Energy Consumption and Performance for Various Desalination Processes

The minimum energy consumption required for separating a saline solution into pure water and concentrated brine under ideal conditions is dependent only on the salt content of the saline solution, regardless of the technology and configuration of the desalination system in question. In other words, all desalination systems, which may be based on different technologies and may have different configurations, share a common minimum energy requirement for driving the separation process, regardless of the system. In practice, however, the energy requirements in all desalination process are considerably higher than those computed for the reversible ideal separation. This is because a certain process irreversibility occurs due to friction losses, non-equilibrium and other thermal losses, including boiling point elevation, flow resistance through membranes and pump efficiencies. Hence, the deviation of the actual energy required in any given desalination system depends on the system's design and engineering characteristics and its principle of operation in the quantity and type of losses encountered during separation. The energy requirement and performance for each of the above desalination processes are reviewed separately below.

1. Energy consumption and performance of the MSF process

Two types of energy are required for the operation of a MSF desalination plant. The first is low temperature heat, which represents the main portion of energy input to the MSF and is usually fed into the system through the heat input section. The second is electricity, which is used to drive the system's pumps. MSF desalination plants in the GCC countries are usually an integral part of dual-purpose power/water production systems. The technical reasons for this integration between power and MSF will be reviewed below. However, low-temperature heat is usually supplied to a MSF desalination system through imported steam from the power generation plant. This steam may be extracted from the steam turbine or from the boiler after entering a pressure-reducing station. Whether the steam is extracted from a turbine or from a boiler/pressure-reducing station, it usually goes through processes of expansion and desuperheating for conditioning prior to its entry to the MSF heat input section.

The efficiency of the utilization of low-temperature heat consumption in an MSF plant, which is an indicator of the process performance, depends on the following:

(a) The maximum temperature of the heat source. The threshold of sulphate-based scale formation in the brine solution and the performance characteristics of the soft scale inhibitor determine the upper limit on this temperature. The maximum temperature reached by the brine solution is usually known as top brine temperature (TBT);

(b) The temperature of the heat sink at which excess heat is rejected from the system. The limit on this temperature is determined by the year-round maximum seawater temperature;

(c) The number of stages of the system. In this case, the capital cost is the main limiting factor on the final number of stages;

(d) Salt concentration in the flashing brine solution;

(e) Geometrical configuration of the flashing stages, which have a direct influence on nonequilibrium losses, pressure drop losses and heat dissipation losses;

(f) Construction material and design configuration of the heat exchanger device inside the stages and the heat input section, which have direct influence on heat transfer losses and efficiency.

The efficiency of low-temperature heat is usually measured by:
(a) The ratio between the amounts of water produced per unit mass of dry saturated steam supplied to the system. This is known as the gain output ratio (GOR);

(b) The amount of product water in kilograms (kg) per one million Joules of low-temperature heat supplied to the system. This is known as the performance ratio (PR).
Typical GOR values for large-scale commercial MSF plants range between 8 and 10 kg/kg with PR between 3.5 and 4.5 kg/MJ. The GOR value of 8 is a very common figure for MSF plants in the GCC countries operating at TBT of approximately 91°C. As the TBT is increased to some 110°C for the same plant, GOR value reaches 8.6. Table 13 shows typical heat input values and their useful electrical equivalent, and performance indicators at two different operating temperatures for a typical MSF plant.

Table 1 indicates that whilst the heat input at GOR of 8.6 is less than that at GOR of 8 by some 9.2 per cent, the useful electrical equivalent is higher at the higher GOR by some 9.1 per cent compared to that at the lower GOR. This is because at the higher GOR, heat is supplied at higher temperature and thus has higher-grade energy. A direct comparison between thermally driven desalination systems on the basis of GOR or heat input values is often deceptive if the thermodynamic state of the heating steam is not taken into consideration.

In addition to the low-temperature heat, electricity is essential for the operation of MSF desalination plants. Pumps are the main consumers of electricity in typical MSF plants. These include the brine recycle, brine blow down, distillate and condensate pumps, in addition to feed water transfer pumps, main intake pumps and other auxiliary pumps for chemical dosing. Thus, specific electricity consumption is very much dependent on plant configuration and site characteristics, which are expected to vary from one plant to another. However, in the GCC region, values of specific electrical energy consumption range between 3.5 to 5.0 kWh/m3 of product water (see table 10). As the plant/unit capacities increase, the specific electrical energy consumption is more likely to be at the lower end of the above range, and the reverse is also true.

Table 1. Thermal Energy Requirements and GOR Values For A Typical MSF Desalination Plant Operating At Different TBT

Parameter/quantity	TBT (°C)	
	90.6[a]	110[b]
Number of stages	24	24
Cooling seawater temperature (°C)	32.3	32.3
Heating steam temperature (°C) and pressure at turbine extraction point	111 and 0.15	127°C and 0.25 Mpa
Heating steam temperature and pressure in the heat input section (Mpa)	100 and 0.1	120 and 0.2
Flashing temperature range (°C)	50.1	68.8
Average temperature difference between stages (°C)	2.1	2.9
GOR (kg/kg)	8	8.6
Product water recovery ratio (percentage)	10.51	13.44
Heat input/m3 of distillate (MJ)	282	256
Useful electrical equivalent per m^3 of distillate (kWh)	16.72	15.32
Specific electrical energy input per m^3 of distillate	4.2	3.68

Source: Mahmoud Abdel-Jawad. "Energy sources for coupling with desalination plants in the GCC countries", consultancy report prepared for ESCWA, (September 2001).

[a]/ Based on a 27,300 m3 per day plant capacity.

[b]/ Based on a 32,700 m3 per day plant capacity.

2. Energy consumption and performance of the MED process

MED is similar to MSF in that it requires two types of energy, namely, low-temperature heat and electricity. The low-temperature heat is the main portion of the total energy input to the system regardless of whether it is supplied by the extracted steam from a power plant, waste heat recovery boiler, or fuel-fired boiler.

TABLE 2. Thermal Energy Requirements And GOR Values For A Typical MED Plant Operating At Different TBT (°C)

Parameter/quantity	TBT (°C)	
	66[a]	72[b]
Number of effects	12	16
Cooling Seawater temperature (°C)	32.3	32.3
Heating steam temperature (°C) and pressure at Turbine extraction point (Mpa)	106.5 and 0.127	110 and 0.14
Heating steam temperature (°C) and pressure in the heat input section (Mpa)	71 and 0.033	77 and 0.042
Operating temperature range across the system	27.6	33.6
Average temperature difference between effects (°C)	2.3	2.1

Product water recovery ratio (percentage)	14.4	12
Gain output ratio kg/kg	8.5	12.2
Heat input/m3 of distillate (MJ)	263.5	189.9
Useful electrical equivalent per m^3 of distillate (kWh)	13.65	9.73
Specific electrical energy input per m^3 of distillate	1.8	2.3

Source: Mahmoud Abdel-Jawad, "Energy for coupling with desalination plants in the GCC countries", consultancy report
prepared for ESCWA, (September 2001).
a/ Based on a 10,000 m^3/d plant capacity.
b/ Computed.

3. *Energy consumption and performance of the vapour compression process*

The VC desalination process is a modified form of the MED process where heat is internally supplied within the system using the principle of heat pumping. As saturated vapour is adiabatically compressed from a given thermodynamic state, using for example a mechanical compressor, its temperature rises as a result of the change in its pressure.

TABLE 3a. Specific Electrical Energy Consumption Data For Typical MVC Plants

Number of effects	1[a]	2[b]	3[c]
Maximum TBT (^{o} C)	74	74	74
Change of temperature per effect (^{o} C)	2.5	2.3	2.1
Product water recovery ratio (percentage)	41.67	41.67	48.08
Total specific electrical energy consumption (kWh/m^3)	12.0	11.5	11.0

Source: Mahmoud Abdel-Jawad, "Energy sources for coupling with desalination plants in the GCC countries", consultancy
report prepared for ESCWA, (September 2001).
a/ Based on a 700 m3 per day unit capacity.
b/ Based on a 1,500 m3 per day unit capacity.
c/ Based on a 3,000 m3 per day unit capacity.

TABLE 3b. Energy Requirements And GOR Values For Typical TVC Plants Operating At Different TBT (°C)

Parameter/quantity	TBT (^{o}C)	
	63[a]	70[b]
Number of effects	16	16
Feed Seawater temperature (°C)	23.3	23.3
Motive steam temperature (°C) and pressure (Mpa)	135 and 0.313	135 and 0.313
Operating temperature range across the system (°C)	33.6	40.6

Average temperature difference between effects (°C)	2.1	2.5
Product water recovery ratio (%)	20.83	20.83
Gain Output Ratio kg/kg	12	12
Heat input/m^3 of distillate (MJ)	227.3	227.3
Useful electrical equivalent/m3 of distillate (kWh)	14.56	14.56
Specific electrical energy input per m^3 of distillate	1.8	1.6

Source: Mahmoud Abdel-Jawad, “Energy sources for coupling with desalination plants in the GCC countries”, consultancy report prepared for ESCWA, (September 2001).
a/ Based on a 6,000 m^3 per day plant capacity.
b/ Based on a 10,000 m^3 per day plant capacity.

4. *Energy consumption and performance of the RO process*
The RO desalination process allows saline solutions at above-atmospheric pressure to flow through a membrane of suitable porosity. This yields a permeated solution at atmospheric pressure that is enriched in pure water and leaves a concentrated solution on the high-pressure side of the membrane.

TABLE 4. **Membrane Area Requirements and Specific Energy Consumption for Typical RO Desalination Plants Using Spiral Wound Membrane Type and Different Feed Water Types**

Parameter/quantity	Feed water type		
	Brackish Water [a]	Seawater (41,518 ppm)[b]	
	(5,000 ppm)	With ER	Without ER
Feed pressure (Mpa)	2.0	5.68	5.68
Feed temperature (^{o} C)	30	25	25
Product water recovery ratio (%)	53	34.24	34.24
Salt Rejection (percentage)	99.6	98.7	98.7
Membrane area requirement $m^2/(m^3$ per day)	1.18	1.42	1.42
Specific electrical energy consumption of high pressure pump and other pumps (kWh/m^3)	2.1 + 0.0	5.1 + 1.05	6.4 + 1.05

Source: Mahmoud Abdel-Jawad, “Energy sources for coupling with desalination plants in the GCC countries”, consultancy report prepared for ESCWA, (September 2001).
a/ Based on average values for different brackish waters.
b/ Based on long operation of 6,00 m^3/d plant capacity.

5. *Energy consumption in the electrodialysis process*
Similar to the RO process, desalination using the ED process is heavily dependent on the characteristics of feed water in terms of salt concentration, composition and

temperature. However, the ED process operates at atmospheric pressures and the electrical energy supplied to the system is utilized mainly in the ions transported across the membranes. Table 5 lists relevant data on the ED process for three feed water salinities with calcium ions less than 100 ppm.

TABLE 5. **Membrane Area Requirements and Specific Energy Consumption For the ED Desalination Process at Different Feed Water Concentrations**

Feed water TDS (ppm)	2 500	3 500	5 000
Membrane area requirement $m^2/(m^3$ per day)	0.62	0.75	0.89
Total specific electrical energy consumption (kWh/m^3)	2.64	3.85	5.50

Source: Mahmoud Abdel-Jawad, "Energy sources for coupling with desalination plants in the GCC countries", consultancy report prepared for ESCWA, (September 2001).