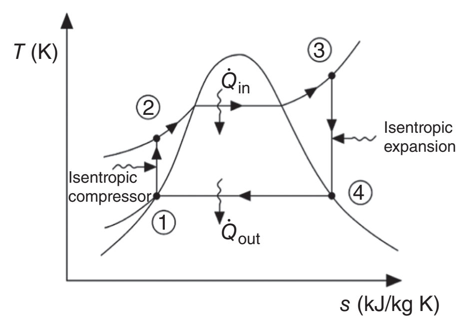
Example 1.7 ***Exergy Analysis of Rankine Cycle (Review)***
Simple Rankine cycle operates with isentropic expansion and isentropic compressor to produce net power of 1750 kW, and steam boiler operates isobarically at 6 MPa pressure; using fuel oil as a fuel, the combustion of fuel produces heat that is added at a source temperature of 800 K, and the produced steam enters steam turbine at 500 °C and 6 MPa to be expand isentropically to 20 kPa as it leaves steam turbine.

The condenser operates at 20 kPa using seawater cooling water at 4 °C (winter season).



Find:

a. Rate of heat supply in the boiler.
b. Rate of heat rejection in the condenser.
c. Cycle thermal efficiency.
d. Availability at each state ($T_o = 298$ K)
e. Exergy destruction in each component assuming heat is added from a source at 800 °C and rejected at 4 °C.
f. Cycle second law efficiency.



Solution

a. $v_1 = v_{f@20\,kPa} = 0.001\,017\ m^3/kg$

$$h_1 = 251.4\ kJ/kg$$

$$s_1 = 0.832\ kJ/kg$$

$$W_{pump} = v_1(P_2 - P_1)$$

$$= 6.1\ kJ/kg\ (\text{work in})$$

Energy balance (first law):

$$\cancelto{0}{\dot{Q}} - \dot{W} = \dot{m}(h_e - h_i)$$

$$h_2 = h_1 + W_{pump}$$

$$= 257.5\ kJ/kg$$

Since $\Delta s = 0$ ($s_2 = s_1$) at state 3 $h_3 = 3423.1$ kJ/kg and $s_3 = 6.8826$ kJ/(kg K) again the isentropic expansion turbine ($s_3 = s_4$) gives $h_4 = 2264.7$ kJ/kg with quality $x_4 = 0.8552$.

Energy balance in turbine:

$$W_{turbine} = h_3 - h_4$$

$$= 1155.6\ kJ/kg$$

and cycle $W_{net} = W_t - W_p$

$$= 1149.5\ kJ/kg$$

then

$$\dot{m}_{steam} = \frac{\dot{W}_{net}}{W_{net}} = \frac{1750}{1149.5} = 1.522\ kg/s$$

The rate of heat added in the boiler (due to fuel burning)

$$\dot{Q}_{in} = \dot{m}_s(\Delta h)$$

$$\dot{Q}_{in} = 4818.0\ kW$$

b. Rate of rejected heat:

$$\dot{Q}_{out} = \dot{m}_s(h_4 - h_1)$$

$$= 3068.5\ kW$$

c. $\eta_{th} = \dfrac{\text{energy output}}{\text{energy supplied (input)}}$

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = 36.32\%$$

d. The thermal availability (exergy) for control volume system defined as

$$\Psi = \dot{m}[(h - h_o) - T_o(s - s_o)]$$

where kinetic and potential exergies are neglected and h_o and s_o are measured at environmental state (298 K).

$$h_o = 104.8 \text{ kJ/kg}$$

$$s_o = 0.367 \text{ kJ/(kg K)}$$

Exergy at state:

$$\Psi_1 = \dot{m}[(h_1 - h_o) - T_o(s_1 - s_o)]$$
$$= 1.522\,[(251.4 - 104.8) - 298\,(0.832 - 0.367)] = 12.22 \text{ kW}$$

$$\Psi_2 = 21.51 \text{ kW}$$

$$\Psi_3 = 2095.26 \text{ kW}$$

$$\Psi_4 = 336.44 \text{ kW}$$

One can notice that Ψ_3 is the highest (explain).

e. Exergy destruction (irreversibility) for steady flow process type is

$$\dot{I} = T_o\dot{S}_{gen}$$

$$= \dot{m}T_o\,(\dot{S}_{system} + \dot{S}_{surrounding})$$

$$= \dot{m}T_o\left(s_e - s_i - \frac{q_{in}}{T_{source}} + \frac{q_{out}}{T_{sink}}\right)$$

$\dot{I}_{1-2} = \dot{I}_{3-4} = 0.0$ (isentropic process which is adiabatic and reversible type)

$$\dot{I}_{3-4} = 1.522 \text{ kg}/s \times 298\,K[(6.8826 - 0.832) - \frac{3165.6 \text{ kJ/kg}}{1073 \text{ K}}$$

$$= 1406.2 \text{ kW}$$

where $q_{in} = h_3 - h_2 = 3165.6$ kJ/kg and $\dot{I}_{4-1} = 1.522$ kg/s × 298 K $\left[0.832 - 6.8826 + \frac{2016.1}{277 \text{ K}}\right] = 556.8$ kW where $q_{out} = h_4 - h_1 = 2016.1$ kJ/kg.

Total amount of exergy destruction (irreversibility):

$$\dot{I}_{tot} = \sum_{1}^{4} I_n$$
$$= 1963 \text{ kW}$$

Note that 40% of energy added (4818 kW) is destructed (wasted) due to irreversible processes, the reasons behind irreversibilities in any thermal system are combustion, heat transfer, mixing, friction, and non-quasi equilibrium processes.

f. The second law efficiency can be defined as

$$\eta_{II} = \frac{\eta_{th}}{\eta_{reversible}}$$

$\eta_{rev} = 1 - \frac{T_L}{T_H} = 74.18\%$ (Carnot efficiency) then

$$\eta_{II} = \frac{36.32}{74.18} = 46.9\%.$$

Extra activity:

Student can perform the following:

a. Explain the exergy value of fluid stream at each state.
b. Explain the sources of irreversibilities in boiler. How can we reduce them?
c. Calculate exergetic efficiency using the following three forms:
   1. $\eta_{II} = 1 - \frac{\dot{I}}{\Psi_{in}}$ (called rational)
   2. $\eta_{II} = \frac{\text{minimum required exergy input}}{\text{actual input exergy}}$

   $$\eta_{II} = \frac{\Psi_{i,min}}{\Psi_{i,actual}}$$

   3. $\eta_{II} = \frac{\text{exergy loss plus consumption}}{\text{exergy input}}$

   Compare and discuss.
d. Resolve example assuming that seawater is at 30 °C (summer season). Explain results, and compare.
e. Find the required fuel flow rate during summer using fuel oil and natural gas, and calculate the amount of emitted emissions: CO_2 and SO_2.

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2 Desalination in Water Treatment (IDA2014). www.IDAdesal.org.
3 Youssef, P.G., AL-Dadah, R.K., and Mahmoud, S.M. (2014). Comparative analysis of desalination technologies. *Energy Procedia* 61: 2604–2607.
4 Alkaisi, A., Mossad, R., and Barforoush, A.S. (2017). A review of the water desalination systems integrated with renewable energy. *Energy Procedia* 110: 268–274.
5 U.S. Environmental Protection Agency (2018). *Edition of the Drinking Water Standards and Health Advisories*. U.S. Environmental Protection Agency.

A. Review Questions

1.1 What is the recent global world capacity of desalted water? State the value of desalting water capacity in your country.

1.2 In which year world capacity of desalted water using RO start to overcome thermal-type (MEE and MSF) production? Highlight on facts and reasons.

1.3 Can freezing desalination technology be considered as a thermal type? Explain.

1.4 Sketch and explain the following processes on $T\text{–}v$, $P\text{–}v$, and $T\text{–}s$ diagrams:
a. Boiling.
b. Flashing.
c. Condensation.

1.5 List the top 10 countries that produce desalted water. What is the rank of your country? List the sources of fresh water in your country.

1.6 Search through the literature to obtain the following worldwide recent statistics:
a. Potable water production.
b. Number of desalination plants.
c. Contribution of each type of desalination technology.
d. Potable water production cost, specify the cost in your country, compare, and comment.

1.7 Define and explain the following glossary:
a. Corrosion.
b. Scaling.
c. Fouling.
d. TDS.
e. Turbidity.
f. pH.

1.8 Present in table form the actual values of salinities in seven selected seas, oceans, and gulfs around the world, and provide information for the nearest one to your country.

1.9 Present in table form freshwater consumption per capita in seven different countries. What is the consumption per capita in your country? Explain.

1.10 Define the following thermal performance parameters.
a. Recovery ratio.
b. Gain ratio.
c. Performance ratio.
d. Concentration factor.

e. Specific energy consumption.
f. Specific exergy consumption.

1.11 Write an essay on the following desalination systems explaining the historical developments, and provide industrial examples:
a. Thermal systems.
b. Membrane systems.
c. Wastewater systems.

1.12 Differentiate between home and industry wastewater, and explain in terms of composition.

1.13 Elaborate on the principles of wastewater desalination process. Can desalted product be considered as potable water? Explain and comment.

1.14 Search through the literature and highlight on three major proposed non-conventional desalination systems that can be considered as a promising and futuristic one.

1.15 Explain the following feed seawater thermo-physical properties:
a. Density.
b. Viscosity.
c. Specific heat.
d. Enthalpy.
e. Thermal conductivity.
f. Boiling point elevation (BPE).
g. Latent heat (h_{fg}).
Provide real values for three types of feedwater salinities (Appendix A).

1.16 Provide recent worldwide statistics for the following:
a. Global desalination capacity by source water type: seawater, brackish water, river, waste, etc.
b. Global desalination capacity by technology type: MEE, MSF, vapor compression (VC), RO, electrodialysis (ED), etc.
c. Country desalination capacity by user type: municipal, irrigation, power, industrial, etc.

1.17 Provide a table that presents the pros and cons for the following: (a) three thermal desalination systems – MEE, MSF, and VC – and (b) two membrane desalination systems – RO and ED/electrodialysis reversed (EDR).

1.18 Select three different desalination systems and write an essay describing their operation. Sketch and explain.

1.19 Provide technical information for four selected commercial desalination systems showing their industrial specifications. Choose one from your country.

1.20 Provide the value of specific energy required to desalt 1 m^3 of safe water for human consumption for the following various water sources:
a. Lake or river.
b. Ground water.
c. Brackish water.
d. Seawater.
e. Wastewater treatment.
f. Wastewater reuse.

1.21 Provide the value of power consumption trend for RO seawater desalination in the last 30 years. Sketch, explain, and justify the trend.

1.22 Provide the values of salt concentration (ppm) for the following feed sources:
a. Pacific Ocean.
b. Atlantic Ocean.
c. Gulf of Mexico.
d. Arabian Gulf.
e. North Sea.
f. Dead Sea.
Explain the reasons behind differences.

1.23 Explain the following concentration units: ppm, ppt, wt%, mg/l, and mg/kg.

1.24 Explain the following molar concentration units: molarity and normality.

1.25 List three operational parameters that affect desalination system performance. Explain their effects.

1.26 Elaborate on the effects of brine salinity on ecosystem.

1.27 Through experimental work, use TDS digital indicator to examine the salinity of the following feed:
a. Tap water (cold).
b. Tap water (hot).
c. Five commercial local mineral water bottles.
d. Five commercial imported mineral water bottles.
e. Industrial wastewater.
Explain and comment.

1.28 Explain the function of the following devices:
a. Hydrometer.
b. Viscometer.
c. Pycnometer.
Provide experimental measurements of three types of feedwater.

1.29 Provide charts showing types of desalination processes based on:
a. Type of energy used (mechanical, thermal, electrical).
b. Type of extracted component (water, salt).

1.30 Explain the status of desalination industry in your country.

1.31 Elaborate on the following patents:
a. Rillieux patent of MEE in 1943.
b. Silver patent of MSF in 1959.