WSTA 15th – Gulf Water Conference

Innovative Approach to Desalination and Cooling Using Forward Osmosis with Thermal Recovery and Vapor Absorption Cycle

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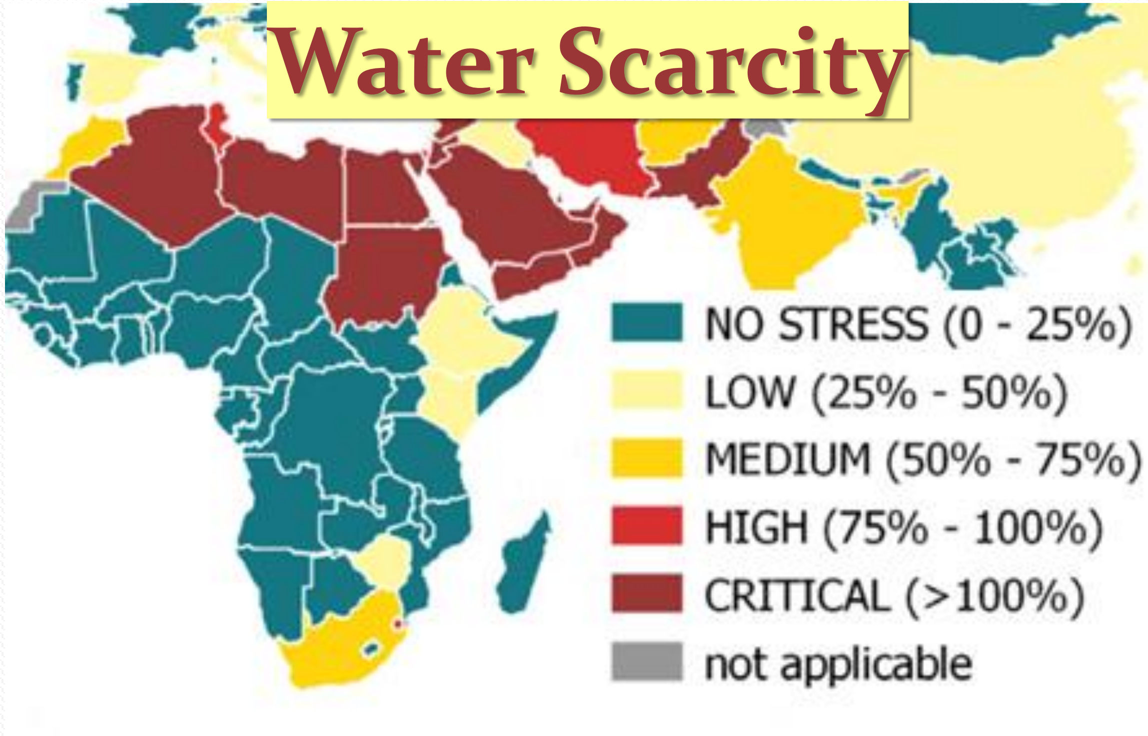
Agenda

- Introduction
- Innovative Technology
- Development of FO Technologies for Desalination at KISR
- Mathematical Modelling & Simulation on Innovative Technology
- Results and Discussions
- Conclusions

The Problem…

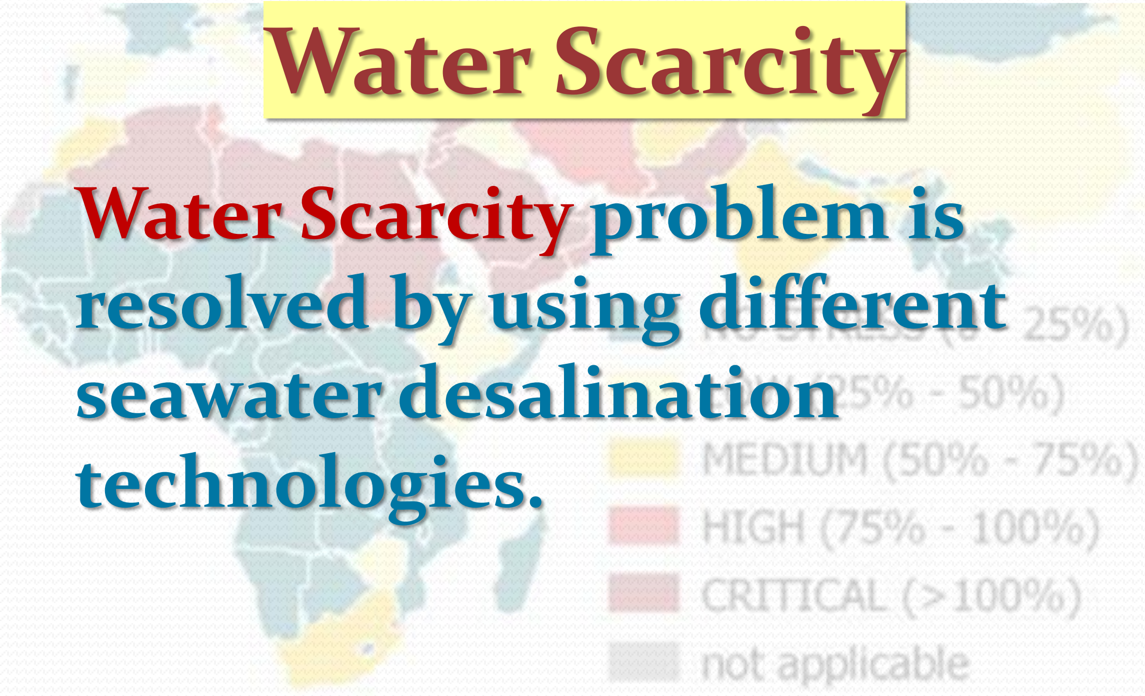


Water scarcity and **hot weather** are two predominant problems facing Kuwait and other GCC countries.

Current Solutions…

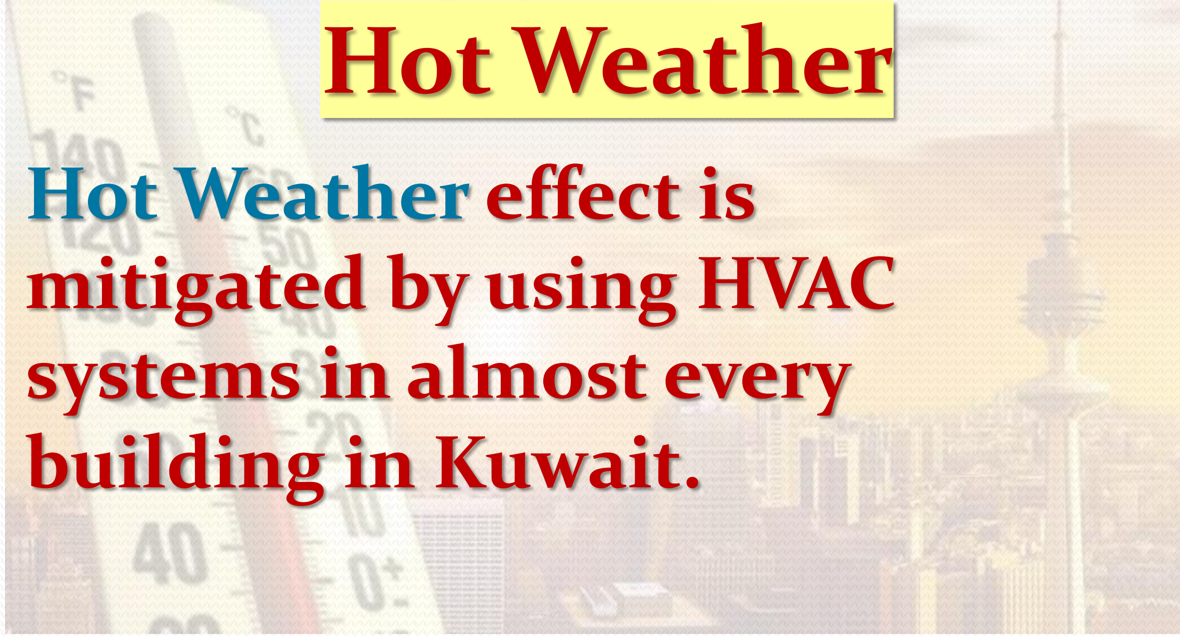
Water Scarcity

Water Scarcity problem is resolved by using different seawater desalination technologies.



Hot Weather

Hot Weather effect is mitigated by using HVAC systems in almost every building in Kuwait.



HVAC: heating, ventilation, and air conditioning.

Challenges …

- The desalination plants in Kuwait consume 462 TJ of energy, which represents 54% of the national fuel consumption[1].
- Air conditioning systems in Kuwait consume about 60% of the total electricity demand in Kuwait [2].
- Both desalination and air conditioning systems are very energy-intensive technologies.

1- Rajesh Komar, (2022) https://www.indiansinkuwait.com/news/World-Water-Day-How-Kuwait-improves-its-water-resource
2- Al-Abdullah, et. al. (2023). Kuwait Energy Outlook 2023: The Security-Transition Nexus of Kuwait. Kuwait City: KISR

Consequently …

- Power plants burn more fuel (Crude Oil and NG) to secure the power needed for desalination and HVAC systems.

Crude-Oil and NG

Lower oil revenues

Negative Environmental Impacts

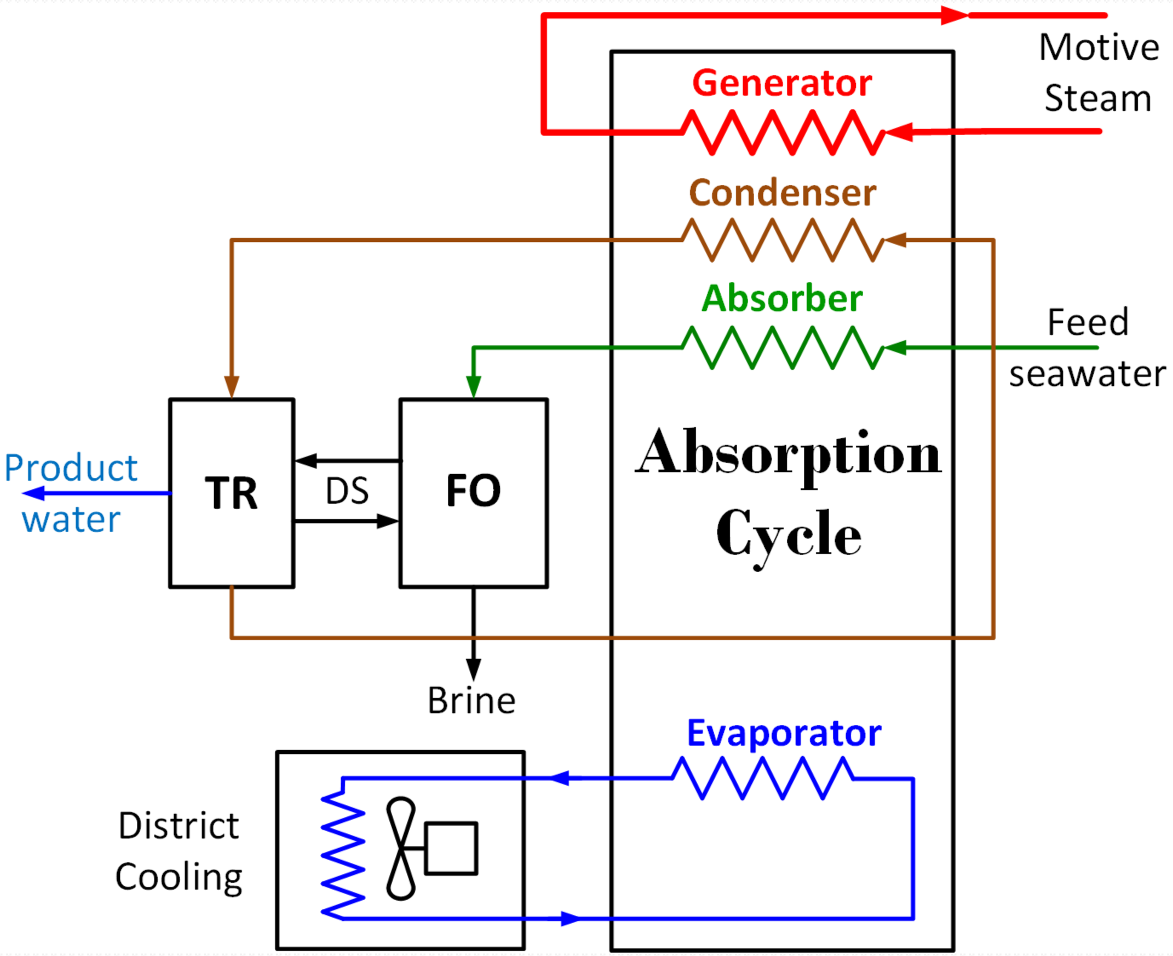
- Sustainable Desalination and AC technologies are greatly needed.

The Innovative Technology

- A combined system for desalination and air conditioning using low-grade thermal energy
- WRC obtained a US patent entitled

"**Desalination and Cooling System**"

US 11,407,659 B1, Aug. 9, 2022



VAC-FO-TR

US011407659B1

(12) **United States Patent**
Abdulrahim et al.

(10) **Patent No.: US 11,407,659 B1**
(45) **Date of Patent: Aug. 9, 2022**

(54) **DESALINATION AND COOLING SYSTEM**

(71) Applicant: **KUWAIT INSTITUTE FOR SCIENTIFIC RESEARCH**, Safat (KW)

(72) Inventors: **Hassan Kamal Mohamed Abdulrahim**, Safat (KW); **Mansour Ahmed**, Safat (KW)

(73) Assignee: **KUWAIT INSTITUTE FOR SCIENTIFIC RESEARCH**, Safat (KW)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **17/372,046**

(22) Filed: **Jul. 9, 2021**

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,617,547	A *	11/1971	Halff	B01D 61/422 210/638
4,280,331	A	7/1981	Yoshii et al.	
11,035,581	B1	6/2021	Abdulrahim et al.	
2006/0144789	A1 *	7/2006	Cath	B01D 61/58 210/641

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CN	104180555	A	12/2014

(Continued)

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Wang, "Proposal and analysis of a high-efficiency combined desalination and refrigeration system based on the LiBr—H2O absorption cycle—Part 1: System configuration and mathematical model," Energy Conversion and Management, vol. 52, Issue 1, Jan. 2011, pp. 220-227.

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CPC *C02F 1/445* (2013.01); *B01D 61/005* (2013.01); *B01D 2313/22* (2013.01); *B01D 2313/36* (2013.01); *C02F 2103/08* (2013.01); *C02F 2303/10* (2013.01)

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CPC B01D 61/002; B01D 61/005; B01D 69/02; B01D 2311/25; B01D 2311/2626; B01D 61/08; B01D 61/00; C01F 9/00
See application file for complete search history.

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International Search & Written Opinion in PCT/IB2022/050829, dated Mar. 23, 2022.

(Continued)

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(57) **ABSTRACT**

A desalination and cooling system includes a single effect water-lithium bromide vapor absorption cycle (VAC) system and a forward osmosis with thermal-recovery (FO-TR) desalination system. The FO system employs a Thermo-
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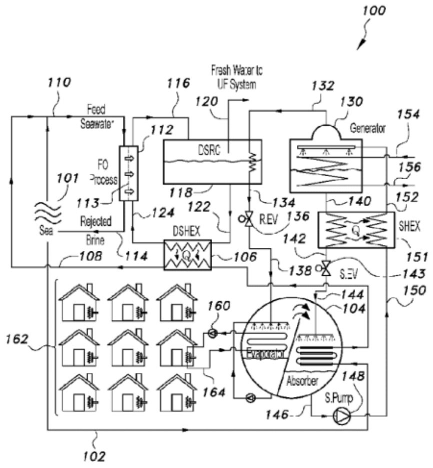

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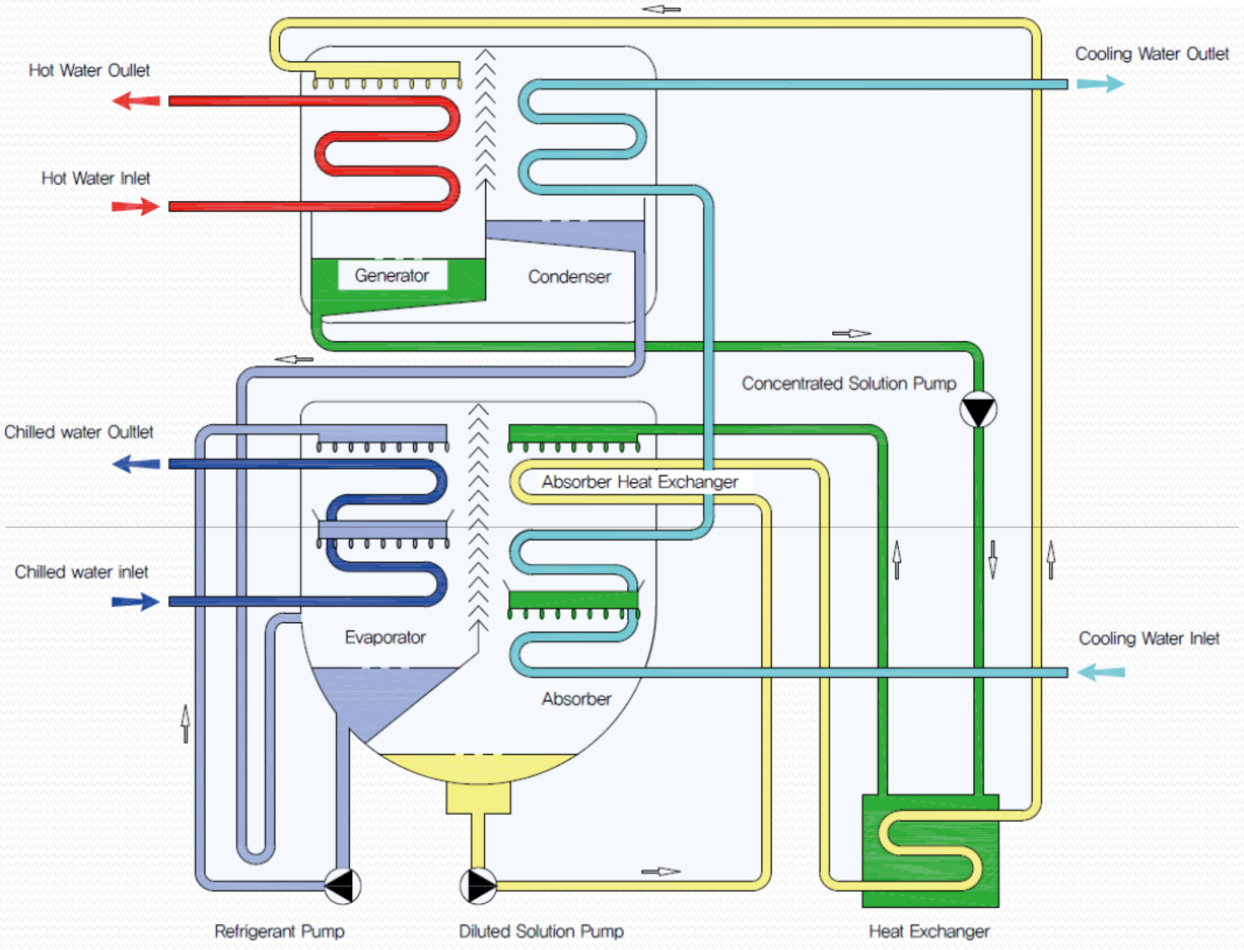
The Cooling System:

Vapor Absorption Cycle (VAC)

- Single effect, H_2O-LiBr absorption chiller
- Operated by low-grade thermal energy.
- Does not use a mechanical compressor; the compressor is replaced by an absorber, pump, and generator.
- Use distilled water as the refrigerant (Eco-friendly refrigerant)

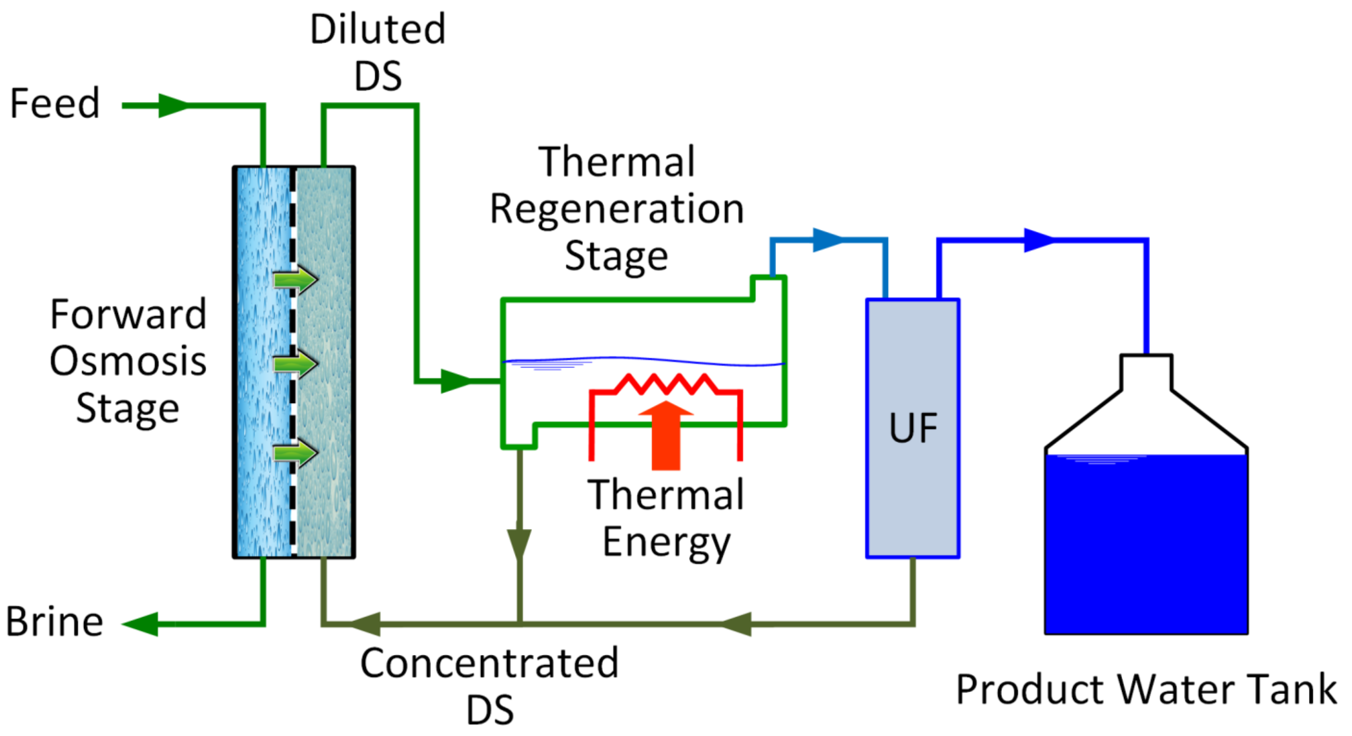


Single effect, H_2O-LiBr absorption chiller

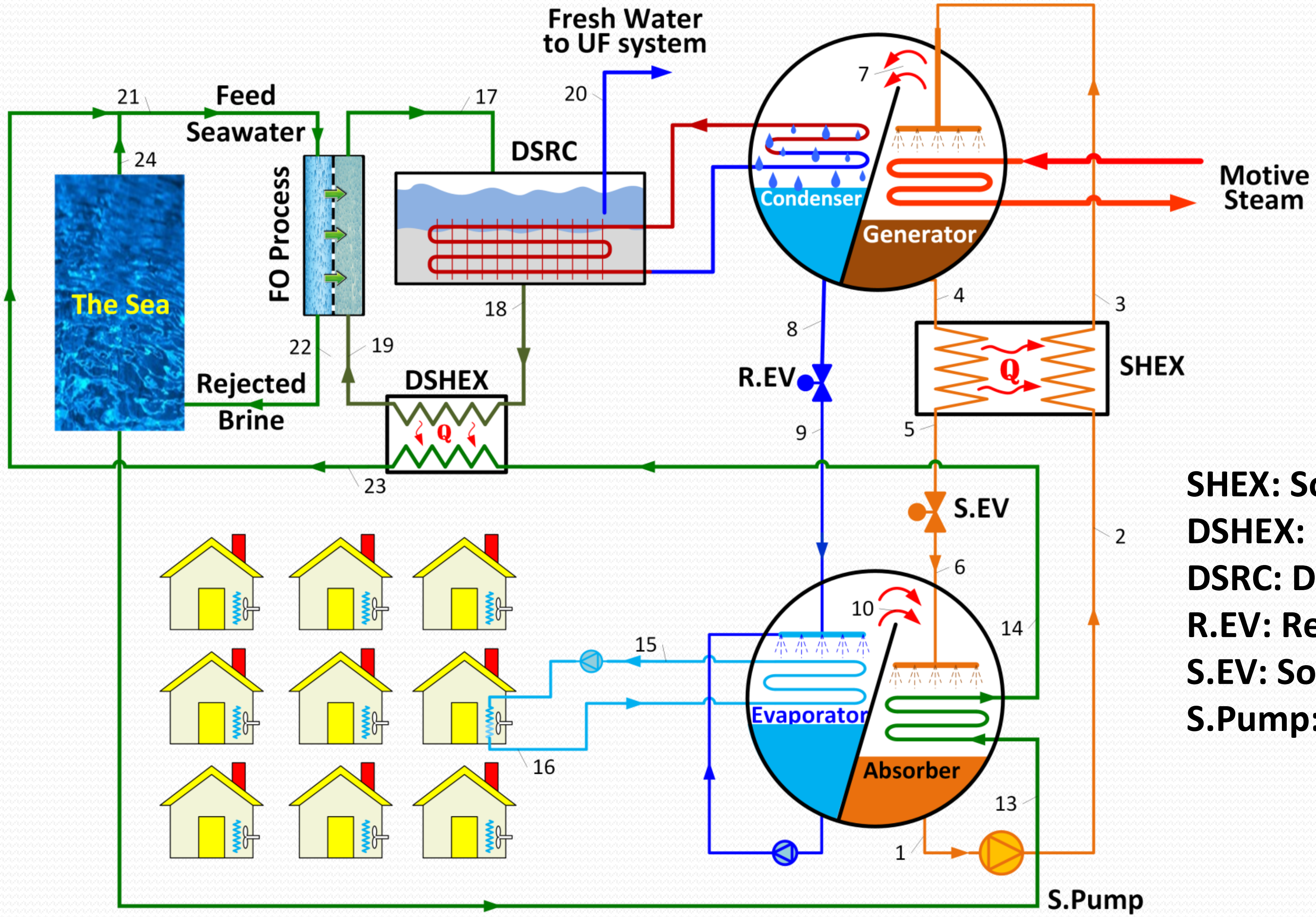
The Desalination System:

Forward Osmosis with Thermal Recovery (FO-TR)

- FO desalination system operates at **low pressure**; hence ordinary material can be used and reduce the capital cost.
- TR process operates at **low temperatures,** which reduce energy cost.
- FO is simple in operation, and the fouling, if happened, is reversible.



VAC-FO-TR

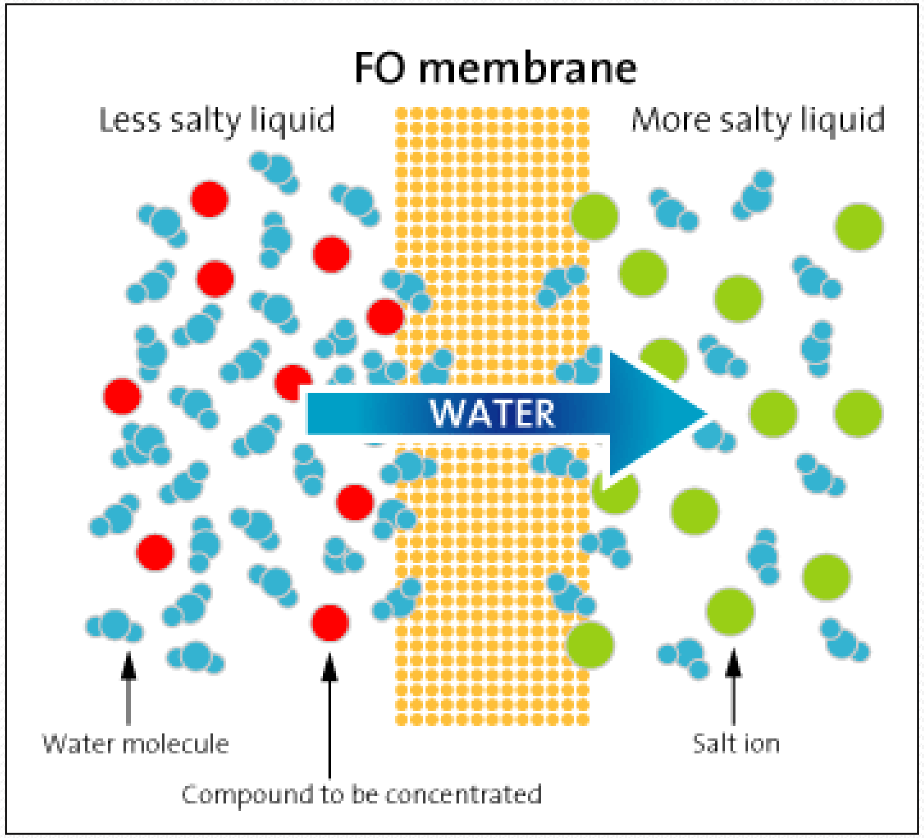


SHEX: Solution heat exchanger
DSHEX: Draw solution heat exchanger
DSRC: Draw solution recovery chamber
R.EV: Refrigeration expansion valve
S.EV: Solution expansion valve
S.Pump: solution pump

Forward Osmosis Principle and Applications

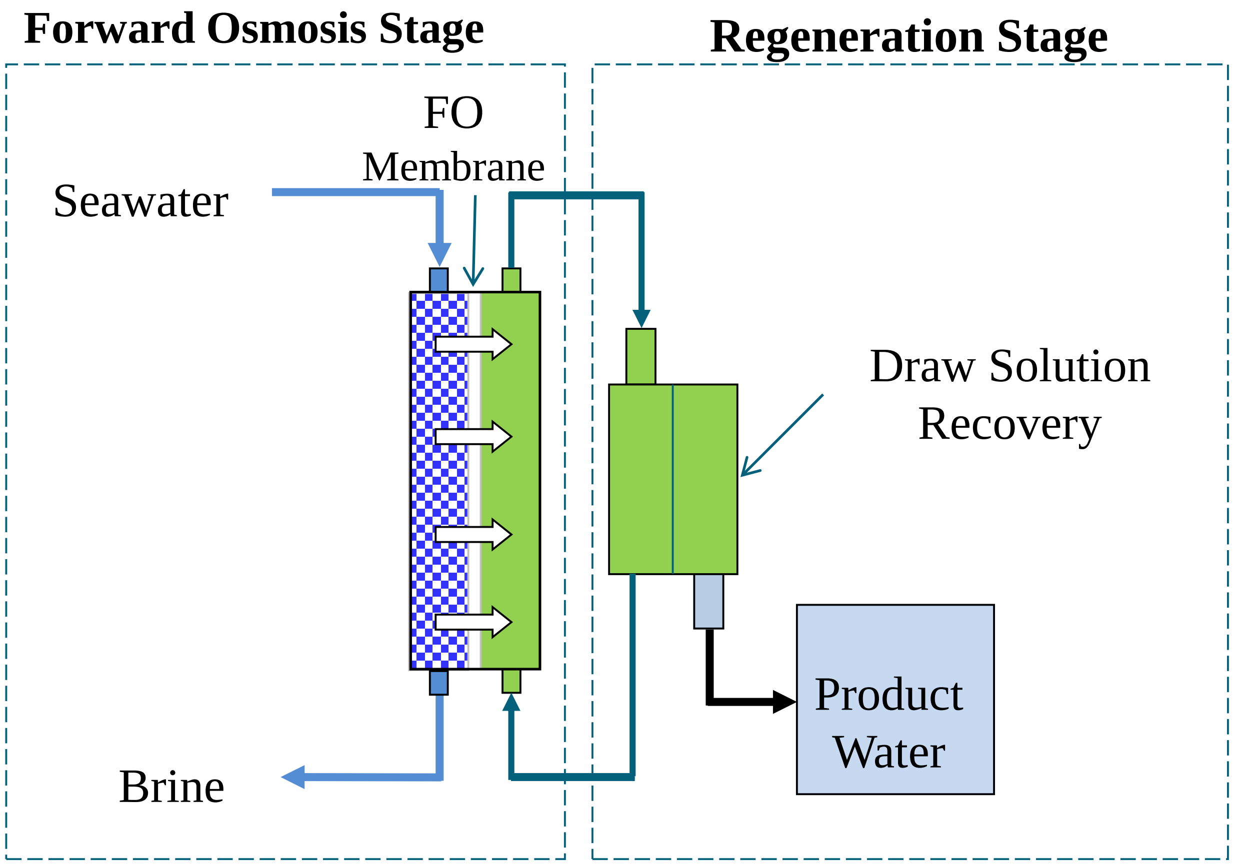
Applications:

- Seawater desalination
- Emergency drinks
- Power generation
- Enhanced oil recovery
- Produced brine treatment
- Fluid concentration
- Water softening
- Water substitution



Solvent Flow in Forward Osmosis

Forward Osmosis Technology for Seawater Desalination



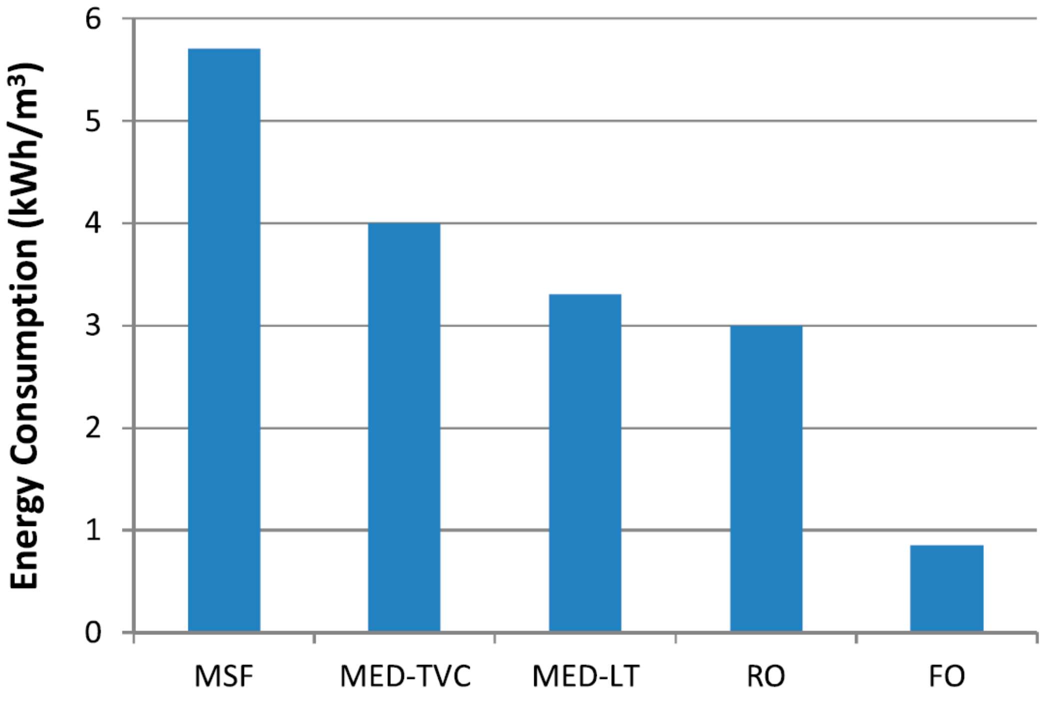
Waste Heat Utilization:
Comparison between Conventional Thermal Desalination Technologies and FO Process on Low-Grade Heat Utilization

Technology	Gain Output Ratio	Water Production Rate (tonne/h)
Multi-Stage Flash Distillation (MSF)	8 – 12	64.9 – 97.4
Multi Effect Distillation (MED)	6 – 12	105.6 – 211.1
Forward Osmosis (FO)	10 – 14.8	222.4 – 329.2

Thermodynamic Analysis was conducted using UNISIM together with OLI property package
Source: M.Y. Park et al., *Applied Energy, 154 (2015), 51–61*.

Equivalent Work:

Energy Consumption by Desalination Technologies



Source: McGinnis and Elimelech, Desalination, 207 (2007), 370-382.

Comparison between RO and FO Membrane Technologies

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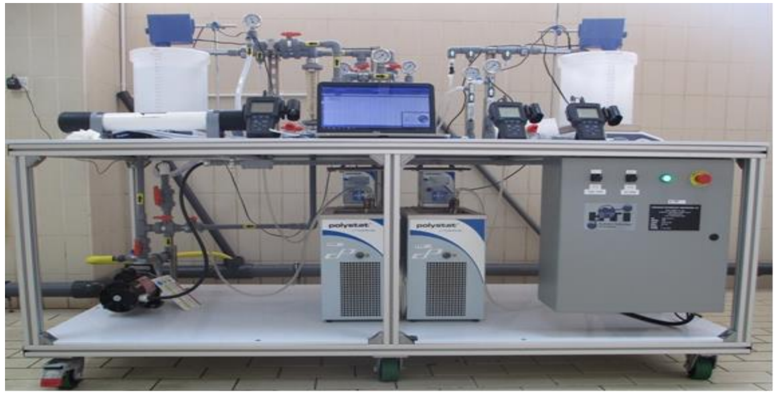
Sort	Reverse Osmosis (RO)	Forward Osmosis (FO)
Driven Pressure	High hydraulic pressure	Osmosis pressure difference
Water Recovery	30-50%	At least 75%
Scaling and Fouling	Seriously	Hardly
Energy Consumption	High energy demand	Low energy demand
Equipment [sic]	High-pressure pumps; Energy recovery unit; Resistant high-pressure pipelines; High investment in equipment [sic]	Low investment in equipment
Environment Effect	Harmfully	Friendly
Modules	Compression resistance	Without particular desire
Application	Normal separation system	Temperature- sensitive system; Pressure-sensitive system; Renewable energy; Controlled release of drug

Development of FO Technologies for Desalination at KISR

Lab-Scale FO Test Unit

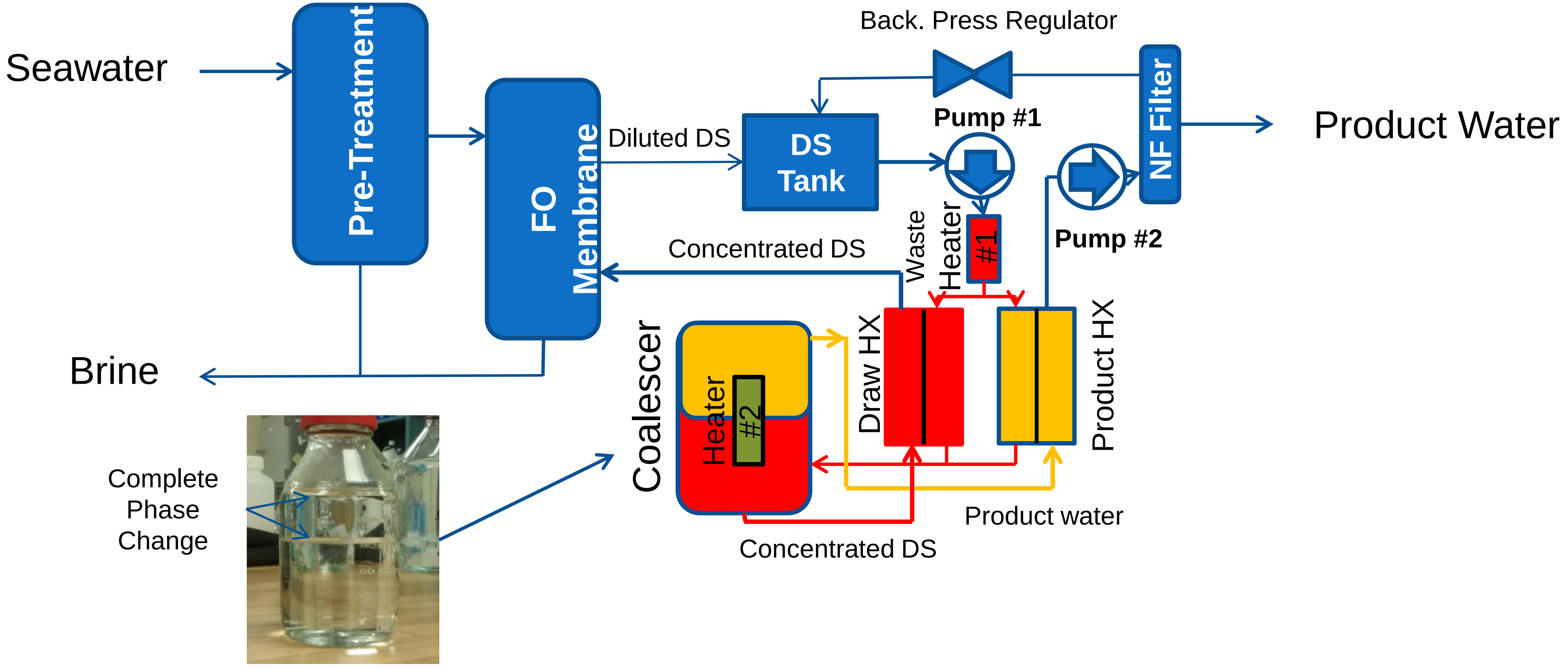


Semi-Pilot FO Test Unit

FO Pilot Test Plant

- KISR has done extensive research in collaboration with international partners in the areas of development of FO membrane technologies for seawater desalination.
- Efforts involve the development of the state of the art of several FO membrane technologies.
- <u>KISR Vision:</u> establishment of FO membrane desalination technologies powered by renewable energy on a commercial-scale.

FO Pilot-Scale Investigations at KISR



Schematic Diagram of the investigated FO Pilot Plant Test Unit at KISR

FO Pilot-Scale Investigations at KISR (cont'd)

Investigated FO Pilot Plant Test Unit at KISR

FO Pilot-Scale Investigations at KISR (cont'd)

Pre-Treatment System

Commercial-Scale FO Membrane

Post-Treatment System

Control & Data Acquisition Systems

Investigated FO Pilot Plant Test Unit at KISR

FO Pilot-Scale Results:

Main Findings & Overall Experimental Results

- **Main Findings:**
  - High water recovery and high purity water production using a single FO membrane in a single-stage operation.
  - The total energy consumption was 3.0 kWh/m^3. The PLC and the control panel consumed around 1.4 kWh/m^3 of energy.
  - It was recommended to integrate the FO process with low-grade heat source such as solar energy and waste-heat.
  - Techno-economical study showed that the proposed systems is feasible for commercial-scale applications (1 MIGD).
- **Overall Experimental Results:**
  - Feed TDS = 45,400 ppm, Product TDS = 100 ppm, Salt Rejection = 99.8%, and Water recovery = 50%

FO Pilot-Scale Results (cont'd):

Major Physiochemical Analysis of Water Samples for Feed and Product

Parameter	Units	Feed	Product Water
EC	mS/cm	58.6	0.2
TDS	mg/L	45,400	100
Ca^{2+}	mg/L	936	4
Mg^{2+}	mg/L	1,312	1
Na^{+}	mg/L	13,560	22
$(SO_4)^{2-}$	mg/L	2,000	0
$(HCO_3)^{-}$	mg/l as $CaCO_3$	130.8	2.4
Cl^{-}	mg/L	25,100	77
NO^{3-}	mg/L	4	2
F^{-}	mg/L	1.70	0.50
Cu^{2+}	mg/L	<0.05	<0.05
Cr^{6+}	mg/L	<0.05	<0.05
Fe	mg/L	<0.05	<0.05
SiO_2	mg/L	23.1	1.2

Simulation Tools for the Integrated System

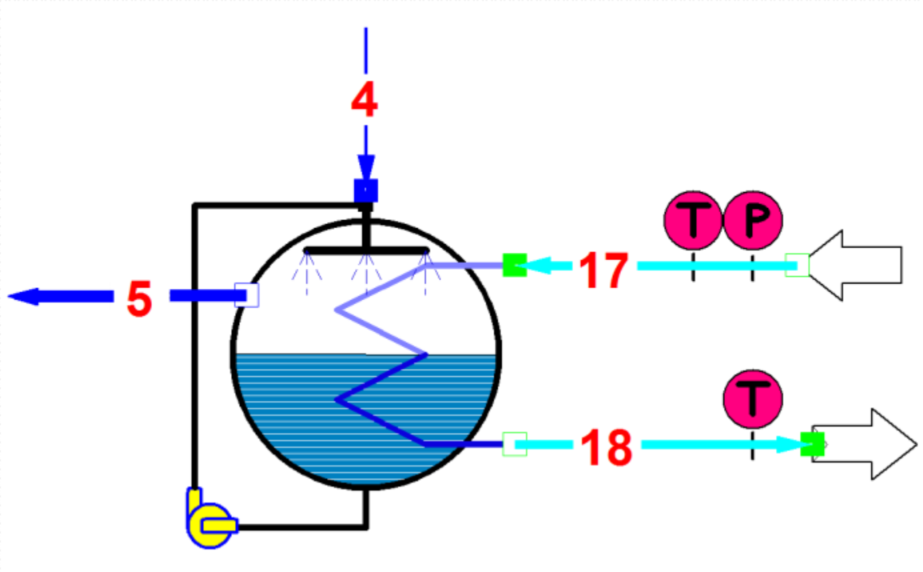
Process Simulation Environment IPSEpro

- IPSEpro calculates heat and mass balances and predicts design and off-design performance
- Monitor and optimize plant performance.
- Plan modifications and upgrades of existing plants.

- EES is a general equation-solving program to solve coupled non-linear algebraic and differential equations.
- EES provides high-accuracy thermodynamic and transport properties for hundreds of substances.

Evaporator Simulation

heat and mass balances



$$\dot{m}_4 = \dot{m}_5 \quad \text{and} \quad \dot{m}_{17} = \dot{m}_{18}$$

mass balance

$$\dot{Q}_{trans} = \dot{m}_4 \times \left(h_5 - h_4\right)$$

$$\dot{Q}_{trans} = \dot{m}_{17} \times \left(h_{17} - h_{18}\right)$$

energy balance

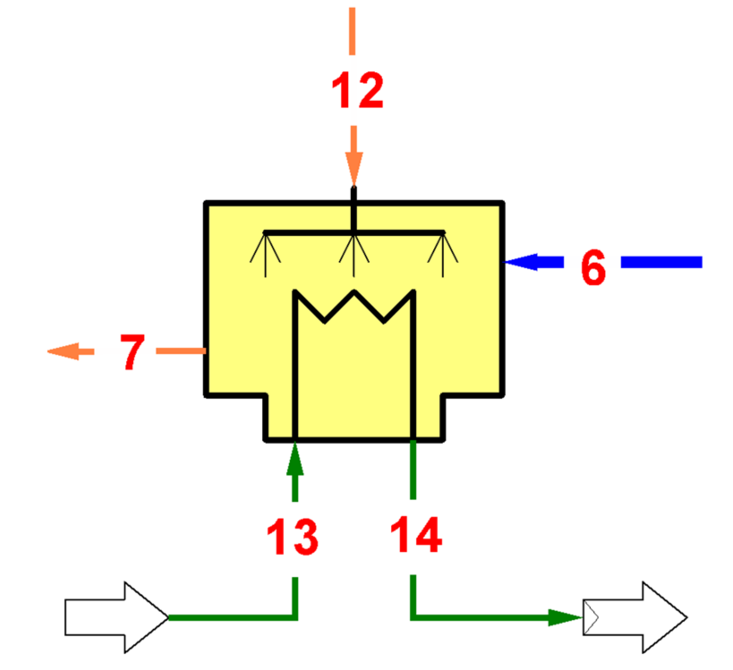
$$\dot{Q}_{trans} = \left(UA\right)_{evap} \left(\Delta T_{LMTD}\right)_{evap}$$

$$\left(\Delta T_{LMTD}\right)_{evap} = \left(\frac{\delta t_1 - \delta t_2}{\ln\left(\delta t_1 / \delta t_2\right)}\right)_{evap}$$

heat transfer

Absorber Simulation

heat and mass balances



$$\dot{m}_{12} + \dot{m}_6 = \dot{m}_7$$

$$\dot{m}_{13} = \dot{m}_{14}$$

$$\dot{m}_{12} \times z_{12} = \dot{m}_7 \times z_7$$

mass balance

$$\dot{Q}_{trans} = \dot{m}_6 h_6 + \dot{m}_{12} h_{12} - \dot{m}_7 h_7$$

$$\dot{Q}_{trans} = \dot{m}_{13} \times \left(h_{14} - h_{13}\right)$$

energy balance

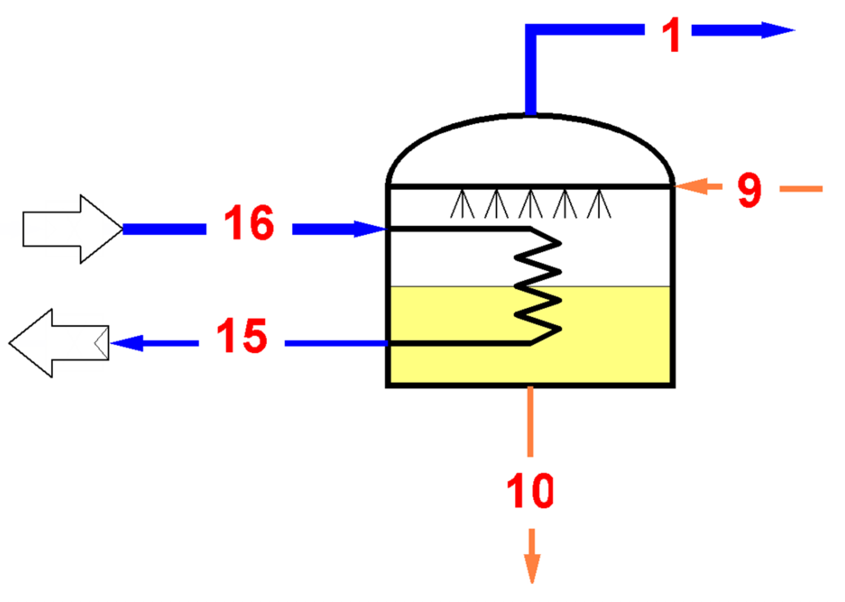
$$\dot{Q}_{trans} = \left(UA\right)_{abs} \left(\Delta T_{LMTD}\right)_{abs}$$

$$\left(\Delta T_{LMTD}\right)_{abs} = \left(\frac{\delta t_1 - \delta t_2}{\ln\left(\delta t_1 / \delta t_2\right)}\right)_{abs}$$

heat transfer

Generator Simulation

heat and mass balances



$$\dot{m}_9 = \dot{m}_1 + \dot{m}_{10}$$

$$\dot{m}_{16} = \dot{m}_{15}$$

$$\dot{m}_9 \times z_9 = \dot{m}_{10} \times z_{10}$$

mass balance

$$\dot{Q}_{trans} = \dot{m}_1 h_1 + \dot{m}_{10} h_{10} - \dot{m}_9 h_9$$

$$\dot{Q}_{trans} = \dot{m}_{16} \times \left(h_{16} - h_{15} \right)$$

energy balance

$$\dot{Q}_{trans} = \left(UA \right)_{gen} \left(\Delta T_{LMTD} \right)_{gen}$$

$$\left(\Delta T_{LMTD} \right)_{gen} = \left(\frac{\delta t_1 - \delta t_2}{\ln\left(\delta t_1 / \delta t_2 \right)} \right)_{gen}$$

heat transfer

Simulation Results

Item	Value	Unit	Description
AC Capacity	500	TR	The cooling capacity of the system
A_a	389.7	m^2	Absorber heat transfer area
A_c	138.6	m^2	Condenser heat transfer area
A_d	173.2	m^2	Desorber heat transfer area
A_e	458.5	m^2	Evaporator heat transfer area
A_{shx}	25.66	m^2	Solution heat exchanger heat transfer area
A_{tot}	1186	m^2	Total heat transfer area
COP	0.692	-	Coefficient of performance of the absorption system
η_{pump}	0.8	-	Pumps efficiency
P_{high}	12.0	kPa	Desorber pressure
P_{low}	0.697	kPa	Absorber pressure

Simulation Results (cont'd)

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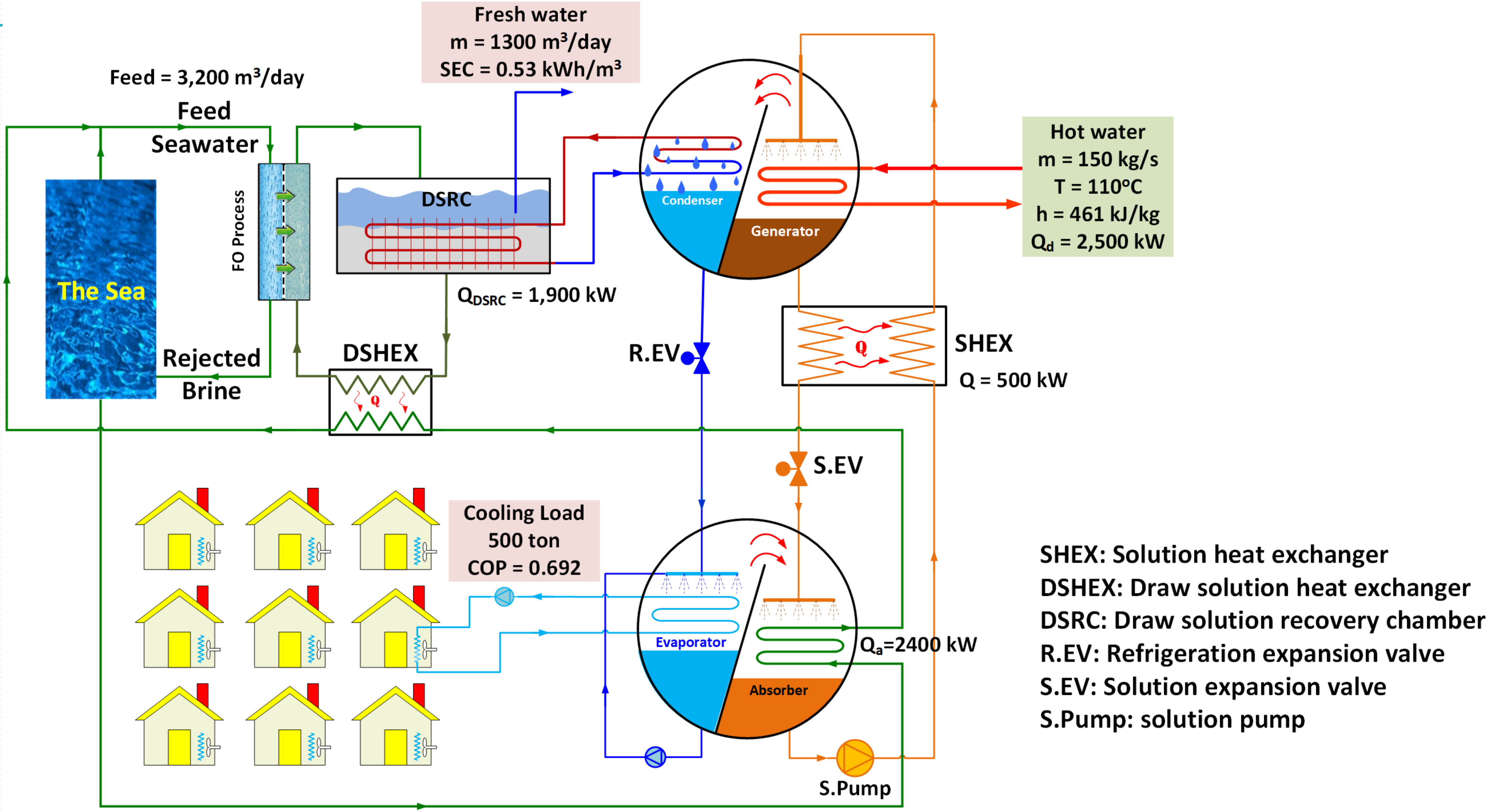
Item	Value	Unit	Description
$\dot{Q}_a$	2420.1	kW	Absorber heat transfer
$\dot{Q}_c$	1879.6	kW	Condenser heat transfer
$\dot{Q}_d$	2541.2	kW	Desorber heat transfer
$\dot{Q}_e$	1758.4	kW	Evaporator heat transfer
$\dot{Q}_{FW}$	3222	m^3/day	Amount of feed water
$\dot{Q}_{PW}$	1289	m^3/day	Amount of product water
Q_{TR}	35	kWh/m^3	Specific energy of the thermal recovery system
Rec	0.4	-	FO system recovery
SEC	0.534	kWh/m^3	FO system-specific energy consumption
T_H	383.2	K	High temperature of heat source
$\dot{W}_{Abs\ Pump}$	0.075	kW	Pumping power of the absorption system
$\dot{W}_{FO\ Pump}$	23.31	kW	Pumping power of the FO system


Fresh water
m = 1300 m³/day
SEC = 0.53 kWh/m³
Feed = 3,200 m³/day
Feed
Seawater
FO Process
DSRC
The Sea
Q_DSRC = 1,900 kW
Rejected
Brine
DSHEX
Q
Condenser
Generator
Hot water
m = 150 kg/s
T = 110°C
h = 461 kJ/kg
Q_d = 2,500 kW
R.EV
SHEX
Q
Q = 500 kW
S.EV
Cooling Load
500 ton
COP = 0.692
Evaporator
Absorber
Q_a=2400 kW
S.Pump
SHEX: Solution heat exchanger
DSHEX: Draw solution heat exchanger
DSRC: Draw solution recovery chamber
R.EV: Refrigeration expansion valve
S.EV: Solution expansion valve
S.Pump: solution pump

Simulation Results (cont'd)

- The equations of the mathematical modeling were solved using EES software, and the results were promising.
- The invented system can provide fresh water and a cooling effect through chilled water.
- It utilizes hot water at 110°C and consumes 2550 kW of low-temperature thermal energy; the system can produce 1300 m^3/d of desalted water at a specific energy consumption of 0.54 kWh/m^3.

Simulation Results (cont'd)

- It can also provide 500 RT (1760 kW, 250 ton/h of chilled water at 5 ^{o}C) of cooling effect, typically consuming 176 kW of electric power if a vapor compression chiller of COP of 10 is used.
- The system can also raise the feed water temperature by 14^{o}C, which enhances the FO system's performance.

Conclusions (cont’d)

- The waste heat generated from this cycle is then effectively utilized to power the FO-TR desalination system. Generally, the following points can be concluded:
  - The system demonstrates high energy efficiency, with a remarkably low specific energy consumption of 0.54 kWh/m³ for desalination.
  - With a thermal energy input of 2550 kW, the system can produce 1300 m³/d of desalted water and 500 RT of cooling effect.
  - The system efficiently recovers waste heat, raising the feed water temperature by 14 °C, significantly enhancing the performance of the FO system.

Conclusions (cont'd)

- The system is technically feasible and highly efficient, as evidenced by comprehensive mathematical modeling and simulation results.
- The patented technology **(US 11,407,659 B1)** leverages low-grade heat sources, such as solar energy or waste heat from power plants, to operate a LiBr-VAC, producing chilled water for air conditioning.

THANK YOU
for your time

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