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A new visual library for design and simulation of solar desalination systems (SDS)

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ABSTRACT

Process simulation has become an accepted tool for the performance, design, and optimization calculations of solar desalination process units. Solving the mathematical models representing these units and systems is a tedious and repetitive problem. Nested iterative procedures are usually needed to solve these models. Also, the process configurations are characterized by existence of a number of recycle streams. To tackle these problems, several researchers have developed different methods, techniques, and computer programs for the simulation of a very wide range of variety of solar desalination process units and systems. It is of interest in this work to show and demonstrate a new program working under Matlab/SimuLink environments for solar desalination processes calculation and modeling. Using these environments a visual design and simulation for different types and configurations of standalone (common) and solar desalination processes can be performed. Embedded user block programming with SimuLink is implemented to construct a flexible reliable and friendly user-interface package. The solar heating systems and desalination plant components (named here as blocks), such as heat exchangers, flash chambers, evaporators, pumps, steam ejector, compressor, reverse osmosis membrane, pipes, etc., are stored as icons in a visual library. This library enables the user to construct different configurations by just clicking the mouse over the required units (blocks). The interface aids designers, and operators to perform different analyses and calculations such as energy, exergy, and thermoeconomics. Typical desalination processes such as multi stage flash, and reverse osmosis are presented to show the wide scope and the validity, reliability, and capability of the developed package.

1. Introduction

The application of renewable energies such as solar energy to produce fresh water is receiving increased interest due to the need for solving the water shortage problems in various areas of the world and at the same time as conventional energy sources used for obtaining water in different scenarios becoming depleted. The use of renewable energy sources in water desalination is of interest, especially for remote areas where a conventional energy supply is not easily available [1].

Solar thermal energy with a power cycle to produce direct mechanical power can also be employed. Water desalination (seawater/brackish) is distinguished by operations as thermal distillation processes (vapor compression, multi stage flash, solar still, and multi effect distillation) and membrane processes (reverse osmosis, forward osmosis, ion exchange, and electro-dialysis). Solar energy as a renewable energy can power these different techniques by providing the required electricity via photovoltaic and/or concentrating thermal power. At the same time, solar desalination processes consist of a number of interactive units. Using these units a wide range of process configurations and types can be obtained. To understand the behavior of these processes under different operating conditions, a flexible computer program is really needed. Using such program a large number of flow sheeting problems can be manipulated. These problems can be generally divided into three classes: (i) performance problems, (ii) design problems, and (iii) optimization problems [2]. In the performance problem, the variables associated with the feed streams to a process unit and all design parameters (such as solar collector area, heat exchanger area, etc.) are assumed to be known. The variables associating the internal and output streams are the unknowns. However, in the design problem, some design parameters and/or feed variables are left unspecified and become unknown. A corresponding number of additional equations (equality constraints) relating some of these variables is added, such that the total number of unknowns equates

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to the number of equations. The optimization problem differs from the design problem in that the number of equality constraints is smaller than that of the variables left unspecified. The unspecified variables are now calculated to optimize an objective function, normally of economic nature. In this case, the solution can be considered also by using inequality constraints.

A number of computer programs have been developed for solar and desalination processes simulation, design and optimization. These computer programs were developed through three stages. In the first stage, a special purpose programs (one-off program) are used to solve problems related to a particular process (or unit) with a fixed configuration. The structure of these programs is rigid, simple, and straightforward. All that the user has to supply is the data and the executive handles the program in the same way, irrespective of the nature of the process simulated. The disadvantage of such programs is that a model exists for only one process and any changes made to that process might require extensive re-programming. However, the specialized program makes it much easier to produce mathematical models of sufficient realism. A large number of the published programs for design and simulation of distillation processes are of this type, e.g., the programs developed by Hamed and Ali [3], and Ithara and Stiel [4]. In the second generation, the developed computer programs are nominated either as general-purpose programs or modular programs (flow sheeting approach) [2]. These programs are developed to overcome the problems and limitations of the first generation. In these programs, the mathematical model is usually formulated in terms of a set of equations representing the unit processes. Each of these sets of equations is regarded as an independent and self-standing module. In the field of power generation plants, a modular computer program was developed by Sonnenschein [5]. This program takes into account the varying in power demands and in operating conditions, as well as varying cycle configurations. A flexible computer program for thermodynamic power cycle calculations was also developed and described by Perz [6]. With this program, the designer can model different cycle schemes by selecting components from an unseen library (under DOS) and connecting them appropriately. In the desalination field, a general flow sheeting program was developed under DOS for design and simulation of thermal desalination processes by Nafey [7]. Calculations for different types and configurations of seawater distillation processes were presented. Mahmoud Bourouis [8] developed a specific FORTRAN program tackling steady-state simulation and data validation for multi stage flash desalination process. The process is carried out using an equation-oriented approach in which the decomposition of the system leads to a sensitivity matrix. This type of programs needs expert users to describe the process topology and to enter the required data. The third generation of computer programming for desalination processes is the visual modular program approach. This approach aids operators and designers to build up the process configuration and enter the required data and parameters easily. A visualized program was developed for power station plants by Woudstra et al. [9]. This program was based on a strong library of thermal units. Different configurations of power plants can be considered by this program. A commercial process simulation tool, ISPEpro, was developed by Schausberger et al. [10] for studying the performance of a combined power and MSF desalination process. The user defines process flow sheets graphically by icons. Javier et al. [11] developed an object-oriented program for the analysis of power and desalination plants. This software was developed in the form of building blocks for water and energy systems by using a multi-platform (Java language). Nafey and Mabrouk [12] developed a visual design and simulation package for the design and simulation of different types and configurations of desalination processes. Object-oriented programming with Visual Basic was implemented to offer a flexible, reliable and friendly user-interface. A visual library was built by Nafey et al. enables the user to construct different configurations by just clicking the mouse over the required units (icons). The interface aids plant designers, operators and other users to perform different calculations such as energy, exergy, and thermoeconomics. In addition, the package enables designers to perform different modifications of an existing plant or to develop a conceptual design for new configurations. A matrix generation technique was used in this program. Large matrix representing the process mathematical model was solved by a developed decomposition technique. This technique is called "Variable Type by Variable Type Technique (VTBVT)". In fact, this decomposition technique imposes some limitations on the program generality and flexibility. So, the visual programming techniques of the second generation provide a good solution for some problems related to the first generation programs. These problems include interface, and data and configuration entry. However, nested recycle streams, and the large size of the matrix representing the considered process are still imposing some limitations on this program generation of solar heating and desalination systems. Now, with the rapid uprising of the personal computer hardware and computational and graphics mathematical software, the third generation of modeling and simulation programs for desalination processes is established. These programs are based on the mathematical computations and modeling capabilities of some available commercial programs. The MatLab/SimuLink browser is one of the best powerful tool softwares introduced in the last decades. Gambier [13] introduced the ability of MatLab/SimuLink to design library for multi stage flash components. In Gamier demonstration, the physical properties, and heat transfer correlations, were simulated individually in embedded MatLab/SimuLink blocks. The main objective of the present work is to demonstrate a developed modular computer program using MatLab/SimuLink environments for different types and configurations of solar desalination units and processes. This modular program has great capabilities to overcome previous programming problems and limitations such as the recycle streams. Some units are modeled to present a good example of the proposed modular program.

2. MatLab/SimuLink software tool

SimuLink [14] is a general-purpose software program for dynamic systems. This program has been selected to carry out the task of solar desalination modeling and simulation because it offers excellent performance qualities for designing regulation algorithms. SimuLink encourages users to try things out. User can easily build models from scratch, or modifying an existing model. For modeling, SimuLink provides a graphical user-interface (GUI) for building models as block diagrams, using click-and-drag mouse operations. With this interface, the user can draw the models just as it would with pencil and paper (or as most textbooks depict them). SimuLink includes a comprehensive block library of sinks, sources, linear and nonlinear components, and connectors. User can also customize and create his own blocks. SimuLink can also utilize many MatLab features. The Library Browser displays the SimuLink block libraries installed on the user system. User builds models by copying blocks from a library into a model window. SimuLink can also utilize many MatLab features. MatLab is a high-performance language for technical computing [15]. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include Math and computation Algorithm development data acquisition modeling, simulation, and prototyping Data analysis, exploration, and visualization scientific and engineering graphics application development, including graphical user-interface building. MatLab is an interactive system whose basic data element is an array that does not require dimensioning. In industry, MatLab is the

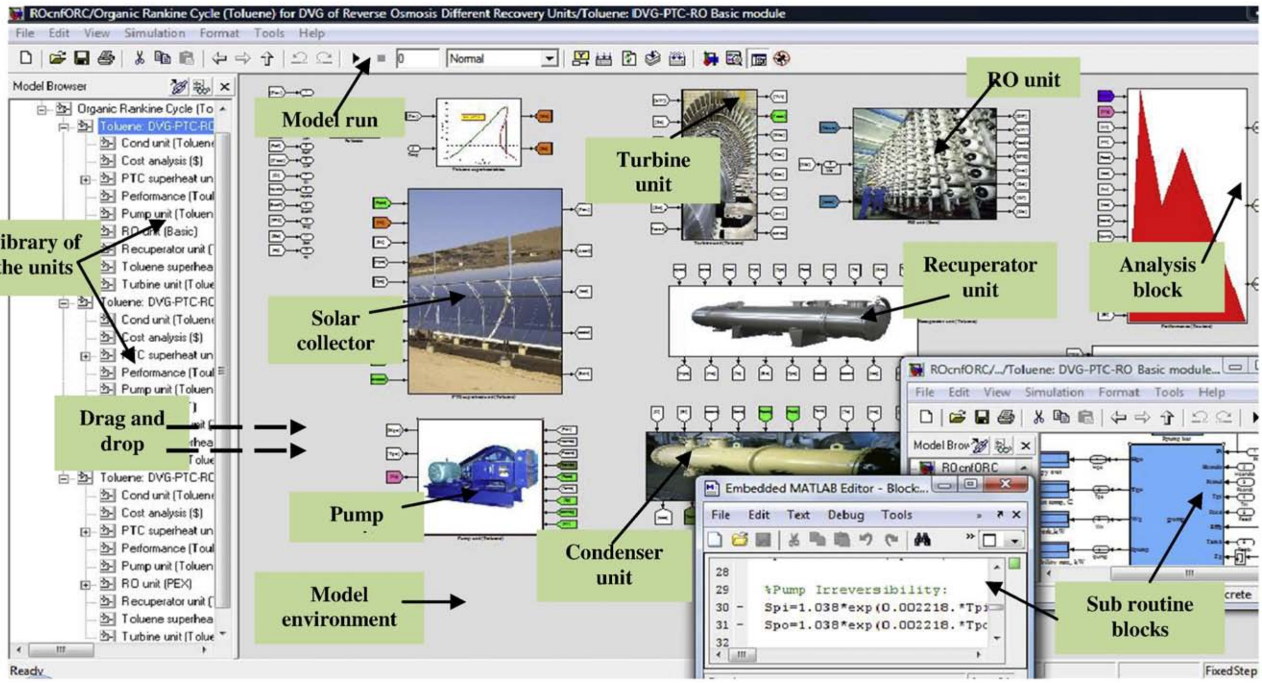


Fig. 1. Interface example of a solar desalination plant (SD-RO) under SDS SimuLink environment.

tool of choice for high-productivity research, development, and analysis [15]. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two. Systems can also be multi-rate, i.e., have different parts that are sampled or updated at different rates.

Table 1
Comparison between Ref. [16] and the developed program (SDS) results.

Time, h	Solar time, h		Zenith angle, deg		Solar radiation W/m^2	
	Ref. [16]	SDS	Ref. [16]	SDS	Ref. [16]	SDS
6	5.61	5.609	86.65	86.636	6.29	6.368
7	6.61	6.609	73.67	73.65	217.93	218.13
8	7.61	7.609	60.35	60.33	451.99	452.19
9	8.61	8.609	46.81	46.79	660.02	660.18
10	9.61	9.609	33.12	33.111	827.49	827.61
11	10.61	10.609	19.37	19.358	943.26	943.3
12	11.61	11.609	5.77	5.756	999.58	999.59
13	12.61	12.609	8.65	8.66	992.67	992.63
14	13.61	13.609	22.35	22.36	923.01	922.92
15	14.61	14.609	36.10	36.10	795.26	795.12
16	15.61	15.609	49.75	49.766	617.95	617.77
17	16.61	16.609	63.26	63.26	402.90	402.7
18	17.61	17.609	76.51	76.52	165.88	165.67
19	18.61	18.609	89.40	89.41	.00	.00

Table 2
A comparison between the SDS and Ref. [17] results for solar Rankine power cycle (direct vapor generation operation).

Parameter	SDS: $\varepsilon_{reg}=0$	Ref. [17] $\varepsilon_{reg}=0$	SDS: $\varepsilon_{reg}=0.8$	Ref. [17] $\varepsilon_{reg}=0.8$
Working fluid	Toluene			
Evaporation temp, °C	**300**	**300**	**300**	**300**
Evaporation pressure, bar	32.75	32.757	32.75	33.737
Superheating temp, °C	300	300	**380**	**380**
Condenser pressure, bar	0.06215	0.0624	0.06215	0.0624
Working fluid flow rate, kg/s	0.5744	0.563	0.4511	0.442
Rejected power, kW	323.2	318.4	208.9	209.8
Rankine efficiency, %	22.82	23.37	31.33	31.78
PTC area, m^2	681.3	672	500	514.3

3. Simulation of different solar desalination units

Solar desalination flow sheets often contain the followings:

1. Solar power cycle (Rankine example) and contains:
   - Solar radiation model to quantify the amount of thermal power.
   - Solar filed (solar collectors) to collect and transfer the amount of thermal power.

Table 3
Specified design parameters of Sharm El-Shiekh RO desalination plant [12].

Variable	Value
Feed flow rate, m^3/h	468
Feed salinity, TDS, ppm	45000
Recovery ratio	0.30
# of stages	1
# of pressure vessels/elements	42/7
Feed temperature, °C	24–40
Fouling factor	0.85
Feed pressure, bar	67

Table 4
SDS results of Sharm El-Shiekh desalination plant vs ROSA6.1 and VDS [12].

Variable	SDS	ROSA6.1 [18]	VDS [12]	Units
SPC	7.75	7.76	7.76	kWh/m^3
HP	1131	1131.42	1130	kW
M_f	485.9	485.9	486	m^3/h
M_b	340.4	340.36	340.23	m^3/h
X_b	64180	62150	66670	ppm
X_d	250	283.83	200	ppm
SR	0.9944	–	0.9927	–
ΔP	6850	6670	6700	kPa

Table 5
SDS and VDS [12] results comparison for Eoun Mousa MSF-BR plant.

Variables	VDS [12]	SDS
Total feed, kg/s	436.11	438.2
Capacity, kg/s	57.87	57.87
Make up, kg/s	183.33	184.2
Recycle flow rate, kg/s	510	507.8
Cooling water splitter ratio	0.42	0.42
Brine recycle splitter ratio	0.724	0.719
Top brine temperature, °C	110	110
Recycle blow down temperature, °C	48.05	49.7
Vapor temperature at last stage, °C	41	41.47
Sea water salinity, ppm	48,620	48,620
Area/heat recovery stages, m^2/#	488/17	440/17
Area/heat rejection stages, m^2/#	357/3	321/3

- Boiler heat exchanger to transfer thermal power (in case of indirect vapor generation).
- Turbine expander unit for electricity generation.
- Condenser/brine-heater unit for preheating and heating processes.
- Pump to overcome the pressure losses in the cycle.

2. Desalination plants which include:
   - Membrane desalination technique (reverse osmosis, forward osmosis, ion exchange, and electro-dialysis).
   - Thermal desalination technique (multi stage flash, multi effect distillation, and thermal vapor compression).

In general, solar desalination plants contain a lot of feedback streams, forward streams, different units, and different types with different configurations for each type. Therefore, simulation and programming for a solar desalination plant are tedious problems. Fig. 1 shows the interface panel of an example of solar desalination plant modeled using SimuLink environment.

3.1. Validity and reliability of the developed SDS program under SimuLink environment

Different solar desalination processes are considered in this section to show the reliability and flexibility of the developed SDS package. Solar radiation model, organic Rankine cycle (ORC), reverse osmosis (RO), multi stage flash (MSF), thermal and mechanical vapor compressions (TVC & MVC), MED processes are considered as examples to show the scope of the package.

3.1.1. Solar radiation model validity

Solar radiation models are highly useful to estimate the flux over solar plant location. Therefore, it is very important to decide on maximum and minimum fluxes over a specified period for the place of operation. It would not be enough for the scientists or engineers in this location to depend on the measured data only, but it would be important to use a useful theoretical model which could correctly estimate and predict the solar radiation. In the absence of measured data, theoretical models are the only available tool for solar radiation estimation. The correlations for daily global radiation (MJ/$m^{2)}$, monthly global radiation (MJ/$m^{2)}$, and instant radiation in W/m^2 for horizontal surfaces are obtained from El-Sayed [16]. For solar radiation correlation model, input parameters include current hours, Julian day, latitude angle, longitude, and altitude. The model can estimate different solar angles for a specified location. (zenith, incidence, azimuth, declination), sun set, sun rise times, day hours during the day light, solar time, equation of time, and global radiation (monthly, daily, hourly, and instantaneously). To show the reliability of the developed SDS program, a comparison example is presented in Table 1. The results of Table 1 were obtained using the following parameters: latitude angle = 21.5°N, Julian day = 172, standard local time zone = 45°, and longitude = 39.5°. The results are obtained according to clear sky model. Results show a good agreement between the two programs.

3.1.2. Solar field model validity

In this section, the validity of the solar field results under the SimuLink environment is illustrated. Different types of thermal solar collectors are designed and modeled in the SDS library, such as; flat plate collector FPC, compound parabolic concentrator CPC, and parabolic trough collector PTC. The PTC collector is illustrated in this article to examine the model validity. Specified input and output parameters and variables are; ambient temperature °C, solar radiation W/m^2, collector width m, collector length m, glass cover

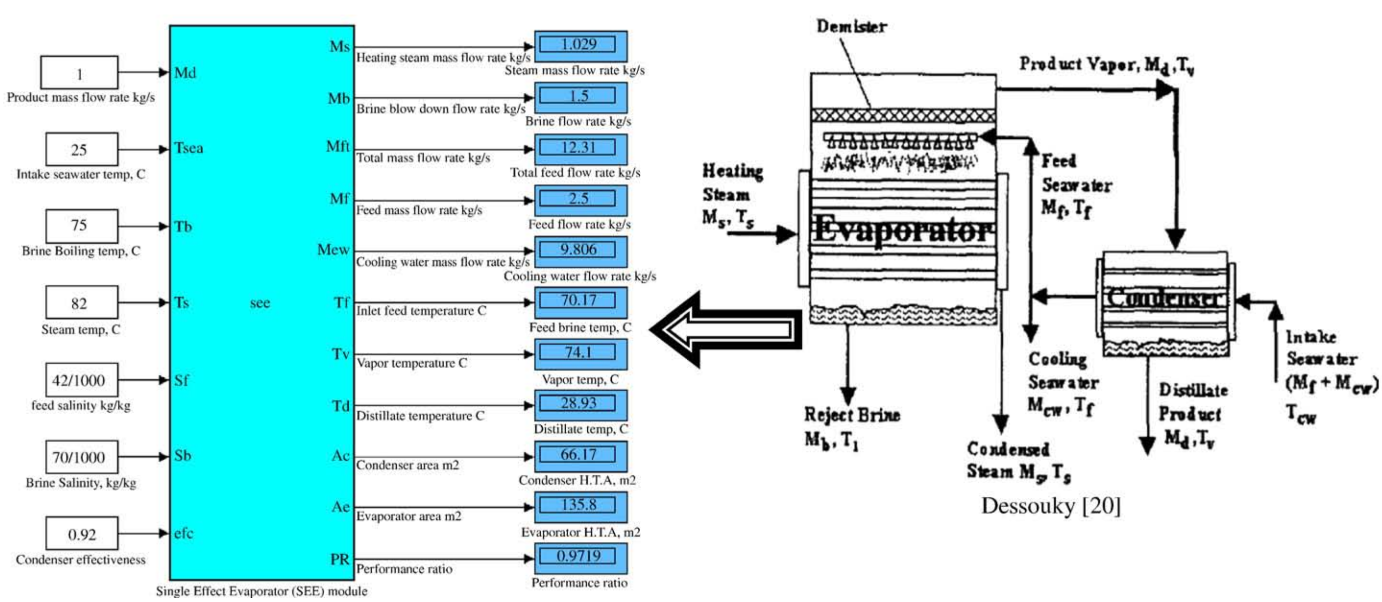


Fig. 2. Schematic display of single effect evaporation (SEE) under MatLab–SimuLink software environment.

envelope m, and inner tube diameter m. Variables such as mass flow rate kg/s, inlet collector temperature °C, enthalpy kJ/kg, and thermoeconomic streams are obtained. Also, the results include thermo-physical properties (pressure, temperature, enthalpy, and entropy), performance analysis (stream exergy, exergy destruction, thermal power, thermal efficiency, and collector exergetic efficiency), and field design variables (total field area, total field length, number of loops, area per each loop, and total number of solar collectors). Table 2 shows the results of the solar PTC block. The validity of these results is examined by comparing it with that obtained by Torres [17].

3.1.3. Turbine model

Turbine model is developed by specifying the input parameters such as the power needed by the load, turbine thermal, and generator efficiencies. The output variables are thermo-physical properties (pressure, temperature, entropy, enthalpy…), thermoeconomic streams, and mass flow rate. The mass flow rate would replace the old value from the memory block after some iteration.

3.1.4. Recuperator and feed heater models

Recuperators are widely used for organic cycle's operations. The presence of the recuperator unit utilizes available energy in the turbine exhaust to preheat the working fluid stream entering the solar field. Open feed heater is basically a mixing chamber, where the steam extracted from the turbine mixes with the feed fluid exiting the pump. The mixture leaves the heater as a saturated liquid at the heater pressure. This kind of regeneration not only improves the cycle efficiency, but also provides a convenient means of de-aerating the feed fluid. The extracted pressure values are assigned based on each working fluid property.

3.1.5. Condenser/brine-heater model

Condenser/brine-heater model is simulated and designed to find out the total area, number of tubes, overall heat transfer coefficient, heat rejection, and effectiveness. The block also calculates thermoeconomic and exergetic values in the output streams. Some data results for the condenser block are illustrated in Table 2.

3.1.6. Pump model

Pump unit is modeled to calculate the power required across inlet and outlet streams and by the pressure loss through the solar filed and condenser unit. The output stream from the pump unit will enter the recuperator unit in case of regeneration, or directly to the solar field in case without regeneration.

3.2. Validity evaluation of some desalination processes under SimLink environment

3.2.1. Reverse osmosis (RO) model

The mathematical model validity of RO is examined in this section. The real data for Sharm El-Shiekh desalination plant [12] is used for this purpose. The model results are compared with the ROSA6.1 [18] software program and VDS [12] software package. The plant design parameters are presented in Table 3.

Fresh water product M_p and the plant recover ratio are specified for design calculations of RO desalination process. The fresh water product will decide the plant power, specific power consumption SPC, the needed feed M_f, the required feed pressure ΔP, the product salinity X_d, the rejected brine M_b, salt rejection percentage SR, and the pump horse power needed HP. The RO pump efficiency is about 80% and the feed flow rate salinity is specified as 45,000 ppm. The input feed sea water temperature is fixed as 25 °C. The plant recovery ratio is specified as 30%. The results of the developed program show a good agreement with the other software results (ROSA6.1, and VDS) as presented in Table 4. This indicates the validity of both the proposed RO mathematical model and the SDS program. RO block is built as one block containing all equations

Table 6
The SDS and Dessouky [20] results comparison for SEE model.

Single effect evaporation (SEE)		
Variables	Dessouky [20]	SDS
Steam mass flow rate kg/s	1.03	1.029
Brine mass flow rate kg/s	1.5	1.5
Total feed mass flow rate kg/s	12.3	12.31
Feed mass flow rate kg/s	2.5	2.5
Cooling water mass flow rate kg/s	9.8	9.806
Feed temperature °C	70	70.17
Vapor temperature °C	74.097	74.1
Distillate temperature °C	28	28.93
Condenser area m^2	65.5	66.17
Evaporator area m^2	135.9	135.8
Performance ratio	0.97	0.9719
*Product mass flow rate kg/s	1	1
*Seawater temperature	25	25
*Condenser effectiveness	–	0.92
*Feed salinity ppm	42000	42,000
*Steam temperature °C	82	82
*Brine temperature °C	75	75
*Brine salinity ppm	70000	70,000
Single effect thermal vapor compression (SETVC)		
Variables	Dessouky [20]	SDS
Steam mass flow rate kg/s	1.03	1.029
Brine mass flow rate kg/s	1.5	1.5
Total feed mass flow rate kg/s	12.3	12.31
Feed mass flow rate kg/s	2.5	2.5
Cooling water mass flow rate kg/s	9.8	9.806
Preheated feed temperature °C	70	69.2
Vapor temperature °C	74.097	74.1
Entrained vapor mass flow rate kg/s	0.37	0.373
Motive steam flow rate kg/s	0.678	0.68
*Product mass flow rate kg/s	1	1
*Seawater temperature	25	25
*Condenser effectiveness	0.9	0.9
*Steam temperature °C	82	82
*Brine temperature °C	75	75
*Brine salinity ppm	70000	70,000
*Feed salinity ppm	42000	42,000
*Motive steam pressure kPa	750	750
*Compression ratio	2.5	2.5
Evaporator area m^2	39.8	41
Condenser area m^2	41	40
Single effect mechanical vapor compression (SEMVC)		
Variables	VDS [12]	SDS
*Product mass flow rate kg/s	17.36	17.36
Steam mass flow rate kg/s	17.36	17.36
Brine mass flow rate kg/s	31.25	31.25
Total feed mass flow rate kg/s	48.61	48.61
*Brine salinity ppm	70000	70000
*Feed salinity ppm	45000	45000
*Seawater temperature	27	27
Vapor temperature °C	60	60
Feed temperature °C	57.93	57.04
Steam temperature °C	96.2	96.17
Distillate blow down temperature °C	32.51	32.93
Brine blow down temperature °C	37.72	37.7
Inlet compressor pressure kPa	20.03	19.84
Outlet compressor pressure kPa	27.047	26.8
*Pressure ratio	1.35	1.35
Compressor power kW	1081	1076
Specific power consumption kWh/m^3	17.291	17.2

*Specified variables.

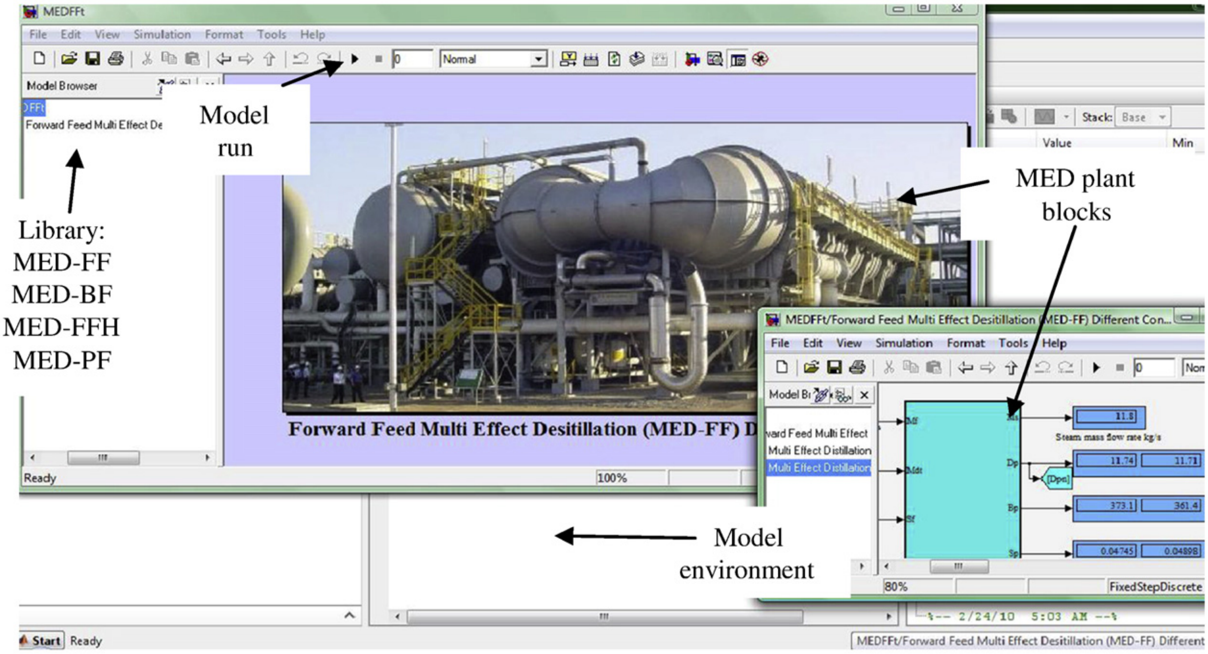


Fig. 3. MED model environment designed using SDS package.

needed for the simulation process. It can then be copied and dragged with solar cycle or with any thermal desalination process such as MSF plant as hybrid processes.

3.2.2. Multi stage flash (MSF) model

Different configurations of MSF desalination processes (brine recycles MSF-BR, once through MSF-OT, and brine mixing MSF-MX) can be manipulated by the developed SDS program under SimuLink environment. For design mode, distillate product, blow down temperature, inlet sea water temperature, top brine temperature, and number of stages are specified. The process validity of MSF-BR (Eoun Mousa, Egypt with capacity of 5000 m^3/day) is examined by comparing the results of VDS [12] program and the present SDS program. Both results are illustrated in Table 5. A good agreement is obtained for both programs.

3.2.3. Single effect thermal and mechanical vapor compression models

Single effect evaporation (SEE) has limited industrial applications. The system is used in marine vessels and this because the system has a thermal performance ratio less than one, i.e.; the amount of water produced is less than the amount of heating steam used to operate the system. However, it is considered here just to examine the program validity for effect evaporation process. Fig. 2 shows a schematic diagram for the SEE system. The main components of the process are the evaporator and the feed pre-heater condenser. The evaporator consist of an evaporator\condenser heat exchanger tubes, a vapor space, un-evacuated water pool, a line for removal of non condensable gases, a water distribution system, and a mist eliminator. Table 6 demonstrates the obtained results by the present SDS program and by Dessouky [20]. Also, results for a single effect thermal and mechanical vapor compression are illustrated in Table 6. Results from the developed SDS program compared with Dessouky [20] and VDS [12]

Table 7
Data validation between SDS and Darwish [22] for MED model.

Effect #	*T* brine °C		*T* feed °C		*M* brine kg/s		*M* distillate kg/s		*S* brine g/kg	
	SDS	Ref. [22]	SDS	Ref. [22]	SDS	Ref. [22]	SDS	Ref. [22]	SDS	Ref. [22]
1	65	65	62	62	373.09	373.18	11.74	11.85	47.44	47.46
2	62.54	62.55	59.54	59.55	361.41	361.37	11.71	11.8	48.98	49.01
3	60.09	60.09	57.09	57.09	349.79	349.62	11.68	11.75	50.6	50.66
4	57.63	57.64	54.63	54.64	338.22	337.91	11.65	11.71	52.33	52.41
5	55.18	55.18	52.18	52.18	326.72	326.26	11.62	11.66	54.18	54.29
6	52.72	52.37	49.73	49.73	315.27	314.65	11.59	11.61	56.14	56.29
7	50.27	50.27	47.27	47.27	303.88	303.09	11.56	11.56	58.25	58.44
8	47.81	47.82	44.82	44.82	292.55	291.58	11.53	11.51	60.51	60.74
9	45.36	45.36	42.36	42.36	281.27	280.12	11.5	11.46	62.93	63.23
10	42.9	42.91	39.91	39.91	270	268.71	11.47	11.41	65.55	65.91
11	40.45	40.45	37.45	37.45	258.87	257.34	11.45	11.36	68.38	68.82
12	38	38	35	35	247.76	246.03	11.42	11.32	71.45	71.99

Table 8
Energy and thermoeconomic results for different techniques.

Variables	SDS results
RO-PEX section	
RO Mass flow rate, m^3/h	486
RO brine loss flow rate, m^3/h	340.2
Brine loss salinity, g/m^3	63.56
Product salinity, g/m^3	0.2682
PEX hydraulic power, kW	607.8
Booster pump power, kW	62.08
High pressure pump power, kW	332.1
High pressure pump pressure, bar	68.74
RO Specific total cost, $\$/m^3$	0.68
Organic power cycle (ORC) section	
Solar field area, m^2	1887
Solar field efficiency, %	73.61
Solar field thermal power, kW	1181
Developed turbine power, kW	394.18
Organic cycle flow rate, m^3/h	6.235
Rankine efficiency, %	32.64
Specific power consumption, kWh/m^3	2.704
Organic pump power, kW	8.89
Condenser power rejection, kW	774.6
Total cycle exergy destruction, kW	2538
Overall exergy efficiency, %	11.61
Total cycle exergy inlet, kW	2871
Total operating and maintenance cost, \$/h	93.26
Thermo-economic product cost, \$/GJ	66.6
Total water price, $\$/m^3$	0.71

shows a good agreement under the same range of operating conditions.

3.2.4. Multi effect distillation models

A multi effect distillation (MED) desalting system with a unit capacity up to 5 MIGD is a strong competitor to the multi stage flash (MSF) desalting system due to its low specific energy consumption and the low temperature steam required to operate the system [21]. The process of adding more evaporators can be continued to a final (n) evaporator. The vapor generated in the last evaporator (n) is directed to a bottom condenser where it is condensed. The heating steam (heat source) is condensed in the first effect at the highest temperature. This is called the n-effect distillation system. The temperature and pressure in each effect are decreased by the increase of the effect number. Different MED configurations and types are simulated and designed using SDS package. The results show a very good agreement with some existing plants. Fig. 3 shows a display of the MED under SDS package. Also Table 7 shows the data results of comparisons between SDS and Darwish [22]. Data comparison with reference [22] is implemented according to Sidem 12-effect units and 11 feed heaters. The unit given in data are: n (number of effects) = 12, output D = 500 ton/h (139 kg/s), TBT = 65 °C, T_b = 38 °C, T_f = 28 °C, feed temperature at condenser exit = 35 °C, feed salinity S_f = 46 g/kg, and maximum salinity S_b = 72 g/kg where f and b are related to feed and brine respectively.

4. Solar power cycle for desalination processes: case study

In this section, a solar organic Rankine cycle for electricity and power generation is combined with reverse osmosis desalination plant. As showed in Fig. 1, the plant contains different units such as; solar PTC field, turbine unit, condenser, and recuperator, pump, and RO block. RO desalination plant is operated with pressure exchanger (RO-PEX) unit. Higher efficiency positive displacement power recovery devices (pressure exchangers), that in the past were only used in small RO seawater units, are also slowly gaining acceptance in large desalination plants. Hydraulic efficiency of this type of equipment is in the range of 94–96% [19]. In this work, the values of 80% and 96% are considered for booster pump and PEX unit respectively. Some of these devices utilize pistons; another transfer energy through a direct contact between the concentrate and the feed stream. The process is modeled and designed under SimuLink environment. By specifying the fresh water demand, the cycle design calculations are performed.

The RO plant productivity is set as 3500 m^3/day. Salinity gradient is 45 g/kg. Recovery ratio is 30%, number of elements per pressure vessels is 7/48, element area is 35.3 m^2, high pressure pump (HPP) efficiency is 80%, and the fouling factor (FF) is set as 85%. The results are obtained. Typical summer operating conditions are considered with a global radiation of 850 W/m^2. The outlet collector temperature is 340 °C with Toluene as a working fluid. The turbine, pump, generator efficiencies are 85%, 75%, and 95% respectively. RO plant life time normally set as 20 years with 5 years for element per vessel, and load factor is set as 90%. The developed model can perform energy, exergy, and cost and thermoeconomic analysis for the considered process. Some results are illustrated in Table 8. The RO section with PEX device exhibits a total area of parabolic trough collector (PTC efficiency = 73%) equal to 1887 m^2 with Toluene as a working fluid. This area would generate a thermal power about 1887 kW with outlet temperature 340 °C. PEX operation reduces the required electric power from the generator to reach 394 kW instead of 1131 kW in basic configuration. Lowering the required power by the existence of PEX would lower all the dependent parameters (solar field area, pump power, mass flow rate, condenser area, exergy destruction, and operational costs).

5. Conclusion

The SDS program is developed for design and simulation of different types and configurations of conventional and solar desalination processes. Embedded block programming with SimuLink environment is used to develop a flexible reliable and friendly user-interface. The desalination plant components such as heat exchangers, flash chambers, evaporators, pumps, steam ejectors, compressors, reverse osmosis membranes, pipes, etc., are modeled and stored as blocks in the SimuLink visual library. This library enables the user to construct different desalination techniques and configurations by just clicking the mouse over the required units (blocks). The interface aids plant designers, operators and other users to perform different calculations such as energy, exergy, and thermoeconomics. In addition, the package enables the designers to perform different modifications of an existing plant or to develop the conceptual design of new configurations. Some operating desalination plants are simulated by the present package to show its reliability and flexibility. The developed SDS package has some features concluded in:

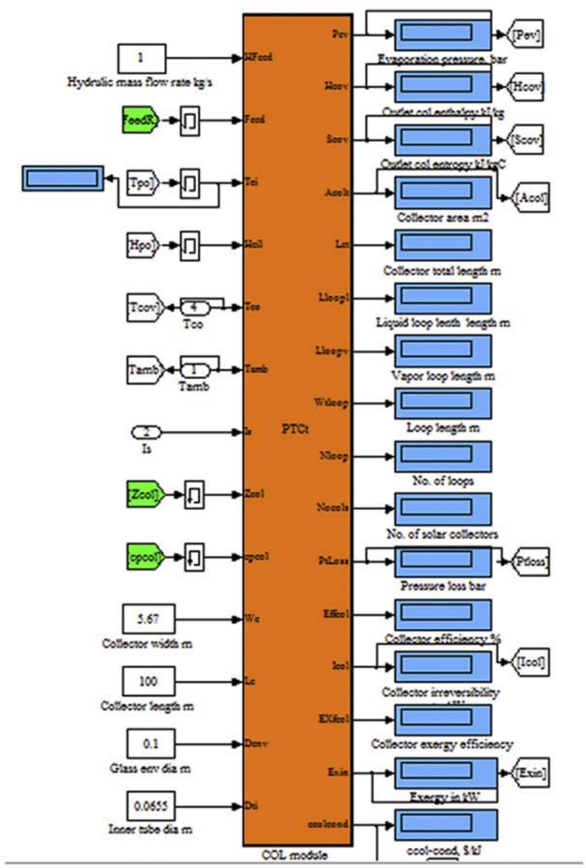
- Easy model construction.
- Easy to convert the designed code to be self executable and work under different computer languages (Visual basic, Visual C, Visual C++, and Visual Fortran).
- The model allows users easily change to the plant variables and different operating conditions with ultimate stream allowance.

The developed program overcomes the problem that appears in other techniques of simulation such as sequential approach, and matrix manipulation technique.

Appendix A

A.1. SDS block libraries

A.1.1. Solar collector field

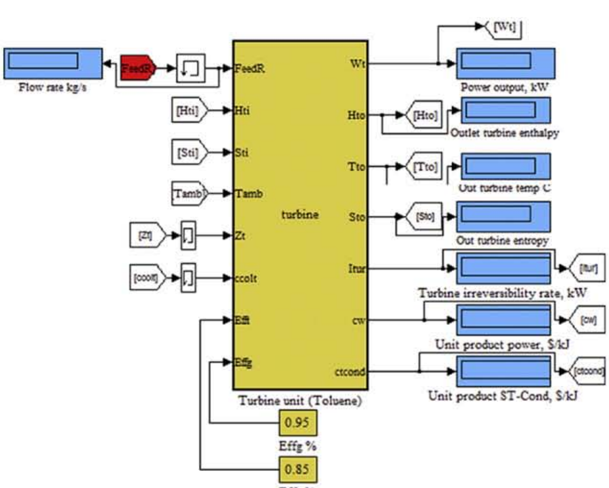


Specified	**Calculated**
• Solar radiation • Ambient temperature • Outlet collector temperature • Hydraulic mass flow rate • Collector width (PTC) • Collector length (PTC) • Envelope diameter (PTC) • Inner tube diameter (PTC)	• Evaporation pressure • Outlet thermophysical stream (enthalpy, entropy) • Total field area • Total field width • Total filed length • Number of loops • Number of solar collectors • Collector energy and exergy efficiencies • Exergy destruction • Outlet thermoeconomic streams

Library blocks used:

1. Constant block
2. User-Defined block
3. SimuLink/Discrete/Memory block
4. SimuLink /Sources/Input
5. SimuLink /Sinks/Display
6. SimuLink /Signal Routing/From
7. SimuLink /Signal Routing/Goto

A.1.2. Turbine unit

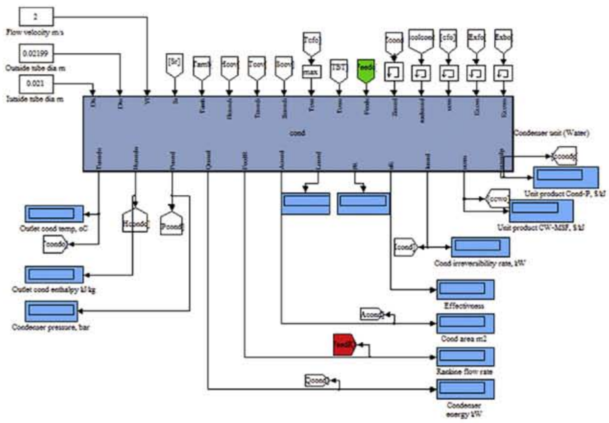


Specified	**Calculated**
• Generator efficiency • Turbine efficiency • Ambient temperature • Hydraulic mass flow rate In some cases (RO-ORC); the work out is assigned by the desalination process, and then the cycle flow rate would be estimated from the turbine unit.	• Work out • Outlet thermophysical stream (enthalpy, entropy) • Exergy destruction • Exergy efficiency • Total filed length • Cost of power • Outlet thermoeconomic streams

Library blocks used:

1. Constant block
2. User-Defined block
3. SimuLink/Discrete/Memory block
4. SimuLink /Sinks/Display
5. SimuLink /Signal Routing/From
6. SimuLink /Signal Routing/Goto

A.1.3. Condenser unit

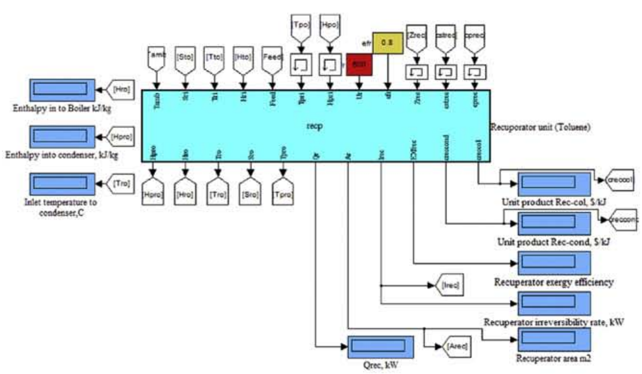


Specified	Calculated
• Hydraulic mass flow rate	• Thermal power rejected
• Outside tube diameter	• Outlet thermophysical stream (enthalpy, entropy)
• Inside tube diameter	• Condensation pressure
	• Condenser effectiveness
	• Total condenser length
	• Total number of tubes
	• Exergy destruction
	• Outlet thermoeconomic streams

Library blocks used:

1. Constant block
2. User-Defined block
3. SimuLink/Discrete/Memory block
4. SimuLink /Sinks/Display
5. SimuLink /Signal Routing/From
6. SimuLink /Signal Routing/Goto

A.1.4. Recuperator unit

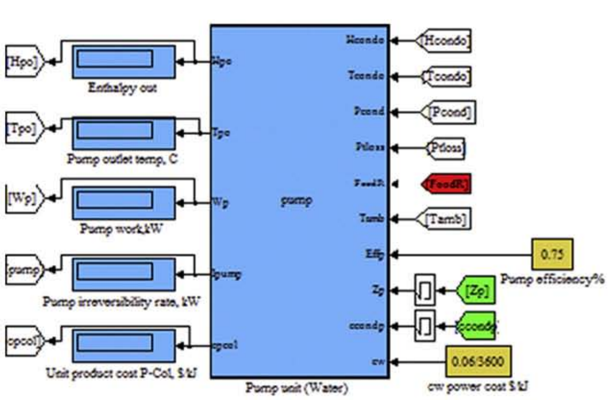


Specified	Calculated
• Recuperator effectiveness	• Thermal power transferred to flow stream
• Outside tube diameter	• Outlet thermophysical stream (enthalpy, entropy)
• Inside tube diameter	• Thermal inlet/outlet pump streams
	• Total recuperator area
	• Total recuperator length
	• Total number of tubes
	• Exergy destruction
	• Outlet thermoeconomic streams

Library blocks used:

1. Constant block
2. User-Defined block
3. SimuLink/Discrete/Memory block
4. SimuLink /Sinks/Display
5. SimuLink /Signal Routing/From
6. SimuLink /Signal Routing/Goto

A.1.5. Pump unit



Specified	Calculated
• Pump efficiency	• Pump work
• Ambient temperature	• Outlet thermophysical stream (enthalpy, entropy, temperature)
For some cases (solar desalination with MSF) the cost of power is specified as input parameter however in case of turbine unit it should be calculated.	• Exergy destruction
	• Outlet thermoeconomic streams

Library blocks used:

1. Constant block
2. User-Defined block
3. SimuLink/Discrete/Memory block
4. SimuLink /Sinks/Display
5. SimuLink /Signal Routing/From
6. SimuLink /Signal Routing/Goto

A.1.6. Reverse osmosis plant

Reverse osmosis plant simulated and blocked as presented before in Fig. (1). However, in energy recovery configurations the systems contain Pelton wheel turbine drive (PWT) and pressure exchanger unit (PEX). PWT and PEX recovery units are simulated and blocked via SimuLink browser as following:

Specified

PWT
- Brine blow down pressure
- PWT efficiency

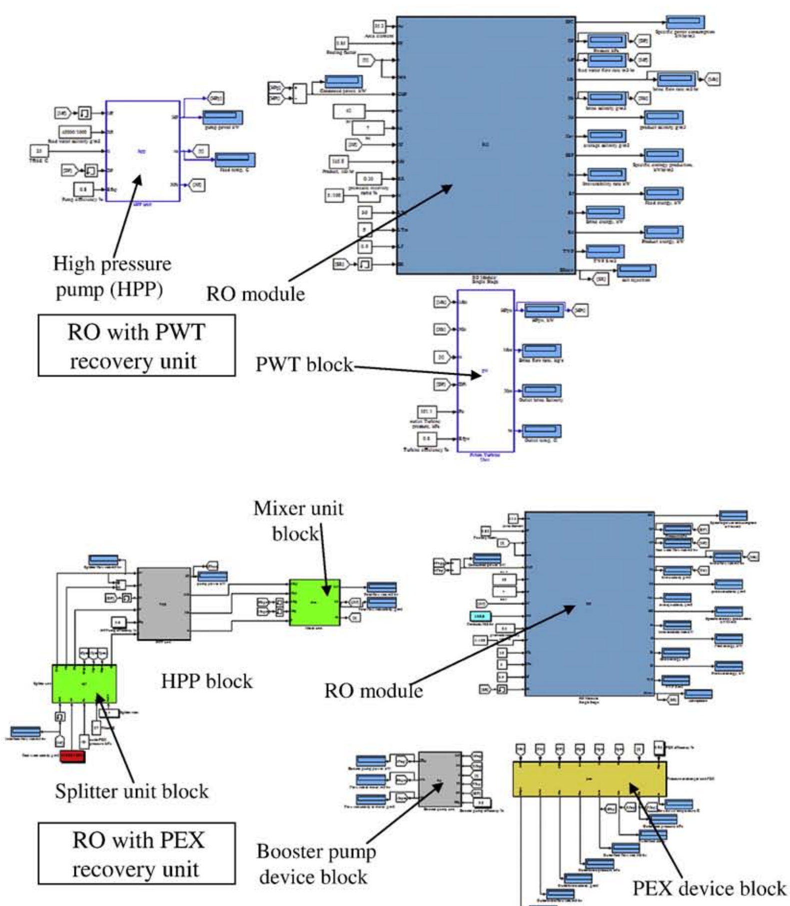
HPP
- Inlet feed temperature
- HPP efficiency
- Inlet seawater salinity
- Horsepower (Guessed value)

Splitter
- Splitter ratio
- Inlet feed temperature

Booster pump
- Booster pump efficiency

PEX
- PEX efficiency
- Fresh water product
- Recovery ratio

Calculated
- Horse power
- Outlet brine mass flow rate
- Outlet brine salinity
- Outlet brine temperature
- Specific power consumption
- Feed flow rate
- Brine flow rate
- Average salinity
- Product salinity
- Exergy streams
- Thermoeconomic streams
- Exergy destruction
- Consumed power
- Salt rejection
- Outlet feed pressure
- PEX hydraulic power



Library blocks used:
1. Constant block
2. User-Defined block
3. SimuLink/Discrete/Memory block
4. SimuLink /Sinks/Display
5. SimuLink /Signal Routing/From
6. SimuLink /Signal Routing/Goto
7. Gain bloc

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