PROSIMPLUS APPLICATION EXAMPLE

SEAWATER DESALINATION

EXAMPLE PURPOSE
This example presents two seawater desalination technologies. One is based on distillation and the other one on membrane filtration (with the serial and/or parallel association of membrane filters). The purpose of this example is to present these technologies and compare their performances.

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CORRESPONDING PROSIMPLUS FILES	
	PSPS_EX_EN-Distillation.pmp3
	PSPS_EX_EN-V1-1-Stage.pmp3
	PSPS_EX_EN-V2-2-Stages-Series.pmp3
	PSPS_EX_EN-V3-2-Stages-Parallel.pmp3
	PSPS_EX_EN-V4-Hybrid-Version.pmp3
	PSPS_EX_EN-V5-1-Stage-ERD.pmp3
	PSPS_EX_EN-V6-Hybrid-Version-ERD.pmp3

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1 Introduction

In some places in the world, clean water production is a real challenge. It is not possible or insufficient to draw water from groundwater or rivers. Moreover, 97.5 % of the world's water resources are made up of seawater or brackish water (unfit for human drinking consumption). In this context, the seawater desalination is an interesting process to produce drinking water.

To achieve the seawater desalination, two major technologies are available:

- Distillation: this process consists in boiling seawater or brackish water concentrated in salt in order to extract drinking water in the vapor state. Then, this steam is condensed. This type of process is very energy-intensive because it is based on the vaporization and condensation of water (the heat of vaporization of water is significant ≈ 2,500 kJ/kg). For these reasons, energy recovery is implemented to limit the energy consumption of the process. One of the strategies for reducing energy consumption is to « stagger » the water vaporization into several effects: this type of process is called the multi-effect distillation [DAN03]. Several cells ("flashes") are placed one after another. The energy contained in the vaporized stream (steam) of drinking water is transmitted to the next cell using the condensation through a heat exchanger.

- Filtration: this process is based on the use of semi-permeable membranes. The operating principle of membrane filters was detailed in the example PSPS_EX_EN-Filtration. To summarize, under the effect of a pressure higher than the osmotic pressure of the mixture, species can cross the membrane from the retentate side to the permeate side. The separation or purification of a stream with a membrane filter generates 2 outlet streams: a retentate (the retained species) and a permeate (the species having crossed the membrane).

For membrane filtration, 6 configurations (versions) of membrane filters are presented:

- One filtration stage (V1);
- Two filtration stages in series, *i.e.*, a second filter is placed at the retentate side outlet (V2)
- Two filtration stages in parallel, *i.e.*, a second filter is placed at the permeate side outlet (V3);
- A hybrid version (« industrial » version) with an intermediate configuration with filters in parallel and in series (V4);
- One filtration stage with an energy recovery device (V5);
- A hybrid version with an energy recovery device (V6).

The purpose of this example is to compare all the processes in order to determine the advantages and disadvantages of the different technologies. To perform this comparison, the feed parameters (flowrate and composition) remain unchanged between the different cases studied. Furthermore, for comparison purpose, the global transfer area remains the same. Finally, the recovery rate, rejection rate and specific consumption (see Appendix: Filtration results definition) will be calculated and compared.

2 COMPOUNDS

The compounds considered in the simulation, their chemical formulas and CAS[1] numbers are presented in the following table. Pure components physical properties are extracted from the ProSimPlus standard database [WIL21].

Compound	Chemical formula	CAS number[1]
WATER	H_2O	7732-18-5
SODIUM CHLORIDE	NaCl	7647-14-5

To simplify, only sodium chloride (NaCl) is considered for seawater modeling for the different cases studied. It is possible to model more complex systems with several electrolyte species thanks to an adapted thermodynamic model.

[1]CAS Registry numbers® are the intellectual property of the American Chemical Society and are used by ProSim SA with the express permission of ACS. CAS Registry Numbers® have not been verified by ACS and may be inaccurate

3 THERMODYNAMIC MODEL

The system is composed of an aqueous solution of sodium chloride. Therefore, the thermodynamic profile “Sour water” is used to model this electrolytic solution. This thermodynamic model is adapted to the constraints of molality, pressure and temperature used in the examples presented in this document.

4 OPERATING CONDITIONS

For all of the processes presented in this document, the following parameters will remain unchanged:

- The seawater feed
- The scripts to calculate the average permeability of filtration units;
- The operating conditions of the ERD (Energy Recovery Device);
- The operating parameters of the membrane filters except for the transfer area.

These unchanged parameters are presented below:

- ✓ Process feed

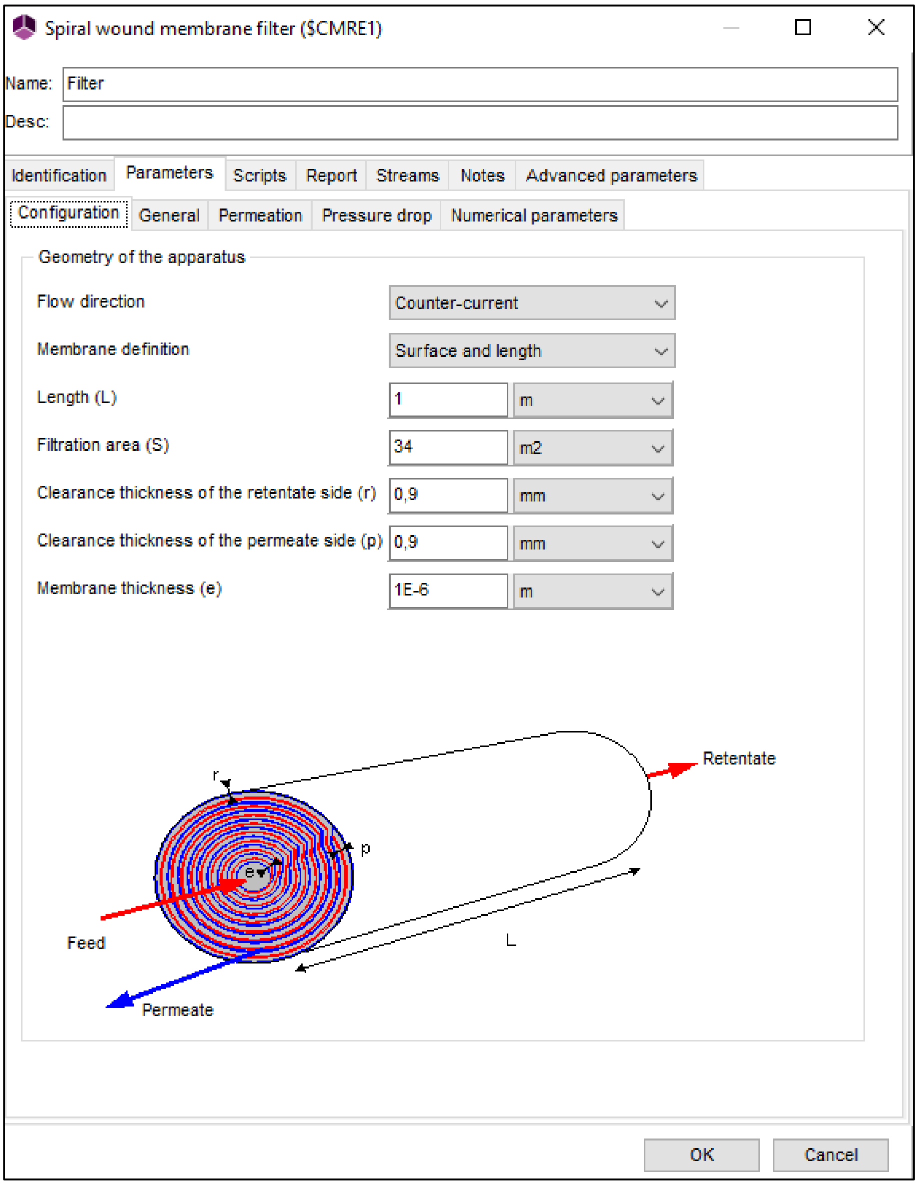
<table>
<tr><th colspan="2"></th><th>Inlet Water NaCl</th></tr>
<tr><td rowspan="2">Mass fraction (%)</td><td>WATER</td><td>96.4</td></tr>
<tr><td>NaCl</td><td>3.6</td></tr>
<tr><td colspan="2">Concentration (g/l)</td><td>36.8</td></tr>
<tr><td colspan="2">Mass flowrate (t/h)</td><td>1.5</td></tr>
<tr><td colspan="2">Temperature (°C)</td><td>30</td></tr>
<tr><td colspan="2">Pressure (atm)</td><td>1</td></tr>
</table>

On earth, the seawater concentration varies classically from 30 to 40 g of sodium chloride per kilogram of water.

- ✓ Spiral wound membrane filter

The configuration of the module is inspired by an industrial filter [DUP20]. The surface of this filter is 34 m². For this desalination example, the total transfer area of the different cases studied will always be equivalent to 34 m² in order to be able to compare the technological solutions.

The configuration of the filter is made throught the 5 tabs presented below:



1. Configuration

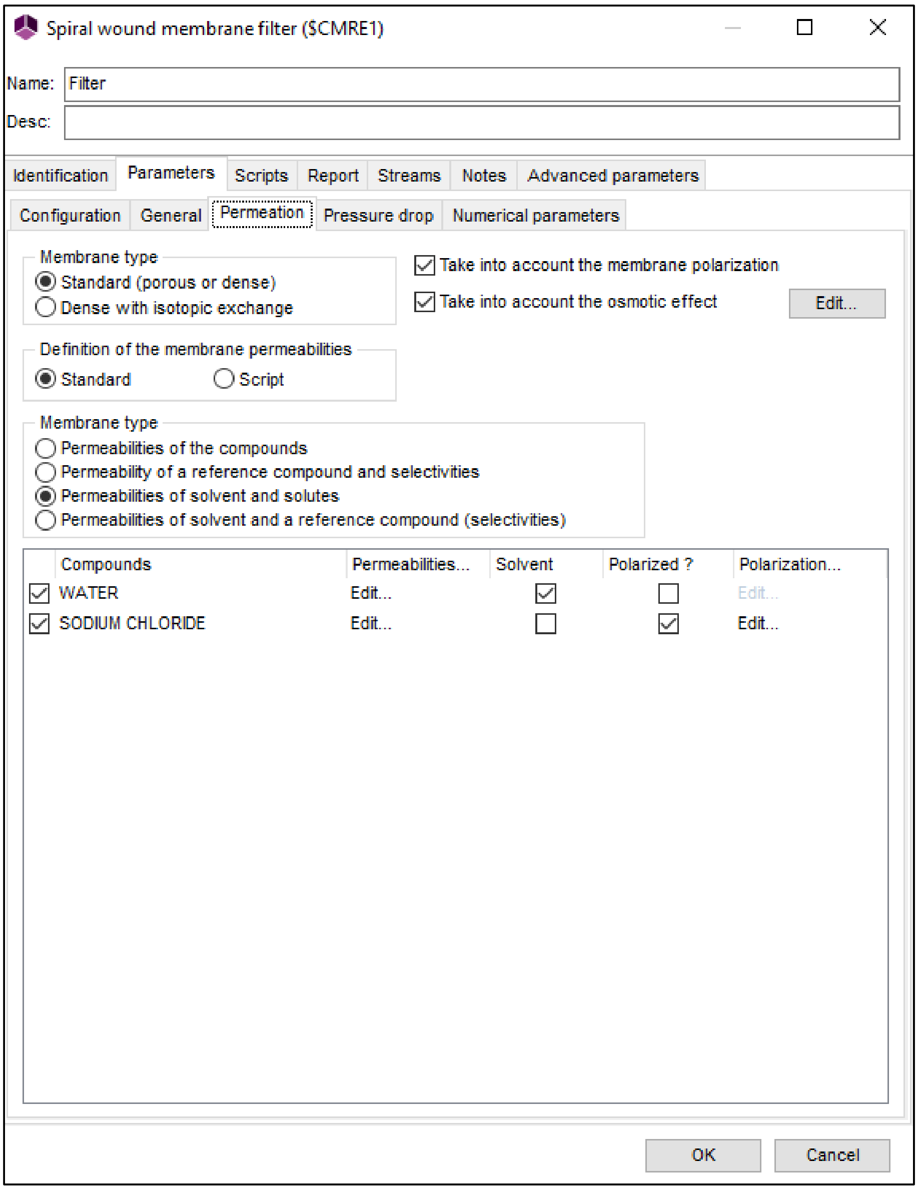
Flow direction	Counter-current
Membrane definition	Surface and length
Length (m)	1
Filtration area (m²)	Variable
Clearance thickness of the retentate side (mm)	0.9
Clearance thickness of the permeate side (mm)	0.9
Membrane thickness (m)	1×10^{-6}

2. General

Temperature (°C)	30
Physical state	Liquid
Permeate side pressure (atm)	1

3. Permeation

All the following checkboxes must be ticked:



For this type of filtration, permeability values can be found in the literature ([MAU74] and [OKA19]).

The default values for the osmotic effect definition are used (calculation of the osmotic pressure by the thermodynamic model).

On the other hand, the values of permeability and polarization for water and sodium chloride are supplied as follows:

Water permeability	
Permeation model	Partial pressure
Definition type	Constant
Type	Volume
Volume permeability (m²/h/bar)	7.1×10^{-10}

NaCl permeability	
Permeation model	Concentration
Permeability (m/s)	1×10^{-7}
NaCl polarization	
Model for the mass transfer coefficient (ki)	Chen and Qin
Di (m²/s)	1×10^{-6}
α	0.031
β	0.9243
γ	0.3495

4. Pressure drop

Default values are used.

5. Numerical parameters

Only the number of cells is changed to 20.

✓ Windows Script

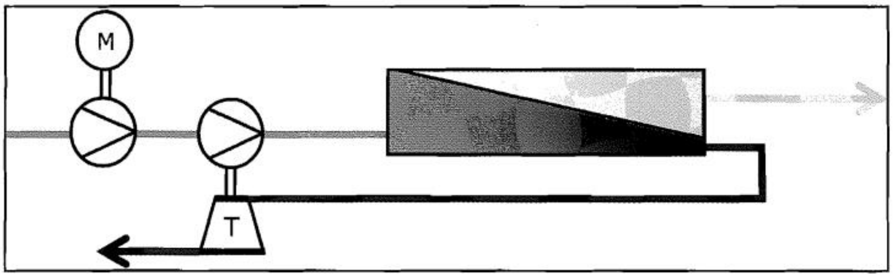
The following script is used in the «Permeability calculation» Windows script module. This script allows to calculate the average permeability and the average osmotic pressure drop of the filter:

```
With CreateObject("Scripting.FileSystemObject")
  ExecuteGlobal .OpenTextFile(Project.ApplicationPath & "Scripts\UnitConversion.vbs", 1).ReadAll()
End With

Function OnCalculation()
  '
  ' Parameters
  Filter_Name = "Filter"
  '
  With Project.Modules(Filter_Name)
    ' Streams
    Set Feed     = .InputStream(1)
    Set Permeate = .OutputStream(2)
    'Osmotic pressure
    Nb_Cells = .GridCellsNumber
    a = (.OsmoticPressureDifferenceProfile(1) + .OsmoticPressureDifferenceProfile(Nb_Cells+1)) / 2
    a = ConvertFromProSim("pressure", a, "bar")
    'Membrane transfer area m2
    S = .TransferTotalArea
  End With
  '
  'Pressure deviation
  b = Feed.Pressure - Permeate.Pressure
  b = ConvertFromProSim("pressure", b, "bar")
  '
  'Permeate flowrate  m3/h
  F = Permeate.VolumeFlowrate
  '
  'Permeability L/m²/h/bar
  Perma2 = F*1000.0/S
  Perma1 = Perma2/(b-a)
  '
  'Save of the parameters
  Module.Parameters(1) = a
  Module.Parameters(2) = b
  Module.Parameters(3) = S
  Module.Parameters(4) = F
  Module.Parameters(5) = Perma1
  Module.Parameters(6) = Perma2

  OnCalculation = True

End Function
```

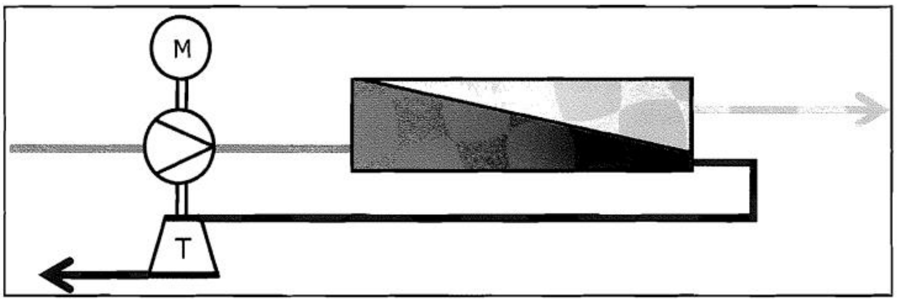
- ✓ ERD

Because of the osmosis effect, the retentate pressure is important. Consequently, the energy consumption of the inlet pump on the retentate side is high. To reduce the power consumption due to the pressure increase, there exists different energy recovery technologies:

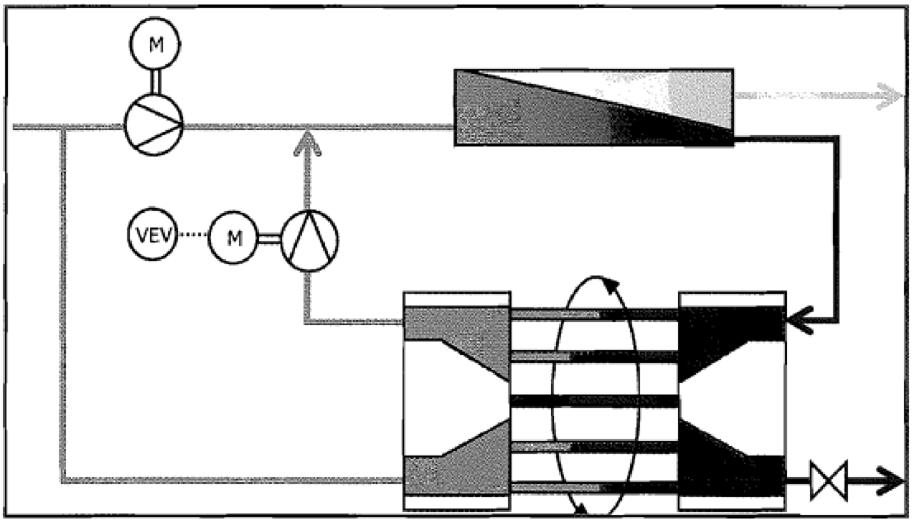
- ➢ Use of a turbopump in series with the high-pressure pump:



- ➢ Use of a Pelton turbine coupled to the high-pressure pump motor:



- ➢ Use of one or more rotary energy exchangers (ERD "Exchanger Recovery Device"):

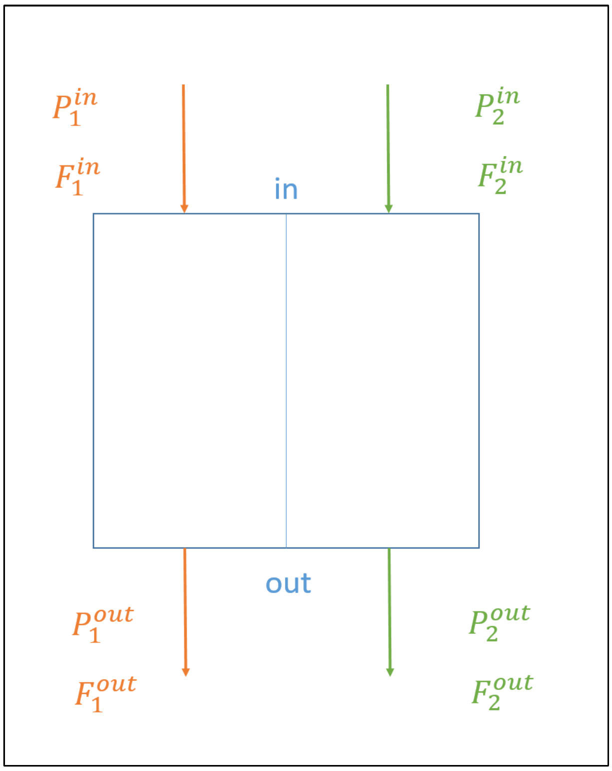


The first two technologies convert hydraulic energy into mechanical energy and then back into hydraulic energy. Pressure exchangers (ERD) directly transfer residual energy from the retentate to the inlet seawater.

For this example, the ERD technology is selected.

The pressure exchanger is a rotating energy recovery device. The pressurized liquid transmits energy during a short period of direct contact between the two fluids. This transfer is done within a rotor. The pressure of the brine (high pressure) is transferred to the seawater feed (low pressure). The rotating device allows the two fluids to be brought into contact and then extracted, avoiding mixing of the two fluids.

Such a device is schematized as follows:



F_i^{in}: Inlet flowrate of fluid i (m³/s)

F_i^{out}: Outlet flowrate of fluid i (m³/s)

P_i^{in}: Inlet pressure of fluid i (Pa)

P_i^{out}: Outlet pressure of fluid i (Pa)

The considered fluids are:

1: seawater

2: retentate

Efficiency is defined as follows:

$$\eta = \frac{F_1^{out} P_1^{out} + F_2^{out} P_2^{out}}{F_1^{in} P_1^{in} + F_2^{in} P_2^{in}}$$

The fluids used in the pressure exchanger are in the liquid state, and the equation is simplified as follows:

$$F_1^{in} \approx F_1^{out}$$

$$F_2^{in} \approx F_2^{out}$$

Finally:

$$\eta = \frac{F_1^{in} P_1^{out} + F_2^{in} P_2^{out}}{F_1^{in} P_1^{in} + F_2^{in} P_2^{in}}$$

In this case, the inlet pressure and molar flow are known for both fluids. Knowing the efficiency of the exchanger and the discharge pressure of the retentate, it is possible to compute the outlet pressure of the sea water:

$$P_1^{out} = \frac{\eta\left(F_1^{in} P_1^{in} + F_2^{in} P_2^{in}\right) - F_2^{in} P_2^{out}}{F_1^{in}}$$

This equation is programmed in the script below implemented in a "Windows Script" module. First, the input streams are copied and pasted to the output. Then, all the variables used are defined and converted into SI units (International System of Units). The calculation of the pressure, the unit conversion and the assignment to the output streams are performed by using the script below.

```
With CreateObject("Scripting.FileSystemObject")
  ExecuteGlobal .OpenTextFile(Project.ApplicationPath & "Scripts\UnitConversion.vbs", 1).ReadAll()
End With

Function OnCalculation()
  '
  set vapor = CreateObject("ProSimPlusScriptableObjects.ProSimStream")
  set liquid = CreateObject("ProSimPlusScriptableObjects.ProSimStream")
  '
  'Exchanger characteristic
  Eta   = 0.96     ' (ERD yield)
  Pout2 = 101325.0 ' (Pa)
  '
  With Module
    ' Copy streams
    .OutputStream(1).CopyFrom(.InputStream(1))
    .OutputStream(2).CopyFrom(.InputStream(2))
    '
    ' Conversions
    Fa = .InputStream(1).VolumeFlowrate
    Fa = ConvertFromProSim("volume flow rate", Fa, "m3/s")

    Fb = .InputStream(2).VolumeFlowrate
    Fb = ConvertFromProSim("volume flow rate", Fb, "m3/s")

    Pa = .InputStream(1).pressure
    Pa = ConvertFromProSim("pressure", Pa, "Pa")

    Pb = .InputStream(2).pressure
    Pb = ConvertFromProSim("pressure", Pb, "Pa")
    '
    ' Output pressures calculation
    Pout1 = (eta*(Fa*Pa+Fb*Pb)-Fb*Pout2)/Fa
    .OutputStream(1).pressure = ConvertToProSim("pressure", Pout1, "Pa")
    .OutputStream(2).pressure = ConvertToProSim("pressure", Pout2, "Pa")
    '
    ' Temperature calculation
    .OutputStream(1).FlashAtHP .OutputStream(1).Temperature, vapRatio, liquidEnthalpy, _
                               vaporEnthalpy, liquidFractions, vaporFractions, equiConstants
    '
    ' Physical state of output stream 2
    .ComputePhysicalState Module.OutputStream(2), vapor, liquid
    .ComputeEnthalpy Vapor
    .ComputeEnthalpy Liquid
    .OutputStream(2).EnthalpyFlux = Vapor.EnthalpyFlux + Liquid.EnthalpyFlux
```

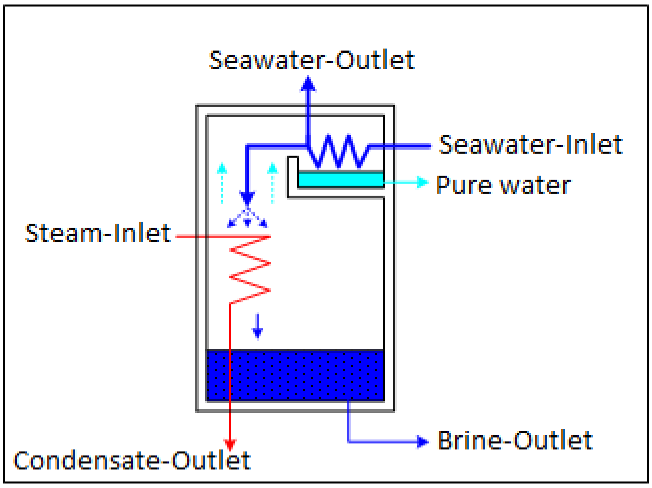
```
  End With

  OnCalculation = True

End Function
```

5 DISTILLATION

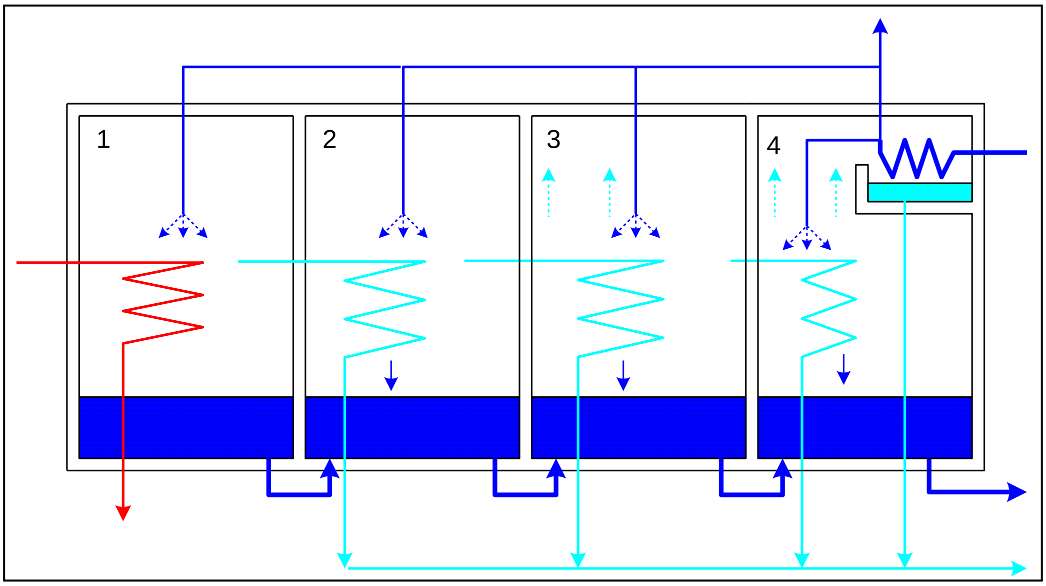
5.1 Process description

A distillation cell consists of two coils and pumps.

The sea water is brought to its boiling point by a first coil (the red coil on the scheme below). Then, this steam is condensed in the second coil (the blue coil). Thus, the brine is in the lower part while the pure water is in the upper part. These two products are evacuated using pumps such as well as the incondensable gases present in the cell.

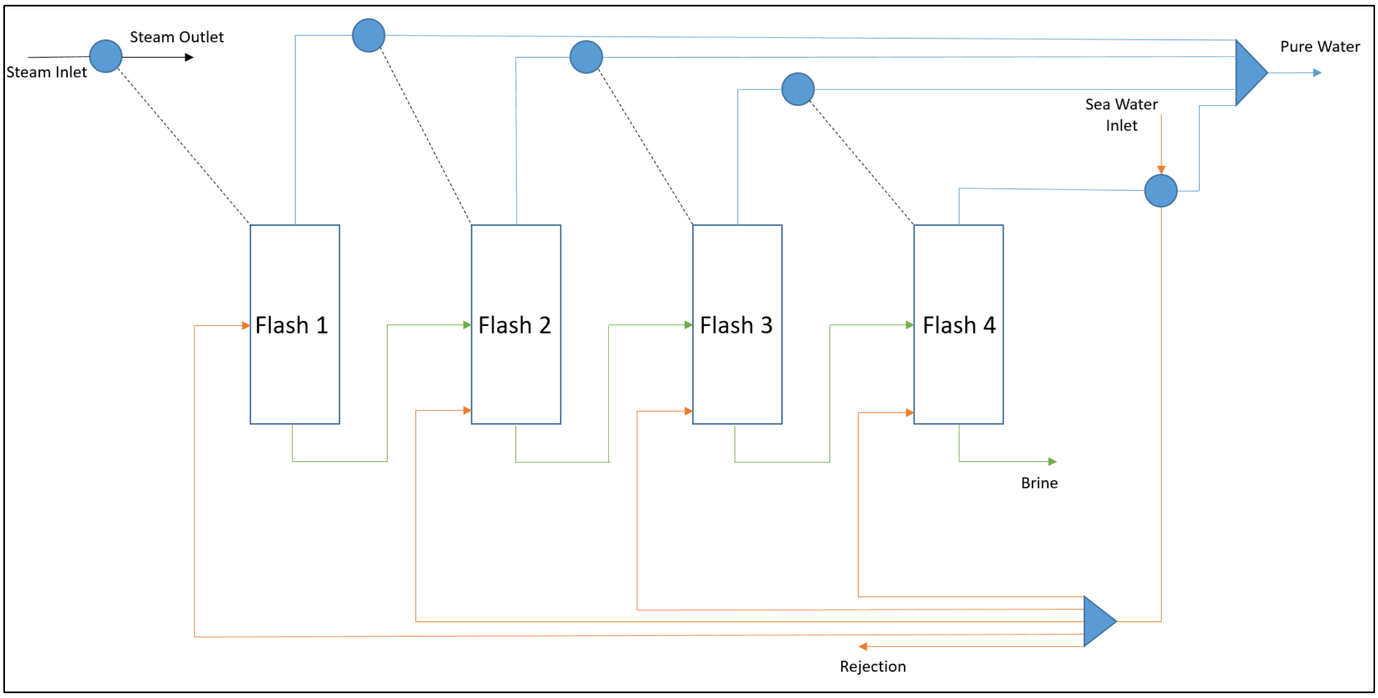


An improvement of this system consists in having different cells in series.



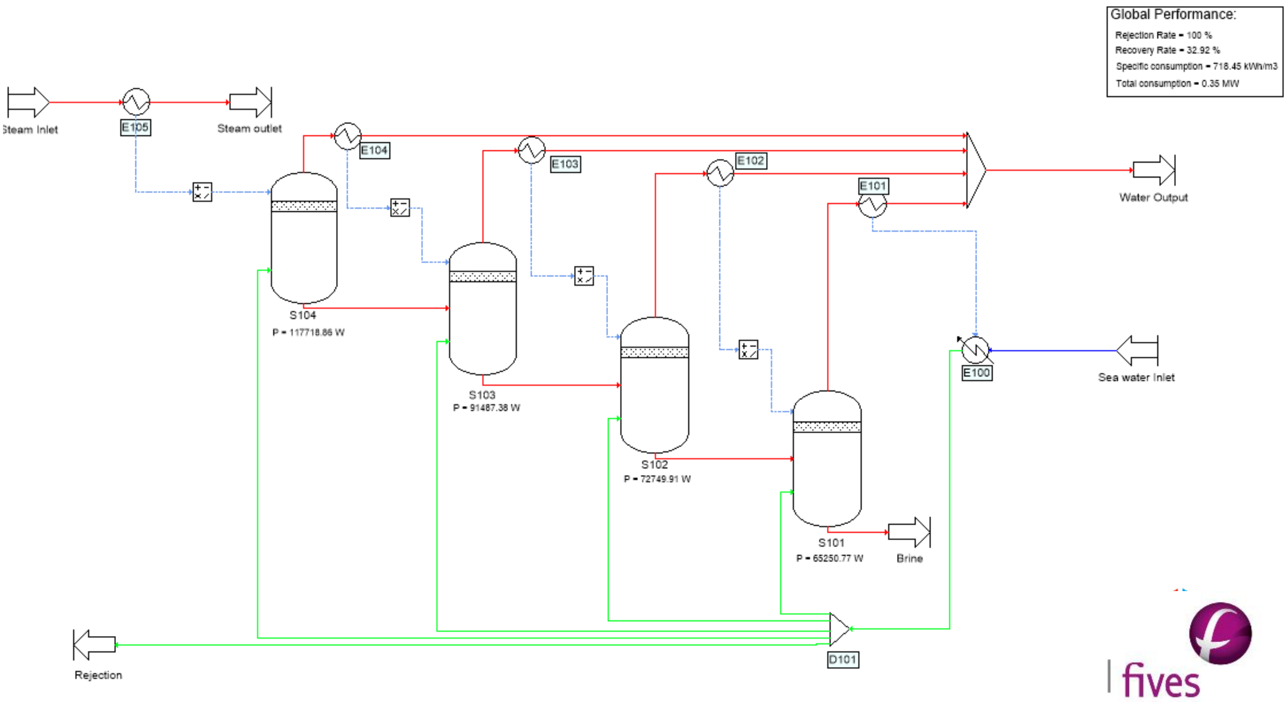
The steam produced in cell n°1 is used in cell n°2 to evaporate seawater. Then, the steam produced in cell n°2 is used in cell n°3 to evaporate the sea water and so on. By adding several cells (effects), it is possible to decrease the energy consumption of the process. This configuration is simulated in the following example. The cells will be modeled by two-phases flashes.

5.2 Process flowsheet



The seawater is preheated using the condensation energy from the outlet of the last cell. The seawater stream is then divided to be injected into the different cells. The flash heat duty is provided by the condensation energy from the previous cells, except for the first cell, whose energy comes from a heat source not modeled in this example.

5.3 Simulation flowsheet



Simulation of seawater desalination by multi-stage distillation

5.4 <u>Operating conditions</u>

✓ Utility feed

		Steam Inlet
Mass fraction (%)	**WATER**	100
	NaCl	0
NaCl Concentration (g/l)		0
Mass flowrate (t/h)		0.1875
Temperature (°C)		Dew point temperature
Pressure (atm)		1

✓ Simple heat exchanger (E100)

Heat duty (kJ/h) (initialization)	-2 000 000

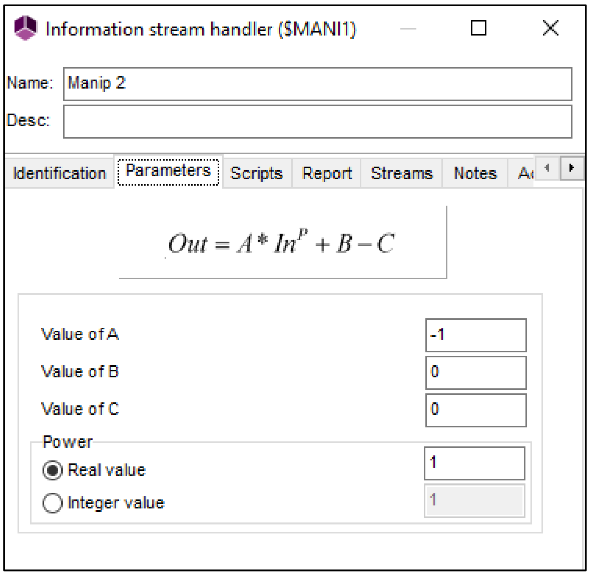
✓ Coolers/heaters

All coolers (E101, E102, E103, E104 and E105) have the following instructions:

Outlet temperature	Bubble point temperature

✓ Information stream handlers

All information stream handlers are configured as follows:



These information stream handlers as well as the information streams are used to simulate the energy recovery. The condensation heat duty of the vapors of the various effects are recovered to heat the flashes.

- ✓ Stream splitter

D101		
Supplied specification	Mass flowrates	
Outlet pressure	Equal to the feed pressure	
Automatically calculated stream	C5	
Streams	**Mass flowrates (t/h)**	**To**
C6	0.09375	S101
C7	0.65625	S104
C8	0.46875	S103
C9	0.1875	S102

- ✓ Liquid-vapor separators

All the flashes (S101, S102, S103, and S104) have the following configuration:

Flash type	Constant pressure and enthalpy flash
Pressure (atm)	1
Heat duty (kJ/h) (initialization)	2 000 000

- ✓ Mixer

The M101 mixer is configured with the default settings.

5.5 Initialization

The calculation sequence is automatically determined by ProSimPlus. A tear stream is detected: "C4" (outlet stream of the "E100" heat exchanger). The following values are used to initiliaze it:

Stream name		C4
From		E100
To		D101
Flowrate (t/h)		1.5
Mass fraction (%)	**WATER**	96.4
	NaCl	3.6
Temperature (°C)		90
Pressure (atm)		1

5.6 Results

✓ Balance

		Sea Water Inlet	**Brine**	**Water Output**	**Rejection**
Mass flowrate (t/h)		1.50	0.94	0.46	0.094
Volume flowrate (m^3/h)		1.47	0.95	0.48	0.09
NaCl concentration (g/l)		36.84	53.42	0	36.84
Mass fraction (%)	**WATER**	0.964	0.946	1	0.964
	SODIUM CHLORIDE	0.036	0.054	0	0.036

- ✓ Performances

Heat duty E105 (kW)	118

Recovered heat (kW)			
S101	S102	S103	S104
91	73	65	62

Recovery rate (%)	30.88
NaCl rejection rate (%)	100
Specific consumption (kWh/m^3)	243.59

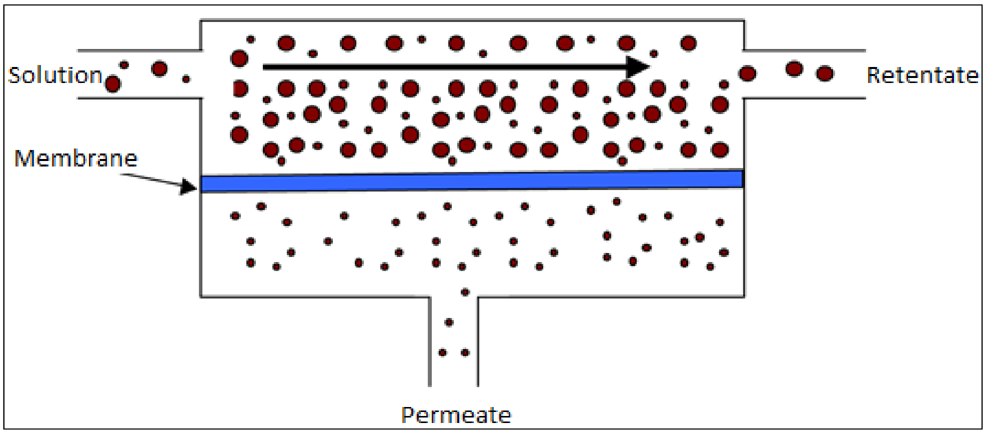
The distillation produces pure water free of salt. The production of pure water is expensive: for a production of 0.48 m^3/h, the total energy consumption is 0.12 MW, so the specific consumption is ≈ 244 kWh/m^3.

6 Filtration

6.1 Process description

This example presents desalination processes using one or more membrane filters and different configurations (series, parallel, hybrid).

Membrane filtration is a physical separation process. It is based on the principle of permeation through a permselective membrane. This permselective membrane, depending on its intrinsic characteristics and its use, constitutes a barrier allowing (or favoring) some transfers of matter and limiting others. The driving forces allowing permeation through the membrane can be diffusion (active transport) but also pressure, concentration, or electrical potential differentials (passive transport).



Depending on the pore size, the filtration membrane is an absolute physical barrier for molecules or particles above a certain size threshold. This is the main advantage of membrane filtration compared to conventional methods (sand filter, activated carbon...). Indeed, these ones do not constitute an absolute filter [CAU17].

With a membrane filtration operation, two streams are generated:

- The retentate (or concentrate) where the molecules and/or particles retained by the membrane are concentrated.
- The permeate, free of retained molecules and/or particles.

The V1 example (see 6.3 one filtration stage) illustrates the seawater desalination by a single membrane filtration stage. Industrially, depending on the specifications (flowrate and concentration specifications), series and/or parallel filter configurations are generally used.

These more complex configurations are sometimes equipped with a power recovery system (ERD "Exchanger Recovery Device") or a Pelton turbine to produce electrical energy (see 4. Operating conditions).

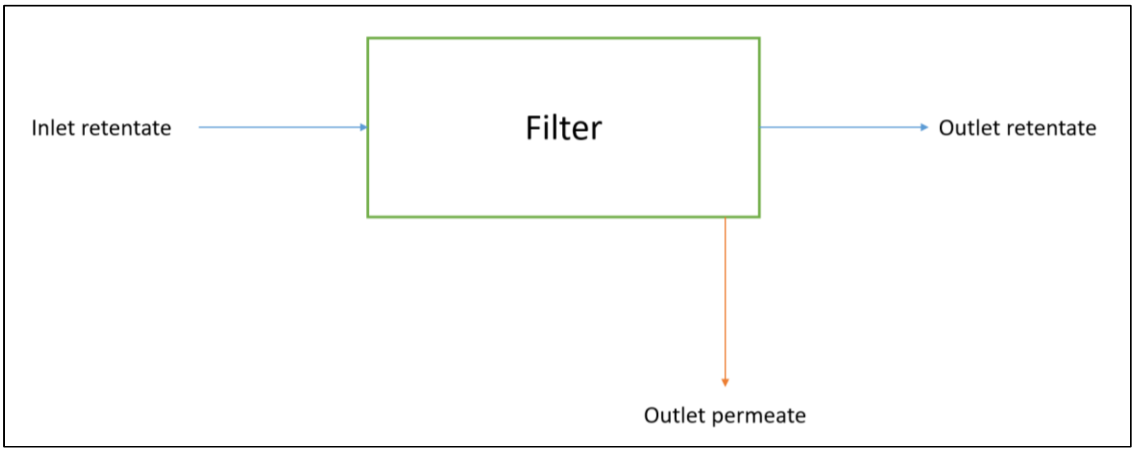
6.2 Process flowsheet

The studied processes of this example are composed of one or more filters. These filters are arranged in:

- Parallel: a second filter is placed on the permeate outlet of the first filter.
- Series: a second filter is placed on the retentate outlet of the first filter.

There are also hybrid configurations between the parallel and series configurations ("industrial" configurations).

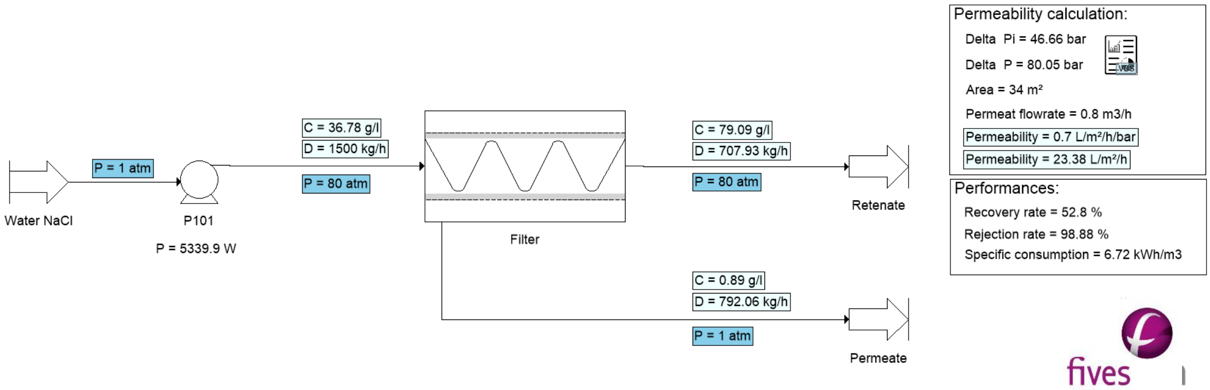
The schematic of a simple filter is provided below:



The stream to be treated enters through the retentate side. It is separated into two streams through the filter. The components passing through the filter exit in the permeate while the retained phase exits on the retentate side.

6.3 One filtration stage

6.3.1 Simulation flowsheet



Simulation of seawater desalination by one filtration stage

6.3.2 Operating conditions

✓ Spiral wound membrane filter

Area (m²)	34

As explained above (see 4 Operating conditions), the configuration of the filter is extracted from a commercial filter [DUP20].

✓ Centrifugal pump

Exhaust pressure (atm)	80
Volumetric efficiency	0.65
Mechanical efficiency	0.95
Electrical efficiency	0.99

6.3.3 Results

✓ Balance

		Feed	Retentate	Permeate
Volume flowrate (m^3/h)		1.47	0.67	0.80
Mass flowrate (t/h)		1.50	0.71	0.79
NaCl Concentration (g/l)		36.78	79.09	0.89
Mass fraction (%)	**WATER**	0.964	0.976	0.9997
	SODIUM CHLORIDE	0.036	0.024	0.0003

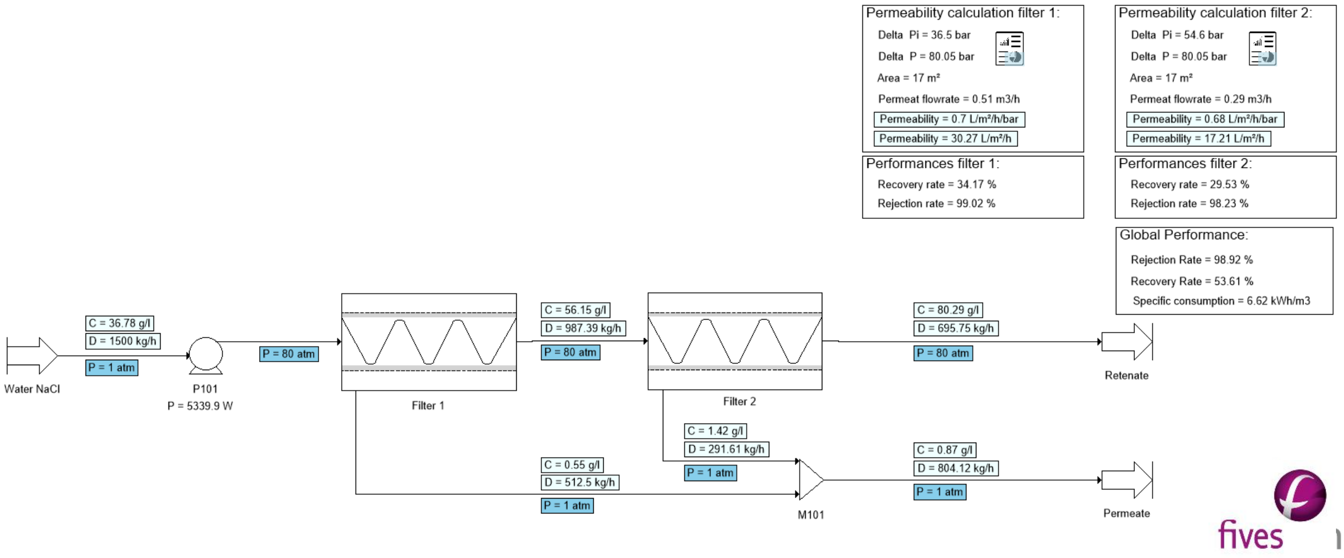
✓ Performances

Recovery rate (%)	52.80
NaCl rejection rate (%)	98.88
Specific consumption (kWh/m^3)	6.72

6.4 Two filtration stages in series

A second filter is placed on the retentate outlet of the first filter.

6.4.1 Simulation flowsheet



Simulation of seawater desalination by two filtration stages in series

6.4.2 Operating conditions

✓ Spiral wound membrane filters

Filter name	Filter 1	Filter 2	Total
Area (m²)	17	17	34

✓ Centrifugal pump

Exhaust pressure (atm)	80
Volumetric efficiency	0.65
Mechanical efficiency	0.95
Electrical efficiency	0.99

6.4.3 Results

✓ Balance

		Feed	Retentate	Permeate
Volume flowrate (m^3/h)		1.47	0.66	0.80
Mass flowrate (t/h)		1.50	0.70	0.80
NaCl concentration (g/l)		36.78	80.29	0.87
Mass fraction (%)	**WATER**	0.964	0.924	0.999
	SODIUM CHLORIDE	0.036	0.076	0.001

✓ Performances

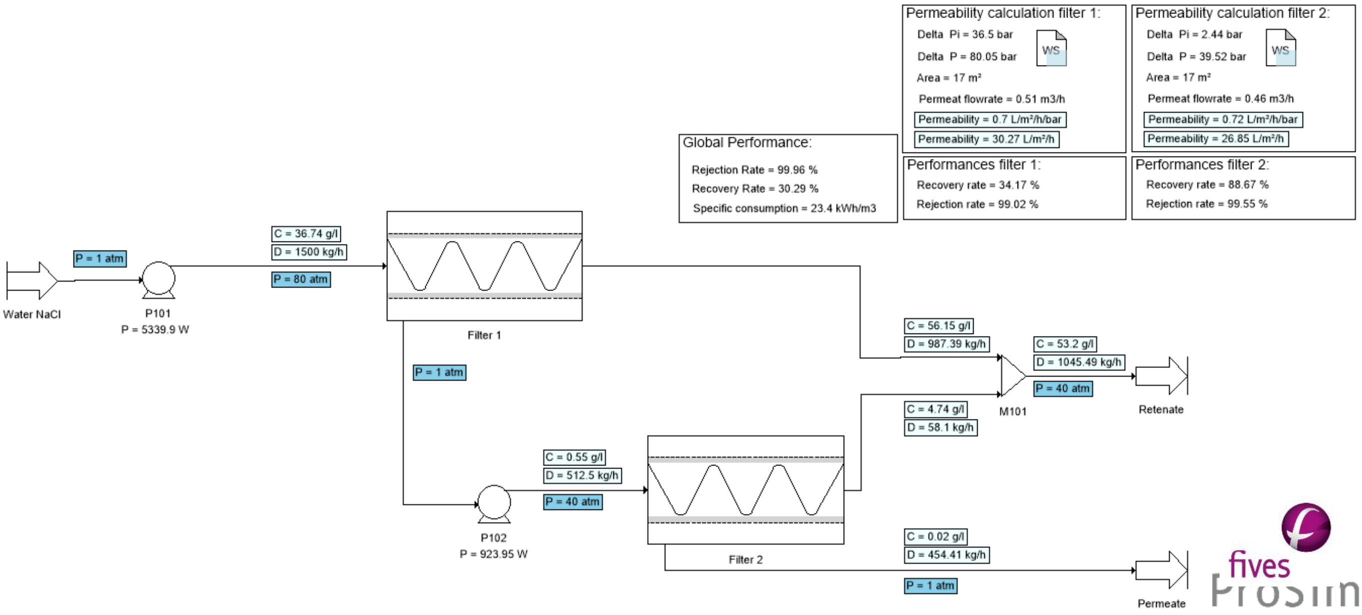
Recovery rate (%)	53.61
NaCl rejection rate (%)	98.92
Specific consumption (kWh/m^3)	6.62

The association in series allows to increase the permeate flowrate produced. But this configuration type tends to degrade the overall quality of the product. In consequence, the NaCl concentration is higher in the permeate stream.

6.5 Two filtration stages in parallel

A second filter is placed on the permeate outlet of the first filter.

6.5.1 Simulation flowsheet



Simulation of seawater desalination by two filtration stages in parallel

6.5.2 Operating conditions

✓ Spiral wound membrane filters

Filter name	Filter 1	Filter 2	Total
Area (m²)	17	17	34

✓ Centrifugal pump (P101)

Exhaust pressure (atm)	80
Volumetric efficiency	0.65
Mechanical efficiency	0.95
Electrical efficiency	0.99

✓ Centrifugal pump (P102)

Exhaust pressure (atm)	40
Volumetric efficiency	0.65
Mechanical efficiency	0.95
Electrical efficiency	0.99

6.5.3 Results

- ✓ Balance

		Feed	Retentate	Permeate
Volume flowrate (m^3/h)		1.47	1.01	0.46
Mass flowrate (t/h)		1.50	1.05	0.45
NaCl concentration (g/l)		36.74	53.2	0.02
Mass fraction (%)	**WATER**	0.964	0.949	0.99998
	SODIUM CHLORIDE	0.036	0.051	0.00002

- ✓ Performances

Recovery rate (%)	30.29
NaCl rejection rate (%)	99.96
Specific consumption (kWh/m^3)	23.4

The parallel association allows to increase the purity. However, the flowrate of the permeate produced decreases.

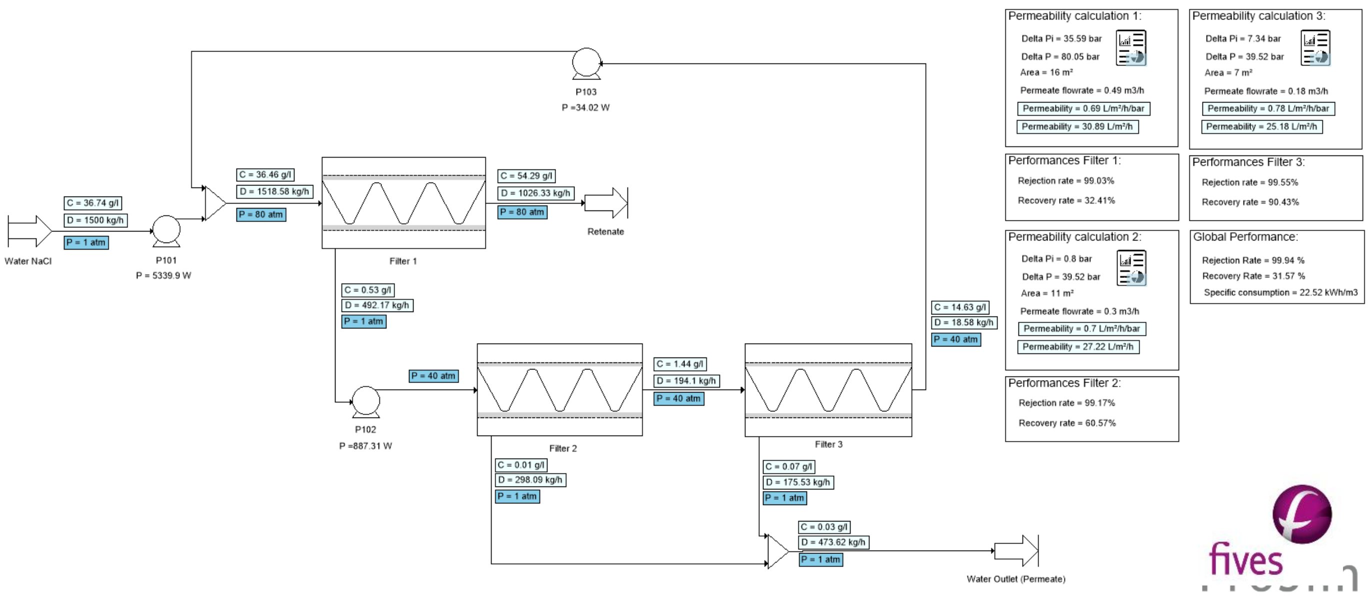
6.6 Hybrid version

The parallel association increases the purity but also decreases the flowrate of the permeate produced. For the series association, the flowrate increases while the purity decreases.

Therefore, it is necessary to find a trade-off between these two configurations in order to achieve the desired purity and flowrate specifications.

The V5 example is based on the Barka II installation [SUE09]. For this industrial plant, the nominal flow rate treated is of 5000 t/h. For the comparison of the performances of the different configurations, the flowrate used to model this case study was set at 1.5 m^3/h (see 4 Operating conditions). Compared to the V5 simulation file, the Barka II installation has more pumps (higher flowrate) and filters (larger surface transfer area) in parallel to treat the nominal flowrate of 5000 t/h (identical configuration).

6.6.1 Simulation flowsheet



Simulation of seawater desalination by a hybrid version

6.6.2 Operating conditions

✓ Spiral wound membrane filters

Filter name	Filter 1	Filter 2	Filter 3	Total
Area (m²)	16	11	7	34

✓ Centrifugal pump (P101)

Exhaust pressure (atm)	80
Volumetric efficiency	0.65
Mechanical efficiency	0.95
Electrical efficiency	0.99

✓ Centrifugal pump (P102)

Exhaust pressure (atm)	40
Volumetric efficiency	0.65
Mechanical efficiency	0.95
Electrical efficiency	0.99

✓ Centrifugal pump (P103)

Exhaust pressure (atm)	80
Volumetric efficiency	0.65
Mechanical efficiency	0.95
Electrical efficiency	0.99

6.6.3 Results

✓ Balance

		Feed	Retentate	Permeate
Volume flowrate (m^3/h)		1.47	0.99	0.48
Mass flowrate (t/h)		1.50	1.03	0.47
NaCl concentration (g/l)		36.74	54.29	0.03
Mass fraction (%)	**WATER**	0.964	0.947	0.99997
	SODIUM CHLORIDE	0.036	0.053	0.00003

✓ Performances

Recovery rate (%)	31.57
NaCl rejection rate (%)	99.94
Specific consumption (kWh/m^3)	22.52

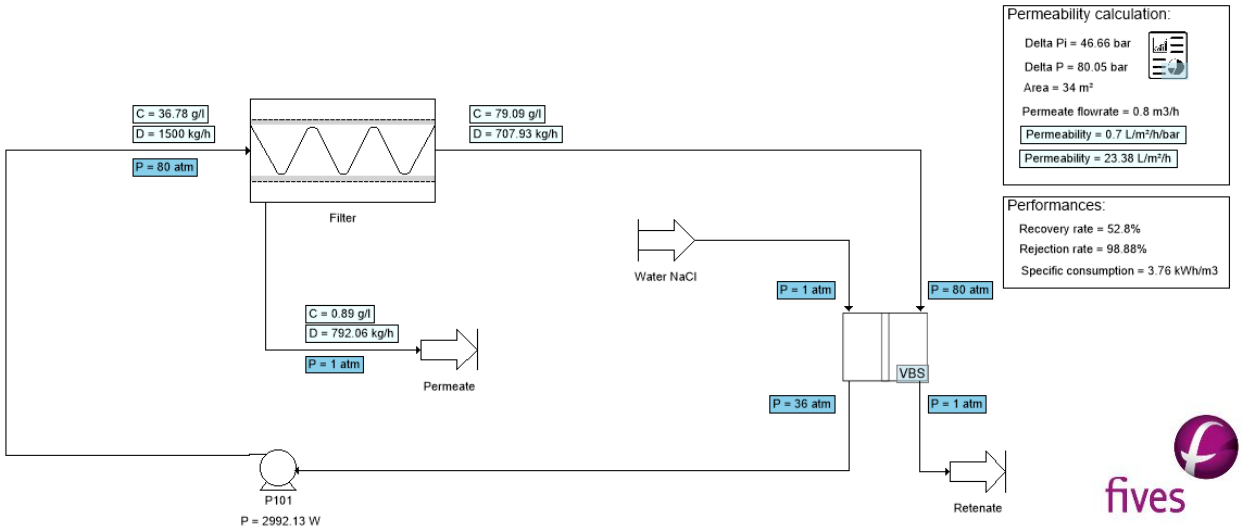
This case is a trade-off between series and parallel filters:

- Better rejection rate and therefore higher purity than the V2 series configuration.
- Better recovery rate than the V3 parallel configuration.

6.7 <u>One filtration stage with energy recovery</u>

As explained previously (see 4 Operating conditions), it is possible to recover hydraulic energy from the retentate stream to reduce the installations electrical consumption. The example presented in this paragraph proposes the addition of a pressure exchanger (ERD).

6.7.1 Simulation flowsheet



Simulation of seawater desalination by one filtration stage with energy recovery

6.7.2 Operating conditions

- ✓ Spiral wound membrane filter

Area (m²)	34

- ✓ Centrifugal pump (P101)

Exhaust pressure (atm)	80
Volumetric efficiency	0.65
Mechanical efficiency	0.95
Electrical efficiency	0.99

- ✓ ERD

The pressure exchanger parameters (ERD) are described in the ERD paragraph of the global operating conditions (see 4 Operating conditions).

6.7.3 Results

✓ Balance

		Feed	Retentate	Permeate
Volume flowrate (m^3/h)		1.47	0.67	0.80
Mass flowrate (t/h)		1.50	0.71	0.79
NaCl concentration (g/l)		36.78	79.09	0.89
Mass fraction (%)	**WATER**	0.964	0.976	0.9997
	SODIUM CHLORIDE	0.036	0.024	0.0003

✓ Performances

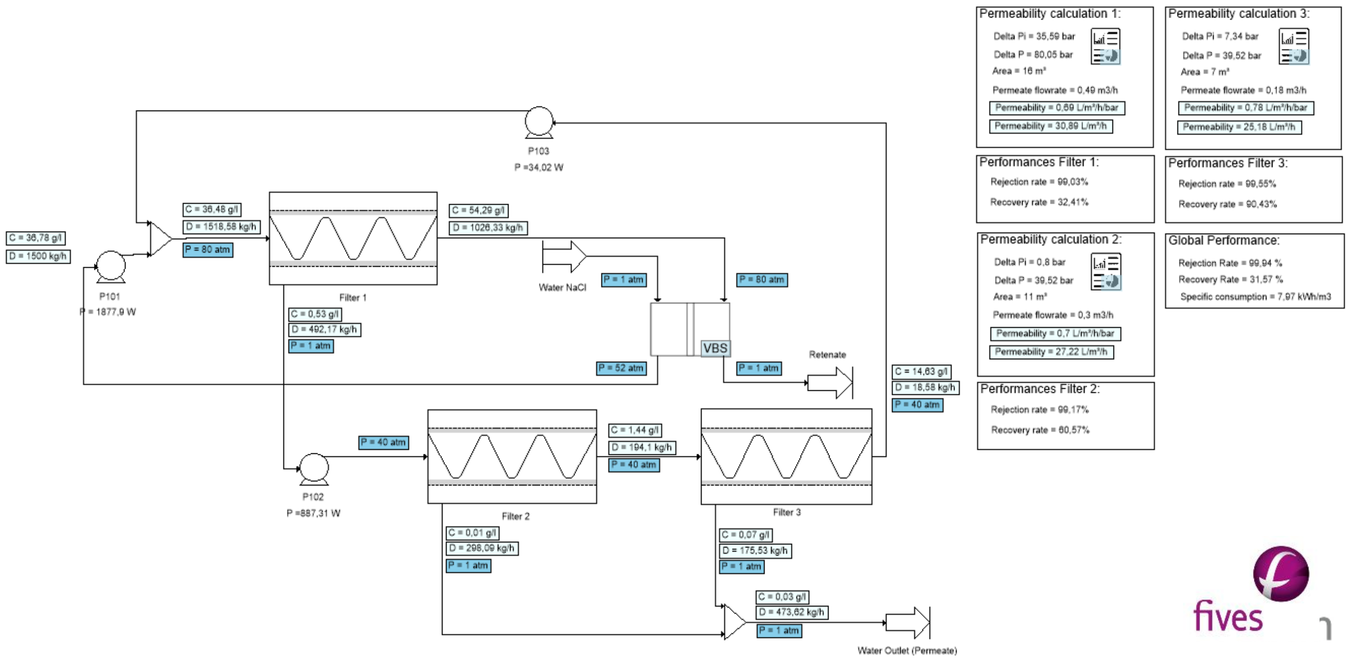
Recovery rate (%)	52.80
NaCl rejection rate (%)	98.88
Specific consumption (kWh/m^3)	3.76

The mass balance, the conversion rate and the sodium chloride rejection rate are unchanged compared to the V1 version without ERD. The pressure exchanger (ERD) only has an influence on the power consumption and thus the specific consumption. Here, it is reduced by 44% compared to the single-stage V1 version.

6.8 Hybrid version with energy recovery

Another version consists of improving the specific consumption of the V5 hybrid version, by using a pressure exchanger (ERD).

6.8.1 Simulation flowsheet



Simulation of seawater desalination by a hybrid version with energy recovery

6.8.2 Operating conditions

✓ Spiral wound membrane filters

Name filter	Filter 1	Filter 2	Filter 3	Total
Area (m^2)	16	11	7	34

✓ Centrifugal pump (P101)

Exhaust pressure (atm)	80
Volumetric efficiency	0.65
Mechanical efficiency	0.95
Electrical efficiency	0.99

✓ Centrifugal pump (P102)

Exhaust pressure (atm)	40
Volumetric efficiency	0.65
Mechanical efficiency	0.95
Electrical efficiency	0.99

✓ Centrifugal pump (P103)

Exhaust pressure (atm)	80
Volumetric efficiency	0.65
Mechanical efficiency	0.95
Electrical efficiency	0.99

✓ ERD

The pressure exchanger parameters (ERD) are described in the ERD paragraph of the global operating conditions (see 4 Operating conditions).

6.8.3 Results

✓ Balance

		Feed	Retentate	Permeate
Volume flowrate (m^3/h)		1.47	0.99	0.48
Mass flowrate (t/h)		1.50	1.03	0.47
NaCl concentration (g/l)		36.74	54.29	0.03
Mass fraction (%)	**WATER**	0.964	0.947	0.99997
	SODIUM CHLORIDE	0.036	0.053	0.00003

✓ Performances

Recovery rate (%)	31.57
NaCl rejection rate (%)	99.94
Specific consumption (kWh/m^3)	7.97

Specific consumption is reduced by 65 % compared to V4 version (see 6.6.3 Hybrid version\Results).

7 Conclusion

Name	Distillation	1 stage	2 stages series	2 stages parallel	Hybrid	1 stage + ERD	Hydrib + ERD
Version		V1	V2	V3	V4	V5	V6
Permeate flowrate (m^3/h)	0.48	0.8	0.81	0.46	0.48	0.8	0.48
NaCl concentration of produced water (g/l)	0	0.89	0.87	0.02	0.03	0.89	0.03
Recovery rate (%)	30.88	52.80	53.61	30.29	31.57	52.80	31.57
Rejection rate (%)	100	98.88	98.92	99.96	99.94	98.88	99.94
Specific consumption (kWh/m^3)	243.59	6.72	6.62	23.4	22.52	3.76	7.97

The combination of filters in series allows to obtain a greater flowrate. In this configuration, the water potability limit is exceeded (according to the WHO (World Health Organization), the threshold is set at 0.2 g/l NaCl [WHO11]). To avoid exceeding this limit, the use of parallel filters can be considered. Nevertheless, this parallel configuration involves a lower permeate flowrate produced.

Finally, the most relevant choice to reach the specifications is to find a trade-off between these two configurations, in series and in parallel. The hybrid configuration presented in this document is used industrially for seawater desalination [SUE09].

In order to reduce energy consumption, a pressure recovery system can be interesting.

The order of magnitude of the specific consumption of seawater desalination units is from 2.5 to 4 kWh/m^3 [OKA19]. This specific consumption has only decreased due to technological advances (more efficient pumps, energy recovery systems, higher membrane efficiency...) from more than 20 kWh/m^3 in the 1980s, to 5 kWh/m^3 in the 1990s and then to 2.5-4 kWh/m^3.

Membrane filtration is more interesting than distillation in terms of energy consumption. However, distillation may be relevant to produce totally pure water.

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APPENDIX: FILTRATION RESULTS DEFINITION

The main results of a membrane filtration are summarized with coefficients traditionally used in the field of filtration:

- ✓ Recovery rate:

$$Recovery\ rate = \frac{F_{p,out} - F_{p,in}}{F_{r,in}}$$

If there is no inlet connection on the permeate side, the formula is simplified as follows:

$$Recovery\ rate = \frac{F_{p,out}}{F_{r,in}}$$

$F_{p,out}$: Permeate outlet mass flowrate (kg/h)

$F_{p,in}$: Permeate inlet mass flowrate (kg/h)

$F_{r,in}$: Feed mass flowrate (retentate inlet) (kg/h)

- ✓ Compound i rejection rate:

$$Rr_i = 1 - \frac{C_{p,i,out}}{C_{r,i,out}}$$

$C_{p,i,out}$: Permeate outlet mass concentration of compound i (kg/m^3)

$C_{r,i,out}$: Retentate inlet mass concentration of compound i (kg/m^3)

- ✓ Specific consumption (kWh/m^3)

$$Specific\ consumption = \frac{Pw}{F_{p,out}}$$

Pw: Total electrical power consumption (kW)

$F_{p,out}$: Permeate outlet volume flowrate (m^3/h)