PROSIMPLUS APPLICATION EXAMPLE

SIMULATION OF DIFFERENT
RANKINE CYCLES

EXAMPLE PURPOSE
This example presents the simulation of different Rankine cycles powered by geothermal energy. Three types of Rankine cycle are presented: simple cycle, flash cycle and mixed cycle.

ACCESS	☑ **Free Internet**	☐ **Restricted to ProSim clients**	☐ **Restricted**	☐ **Confidential**

CORRESPONDING PROSIMPLUS FILES	*PSPS_EX_EN-Rankine-cycles-simple-cycle.pmp3* *PSPS_EX_EN-Rankine-cycles-single-flash.pmp3* *PSPS_EX_EN-Rankine-cycles-single-flash-sour-water.pmp3* *PSPS_EX_EN-Rankine-cycles-double-flash.pmp3* *PSPS_EX_EN-Rankine-cycles-mixed-cycle.pmp3*

TABLE OF CONTENTS

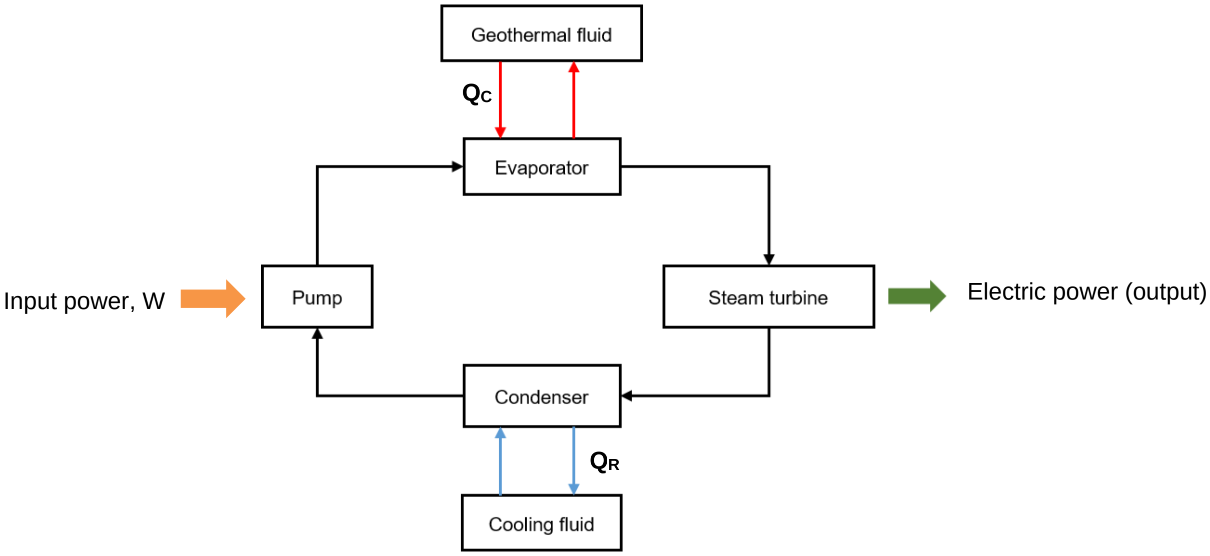
1. PROCESSES MODELING

1.1. Processes description

This example presents the simulation of several Rankine cycles powered by geothermal energy. Geothermal energy is a natural heat flow extracted from the sub-surface of the earth. Unlike fossil fuels, geothermal energy is considered to be clean and renewable.

The geothermal resources are exploited in various industrial applications. In this example, the heat from the high-temperature well (water) is valorized in a geothermal power plant with the aim of electricity production. Geothermal power plants are usually based on a Rankine cycle. The Rankine cycle is a thermodynamic cycle that converts heat into mechanical work. The heat is supplied externally to a closed loop which uses a working fluid (*e.g.* water).

In general, the geothermal fluid, which will be assimilated to water, transfer its heat to the working fluid of the Rankine cycle in the evaporator, before being reinjected back into the well. The vaporized working fluid produced in the evaporator is then expanded in the turbine to produce electricity. The vapor exits into a heat exchanger, where it is condensed and cooled by a cooling medium (river water for instance).



Block diagram of Rankine cycle

In this example, three types of Rankine cycles are presented: simple cycle, flashes cycle and mixed cycles. The simulation diagrams in paragraph 1.2 illustrate the process flowsheet of these three types of cycles.

1.1.1. Simple cycle

First, a simple organic Rankine cycle (ORC) is presented. An organic fluid R600 (n-butane) is used to simulate the process. The cycle can be modelled with an "Organic Rankine Cycle (ORC)" module or with independent unit operations connected between each other. The 2 simulations give the same results as illustrated later in the document.

1.1.2. Flash cycle

The flash cycle uses water as the working fluid in the Rankine cycle. At the process inlet, the water is expanded to obtain a vapor-liquid mixture. The vapor and the liquid are then separated in a separator. It is possible to expand and to condense the vapor before its reinjection into the well, while the liquid is directly reinjected. In several cases where the pressure at the well's outlet is sufficient, it is possible to carry out a double flash, which allows to produce vapor at two different pressures and to increase the plant's performance. In this document, the single flash cycle and double flash cycle are presented [VAL11].

A third flash cycle is also presented. This cycle demonstrates a single flash cycle that uses a particular geothermal fluid. In fact, the geothermal fluid does not actually contain only pure water. Many impurities and salts are also present in the geothermal fluid. The presence of these components could lead to many conception and maintenance problems (precipitation of the components at high pressure in the well, scaling problems, corrosion…). The well's stream is composed of water and some electrolytes such as Na^+, K^+, Ca^{2+}, HCO^{3-} et SO_4^{2-} (example " PSPS_EX_EN-Rankine-cycles-single-flash-sour-water.pmp3"). An appropriate thermodynamic model represents the electrolyte aqueous solution.

1.1.3. Mixed cycle

Technically and industrially, a geothermal power plant is more complicated and looks more likely as illustrated in the last flowsheet. It consists of a mixed cycle associating a flash with an ORC. The geothermal fluid is first expanded through the turbine to a pressure lower than the production well pressure, which produces a vapor-liquid mixture. The vapor flow feeds the "Combined cycle" block, while the liquid fraction circulates in a lower pressure cycle.

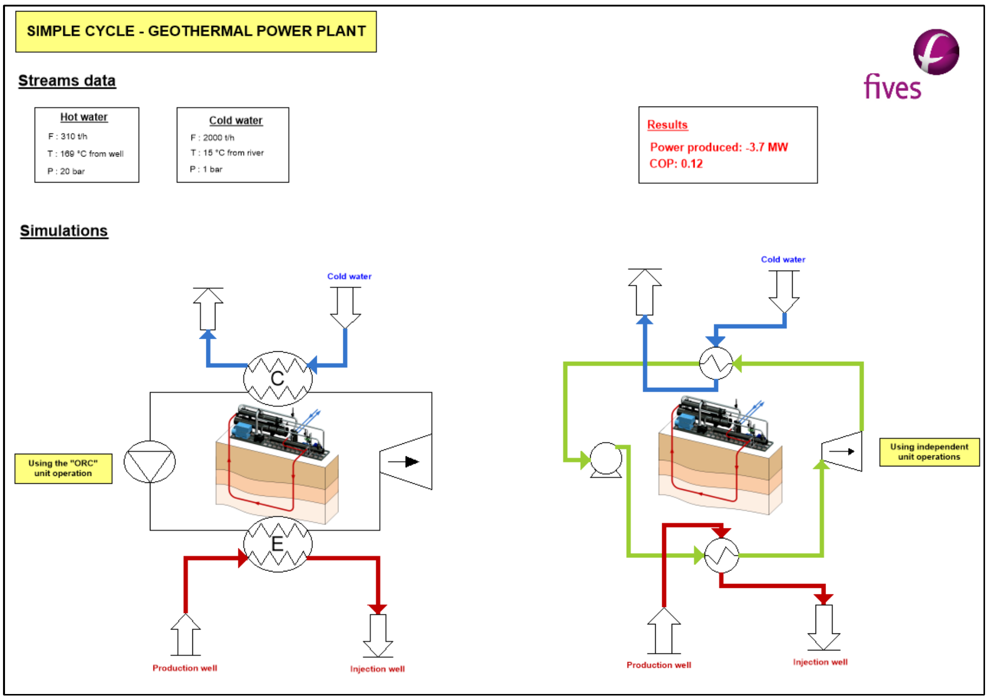
In the "Combined cycle", the water vapor first enters the turbine for electricity generation. Next, a heat exchanger is used to transfer the available heat from the water vapor to the organic fluid R600 in the first organic Rankine cycle. For the low-pressure cycle, the liquid fraction transfers the necessary heat to another organic fluid: the R245fa.

The exit stream of the process is still thermally beneficial. The available heat from the process outlet is recovered in the heat exchanger before reinjection. The heat exchanger could supply an urban heating network (not presented in this example).

1.2. Simulation flowsheets

1.2.1 Simple cycle

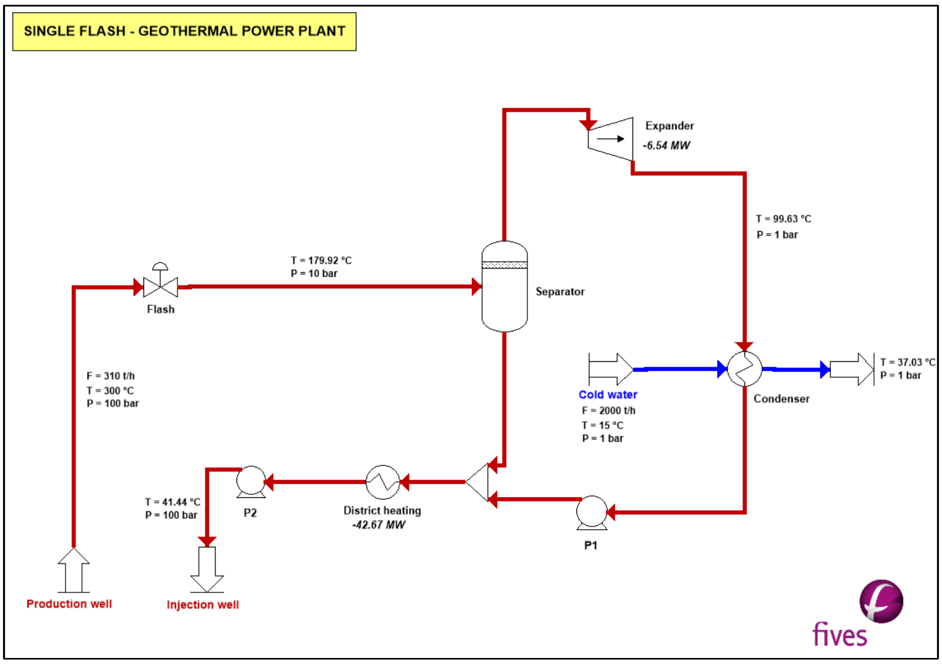
This flowsheet is presented in: “PSPS_EX_EN-Rankine-cycles-simple-cycle.pmp3”.



1.2.2 Flashes cycles

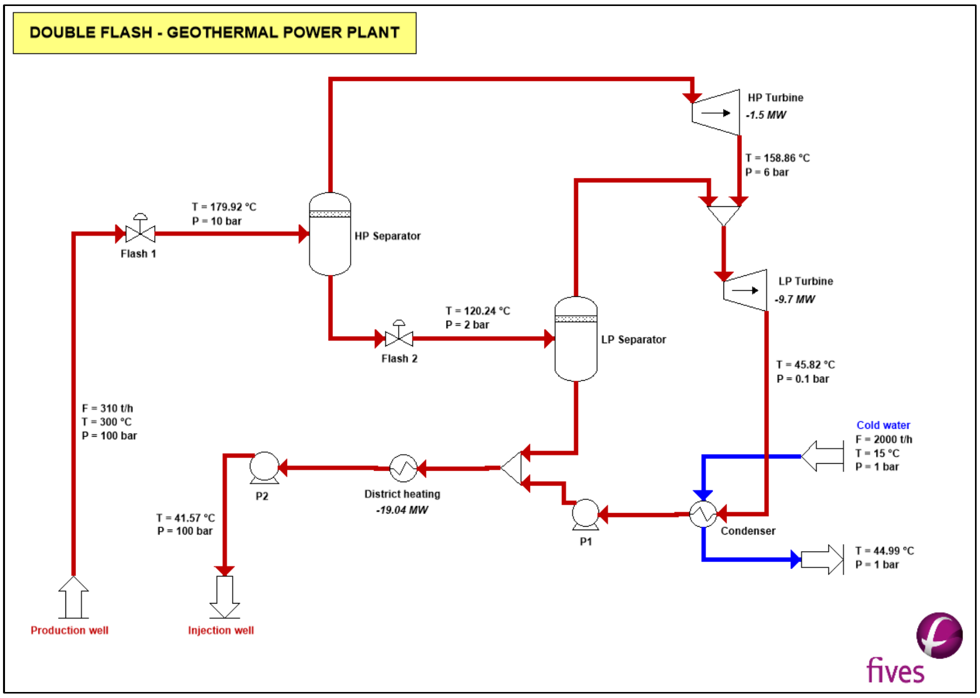
1.2.2.1 Single flash cycle

This flowsheet is presented in: “PSPS_EX_EN-Rankine-cycles-single-flash.pmp3” and “PSPS_EX_EN-Rankine-cycles-single-flash-sour-water.pmp3”.



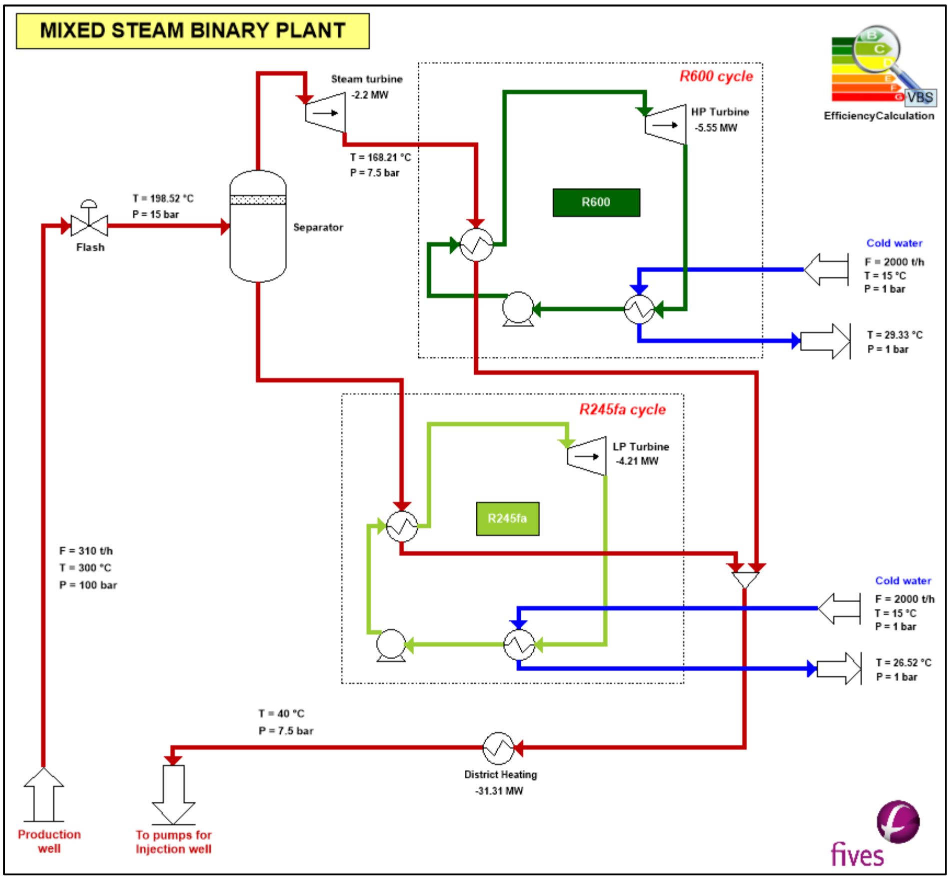
1.2.2.2 Double flash cycle

This flowsheet is presented in: “PSPS_EX_EN-Rankine-cycles-double-flash.pmp3”.



1.2.3. Mixed cycle

This flowsheet is presented in: “PSPS_EX_EN-Rankine-cycles-mixed-cycle.pmp3”.



1.3. Components

Components taken into account in the simulation, their chemical formula and CAS(*) number are presented in the following table. Pure components physical properties are extracted from the ProSimPlus standard database [WIL19].

Component	Chemical formula	CAS number
Water	H_2O	7732-18-5
R600 (n-Butane)	C_4H_{10}	106-97-8
R245fa (1,1,1,3,3-Pentafluoropropane)	$C_3H_3F_5$	460-73-1
Sodium chloride	NaCl	7647-14-5
Potassium chloride	KCl	7447-40-7
Calcium chloride	$CaCl_2$	10043-52-4
Sodium sulfate	Na_2SO_4	7757-82-6
Sodium bicarbonate	$NaHCO_3$	144-5-8

1.4. Thermodynamic models

Several calculators are defined to simulate the examples of “Rankine Cycles”:

- “Water”: this calculator is only composed of the water component. Hence it uses the “pure water“ thermodynamic model. This calculator is used to simulate the geothermal fluid streams and the cooling water.
- “R600”: this calculator contains the R600 also named n-Butane component. Given the nature of this compound, the thermodynamic model used to represent the phase’s equilibria and the enthalpy calculations is the Peng Robinson equation of state (PR).
- “R245fa”: this calculator contains the “R245fa” (1,1,1,3,3-Pentafluoropropane). Given the nature of this compound, the thermodynamic model used to represent the phase’s equilibria and the enthalpy calculations is the Soave Redlich and Kwong equation of state (SRK). This calculator is used exclusively in the mixed cycle.
- “Well water”: this calculator contains all the components listed in paragraph 1.3 except the organic fluids (R600 and R245fa). This calculator is used to simulate the geothermal fluid streams entering the flowsheet “PSPS_EX_EN-Rankine-cycles-single-flash-sour-water.pmp3”. The thermodynamic profile used to represent the phase’s equilibria and the enthalpy calculations is “Sour Water”.

The thermodynamic models used are documented in the thermodynamic help accessible from the calculator definition window.

(*)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

1.5. Operating conditions

1.5.1. Simple cycle

The operating conditions of the different modules in the simple cycle are the following:

- ✓ Process feeds

Name	**Production well**	**Cold water**
Partial mass flowrates (t/h):		
Water	310	2000
R600	0	0
Temperature (°C)	169	15
Pressure (bar)	20	1

- ✓ Organic Rankine Cycle

Operating mode	Simple cycle
Constraint	On the evaporator utility
Outlet temperature of utility (°C)	96.43

  - ○ Evaporator

Organic fluid superheating (K)	2
Calculation mode: Pinch model	Only pinch provided
Pinch value (K)	10

  - ○ Turbine

Isentropic yield (%)	**Mechanical yield (%)**	**Alternator yield (%)**
75	92	98

  - ○ Condenser

Organic fluid subcooling (K)	2
Calculation mode: Pinch model	Only pinch provided
Pinch value (K)	2

- Pump

Isentropic yield (%)	Mechanical yield (%)	Alternator yield (%)
70	90	98

- Organic fluid

Composition type	Weight
Weight fractions:	
Water	0
R600 (n-BUTANE)	1

Side note: The “Load a predefined fluid” button of the unit operation is used to import the organic fluid calculator and define it as the organic fluid calculator of the Rankine cycle. A new calculator “R600” is then added to the list of calculators.

✓ Generalized heat exchangers

Name	Evaporator	Condenser
Exchanger type	Counter current or multipasses	Counter current or multipasses
Specification type	Other	Other
Specification	Minimal internal temperature approach	Minimal internal temperature approach
Specification value (K)	10	2

✓ Expander

Specification	Outlet pressure supplied by user
Outlet pressure (atm)	2.46
Isentropic efficiency	0.75
Mechanical efficiency	0.92
Electrical efficiency	0.98

- ✓ Centrifugal pump

Specification supplied	Supplied
Exhaust pressure (atm)	29.18
Isentropic efficiency	0.7
Mechanical efficiency	0.9
Electrical efficiency	0.98

1.5.2. Flashes cycles

In this example, two types of flash cycle are presented; the single flash cycle and the double flash cycle.

1.5.2.1. Single flash cycle

The operating conditions of the different modules in the single flash cycle are the following:

- ✓ Process feeds

Name	**Production well**	**Cold water**
Partial mass flowrate of water (t/h)	310	2000
Temperature (°C)	300	15
Pressure (bar)	100	1

For the simulation with electrolytes, the main feed of the process is replaced by the electrolyte aqueous solution. The operating conditions of the stream are the following:

Name	**Production well**
Total mass flowrates (t/h)	310
Mole fractions:	
Water	0.99
Sodium chloride	0.005
Potassium chloride	0.001
Calcium chloride	0.001
Sodium sulfate	0.002
Sodium bicarbonate	0.001
Temperature (°C)	300
Pressure (bar)	100

- ✓ Expansion valve “Flash”

Constraint type	Pressure specification
Pressure specification	Supplied
Pressure (bar)	10

- ✓ Liquid-vapor separator “Separator”

Flash type	Constant pressure and enthalpy flash
Pressure specification	The lowest of the feed streams
Pressure drop (atm)	0
Heat duty specification	Adiabatic

- ✓ Expander

Exhaust pressure (bar)	1
Isentropic efficiency	0.75
Mechanical efficiency	0.92
Electrical efficiency	0.98

- ✓ Generalized heat exchanger “Condenser”

Exchanger type	**Specification type: “Hot stream”**	**Vapor fraction**
Counter current or multipasses	Outlet molar vapor fraction	0

- ✓ Cooler/Heater “District Heating”

Outlet temperature (°C)	40

- ✓ Centrifugal pumps

Name	**P1**	**P2**
Exhaust pressure (bar)	10	100
Volumetric efficiency	0.65	0.65
Mechanical efficiency	0.9	0.9
Electrical efficiency	0.98	0.98
Constraint	-	Fixed liquid physical state

Remark: the mixer “Mixer” is defined with default operating parameters (the outlet pressure is equal to the lowest of the feeds pressures).

1.5.2.2. Double flash cycle

The operating conditions of the different modules in the double flash cycle are the following:

- ✓ Process feeds

Name	Production well	Cold water
Partial mass flowrate of water (t/h)	310	2000
Temperature (°C)	300	15
Pressure (bar)	100	1

- ✓ Expansion valves

Name	Flash 1	Flash 2
Constraint type	Pressure specification	Pressure specification
Pressure specification	Supplied	Supplied
Pressure (bar)	10	2

- ✓ Liquid-vapor separators

The separators “HP Separator” and “LP Separator” are defined with the default operating parameters as shown below:

Flash type	Constant pressure and enthalpy flash
Pressure specification	The lowest of the feed streams
Pressure drop (atm)	0
Heat duty specification	Adiabatic

- ✓ Expanders

Name	HP Turbine	LP Turbine
Exhaust pressure (bar)	6	0.1
Isentropic efficiency	0.7	0.75
Mechanical efficiency	0.92	0.92
Electrical efficiency	0.98	0.98

- ✓ Generalized heat exchanger “Condenser”

Exchanger type	Specification type: “Hot stream”	Vapor fraction
Counter current or multipasses	Outlet molar vapor fraction	0

- ✓ Cooler/Heater “District Heating”

Outlet temperature (°C)	40

- ✓ Centrifugal pumps

Name	P1	P2
Exhaust pressure (bar)	2	100
Volumetric efficiency	0.65	0.65
Mechanical efficiency	0.9	0.9
Electrical efficiency	0.98	0.98
Constraint	-	Fixed liquid physical state

Remark: all the mixers (“M1” and “M2”) are defined with default operating parameters (the outlet pressure is equal to the lowest of the feeds pressures).

1.5.3. Mixed cycle

The operating conditions of the different modules in the mixed cycle are the following:

- ✓ Process feeds

Name	Production well	Cold water input 1	Cold water input 2
Partial mass flowrates (t/h):			
Water	310	2000	2000
R600	0	0	0
R245fa	0	0	0
Temperature (°C)	300	15	15
Pressure (bar)	100	1	1

- ✓ Expansion valve “Flash”

Constraint type	Pressure specification
Pressure specification	Supplied
Pressure (bar)	15

- ✓ Liquid-vapor separator “Separator”

Flash type	Constant pressure and enthalpy flash
Pressure specification	The lowest of the feed streams
Pressure drop (atm)	0
Heat duty specification	Adiabatic

- ✓ Expanders

Name	**Steam turbine**	**HP Turbine**	**LP Turbine**
Specification	Expansion ratio	Outlet pressure	Outlet pressure
Specification value	2	2.5 atm	1.5 atm
Isentropic efficiency	0.75	0.75	0.75
Mechanical efficiency	0.92	0.92	0.92
Electrical efficiency	0.98	0.98	0.98

- ✓ Generalized heat exchangers

Name	**Exchanger type**	**Constraint type: “Other”**	**Temperature deviation (K)**
HP Evaporator	Counter current or multipasses	Minimal internal temperature approach	5
LP Evaporator	Counter current or multipasses	Minimal internal temperature approach	5

Name	**Exchanger type**	**Constraint type: “Hot stream”**	**Temperature difference (K)**
HP Condenser	Counter current or multipasses	Subcooled below its bubble point	2
LP Condenser	Counter current or multipasses	Subcooled below its bubble point	2

- ✓ Cooler/Heater “District heating”

Outlet temperature (°C)	40

- ✓ Centrifugal pumps

Name	**HP Centrifugal pump**	**LP Centrifugal pump**
Exhaust pressure (atm)	33	25
Isentropic efficiency	0.7	0.7
Mechanical efficiency	0.9	0.9
Electrical efficiency	0.98	0.98

Remark: the mixer “Mixer” is defined with default operating parameters (the outlet pressure is equal to the lowest of the feed).

1.6. Initialization

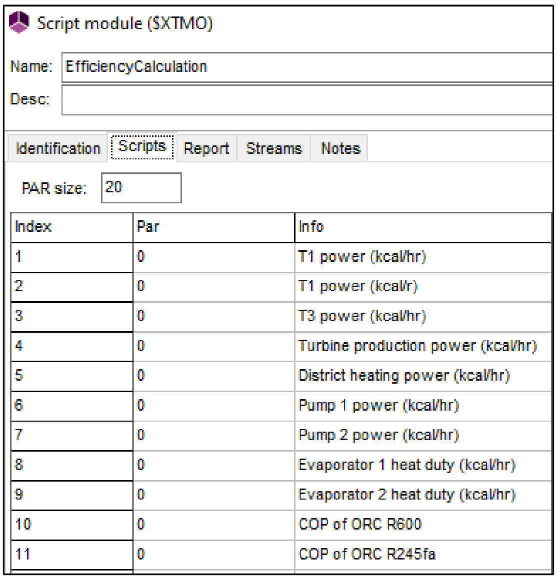
The calculation sequence is automatically determined by ProSimPlus. Only one tear stream was detected in the simple cycle: the stream “S8” (inlet of the evaporator), while there are two tear streams in the mixed cycle: the stream “4” (inlet of the evaporator “HP Evaporator”) in the first ORC cycle and the stream “B4” (inlet of the evaporator “LP Evaporator”) in the second ORC cycle. The following initializations of the streams are used:

	Simple cycle	**Mixed cycle**	
Stream	S8	4	B4
Partial mass flowrates (t/h):			
R600 (n-BUTANE)	190	250	0
R245fa	-	0	333.33
Water	0	0	0
Temperature (K)	330	330	330
Pressure (atm)	34	34	34

2. RESULTS

2.1. Results summary

A Windows script module called “Efficiency Calculation” can be found in the simulation “PSPS_EX_EN-Rankine-cycles-mixed-cycle.pmp3”. It is used to summarize the global performance of the geothermal power plant along with the COP of the Rankine cycles.



Name: EfficiencyCalculation

Desc:

PAR size: 20

Index	Par	Info
1	0	T1 power (kcal/hr)
2	0	T1 power (kcal/r)
3	0	T3 power (kcal/hr)
4	0	Turbine production power (kcal/hr)
5	0	District heating power (kcal/hr)
6	0	Pump 1 power (kcal/hr)
7	0	Pump 2 power (kcal/hr)
8	0	Evaporator 1 heat duty (kcal/hr)
9	0	Evaporator 2 heat duty (kcal/hr)
10	0	COP of ORC R600
11	0	COP of ORC R245fa

The following script has been used in the “Efficiency Calculation” Windows script module in order to calculate the total electric power produced and the efficiency of the cycle:

```
'-----------------------------------------------------------------------------'
' CALL OF "UNIT CONVERSION" SCRIPT
'-----------------------------------------------------------------------------'
with CreateObject("Scripting.FileSystemObject")
  ExecuteGlobal .OpenTextFile(Project.ApplicationPath & "Scripts\UnitConversion.vbs", 1).ReadAll()
  ExecuteGlobal .OpenTextFile(Project.ApplicationPath & "Scripts\FormatDouble.vbs", 1).ReadAll()
end with

'-----------------------------------------------------------------------------'
' Calculation of the total electric power and efficiencies
'-----------------------------------------------------------------------------'
Function OnCalculation()
' COP of Organic Rankine Cycle R600
    Module.parameter(10) = (abs(Project.Modules("HP Turbine").Power) - abs(Project.Modules("HP
Centrifugal pump").UsefulPower)) / abs(Project.Modules("HP Evaporator").HeatDuty)
    Module.parameter(11) = (abs(Project.Modules("LP Turbine").Power) - abs(Project.Modules("LP
Centrifugal pump").UsefulPower)) / abs(Project.Modules("LP Evaporator").HeatDuty)

' Total electric power of steam turbines
    Module.parameter(1) = abs(Project.Modules("Steam turbine").Power)
    Module.parameter(2) = abs(Project.Modules("HP Turbine").Power)
    Module.parameter(3) = abs(Project.Modules("LP Turbine").Power)
    Puissance_Tot = Project.Modules("Steam turbine").Power + Project.Modules("HP Turbine").Power +
Project.Modules("LP Turbine").Power
    Module.parameter(4) = Puissance_Tot
'
' Thermal energy for district heating
    Module.parameter(5) = Project.Modules("District Heating").HeatDuty
'
    OnCalculation = true
End Function
```

```
'------------------------------------------------------------------------------
' Print results
'------------------------------------------------------------------------------
Sub OnPrintResults()
     Module.PrintReport("COEFFICIENT OF PERFORMANCE (COP) OF ORGANIC RANKINE CYCLE (ORC)")
     Module.PrintReport("COP of R600 ORC = " & NiceFloat(Module.parameter(10)))
     Module.PrintReport("COP of R245fa ORC = " & NiceFloat(Module.parameter(11)))
     Module.PrintReport("")
     Module.PrintReport("")
     Module.PrintReport("ELECTRIC POWER")
     Module.PrintReport("Steam turbine (MW) = " & NiceFloat(ConvertFromProSim("Power",
abs(Module.parameter(1)), "MW"))& "(MW)")
     Module.PrintReport("HP Turbine (MW) = " & NiceFloat(ConvertFromProSim("Power",
abs(Module.parameter(2)), "MW"))& "(MW)")
     Module.PrintReport("LP Turbine (MW) = " & NiceFloat(ConvertFromProSim("Power",
abs(Module.parameter(3)), "MW"))& "(MW)")
     Module.PrintReport("-----------------------------------------------------------------")
     Module.PrintReport "Total power produced (MW) = " & NiceFloat(ConvertFromProSim("Power",
abs(Module.parameter(4)), "MW"))& "(MW)")
     Module.PrintReport("")
     Module.PrintReport("")
     Module.PrintReport("THERMAL ENERGY POWER")
     Module.PrintReport "District heating power (MW)    = " & NiceFloat(ConvertFromProSim("Power",
abs(Module.parameter(5)), "MW"))& "(MW)")
     Module.PrintReport("")
     Module.PrintReport("")


End Sub
```

2.2. Net power output and heat recovery

Simulation results	Notation	Simple cycle	Single flash cycle	Double flash cycle	Mixed cycle
Expander (MW)	A	3.7	6.5	-	-
Steam turbine (MW)	B	-	-	-	2.2
HP Turbine (MW)	C	-	-	1.5	5.5
LP Turbine (MW)	D	-	-	9.7	4.2
Total electric power produced (MW)	E (=A+B+C+D)	3.7	6.3	11.2	12.0
Heat recovered at “District heating” (MW)	F	-	42.7	19	31.3

2.3. Coefficients of performance (COP) of Rankine cycles

2.3.1. Simple cycle

Simulation results	Notation	Using the module "ORC"	Using independent unit operations
Expander (MW)	G	3.7	3.7
Pump (MW)	H	0.4	0.4
Evaporator (MW)	I	26.7	26.7
COP	J (=(G-H)/I)	0.12	0.12

2.3.2. Flashes cycles

Simulation results	Notation	Single flash cycle	Double flash cycle
Output power of turbines (MW)	O	6.5	11.2
Output power of pumps (MW)	P	1.4	1.5
Heat supplied to system (MW)	Q	100	100
COP	R (=(O-P)/Q)	0.05	0.097

Remark: the heat supplied to the system is obtained by subtracting the enthalpy of the process outlet material stream (stream "10" for the single flash cycle; "14" for the double flash cycle) with the enthalpy of the process inlet (stream "01").

2.3.3. Mixed cycle

Simulation results	Notation	ORC of R600	ORC of R245fa
Expander (MW)	K	5.5	4.2
Pump (MW)	L	0.6	0.3
Evaporator (MW)	M	38.9	31.2
COP	N (=(K-L)/M)	0.128	0.126

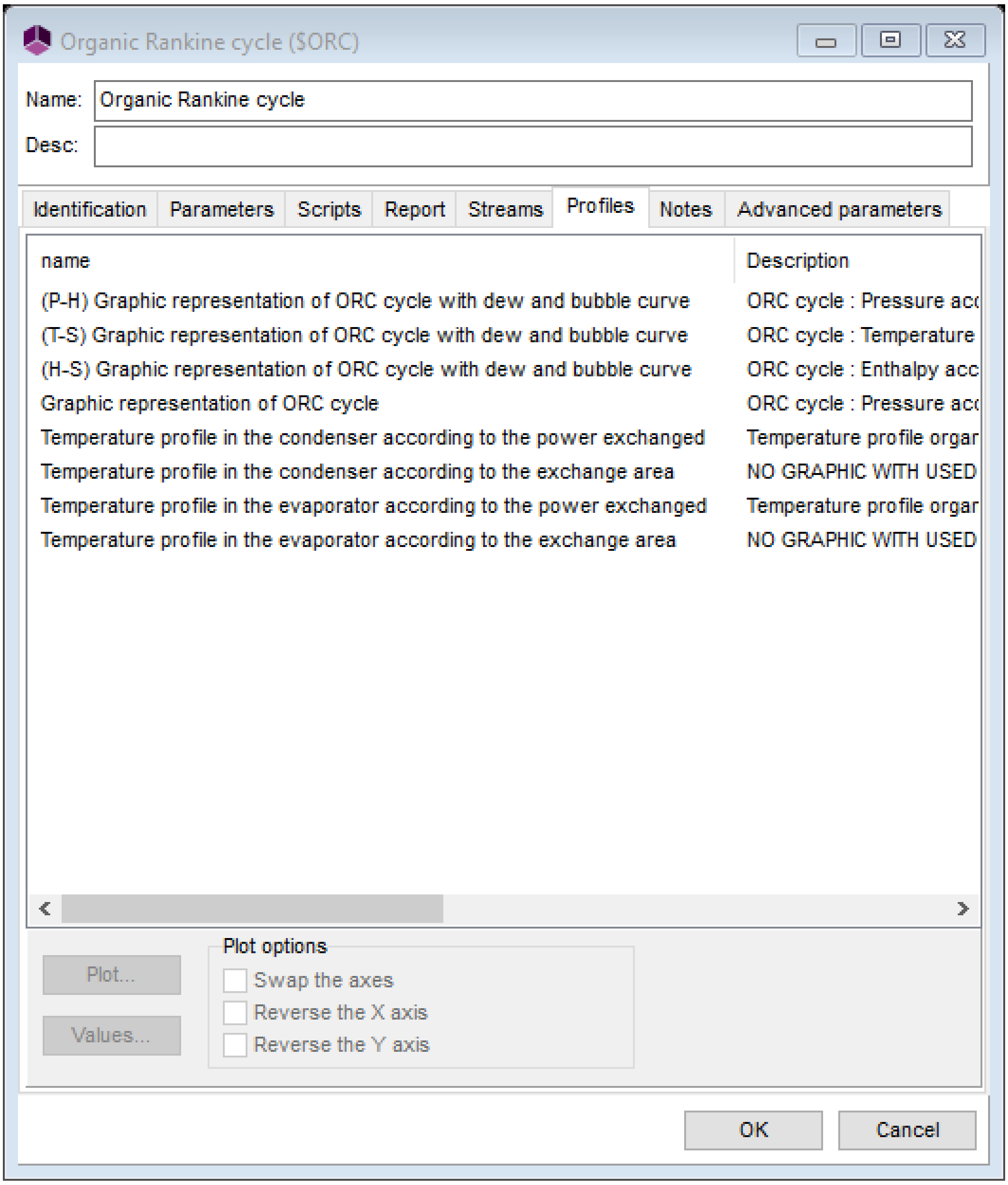
2.4. Comparison between process feed’s pure water and aqueous electrolyte solution

Feed	**Pure water**	**Water - Electrolytes**
Vaporized molar fraction	0.29	0.27
Electric power produced (MW)	6.5	5.7
Heat recovered at “District heating” (MW)	42.7	40.9

2.5. Thermodynamic cycles

2.5.1. Simple cycle

It is possible to plot the Pressure (P) – Enthalpy (H) diagram of the cycle directly in the “Organic Rankine Cycle (ORC)” module. In the “Profiles” tab, double-click on “P-H diagram”:

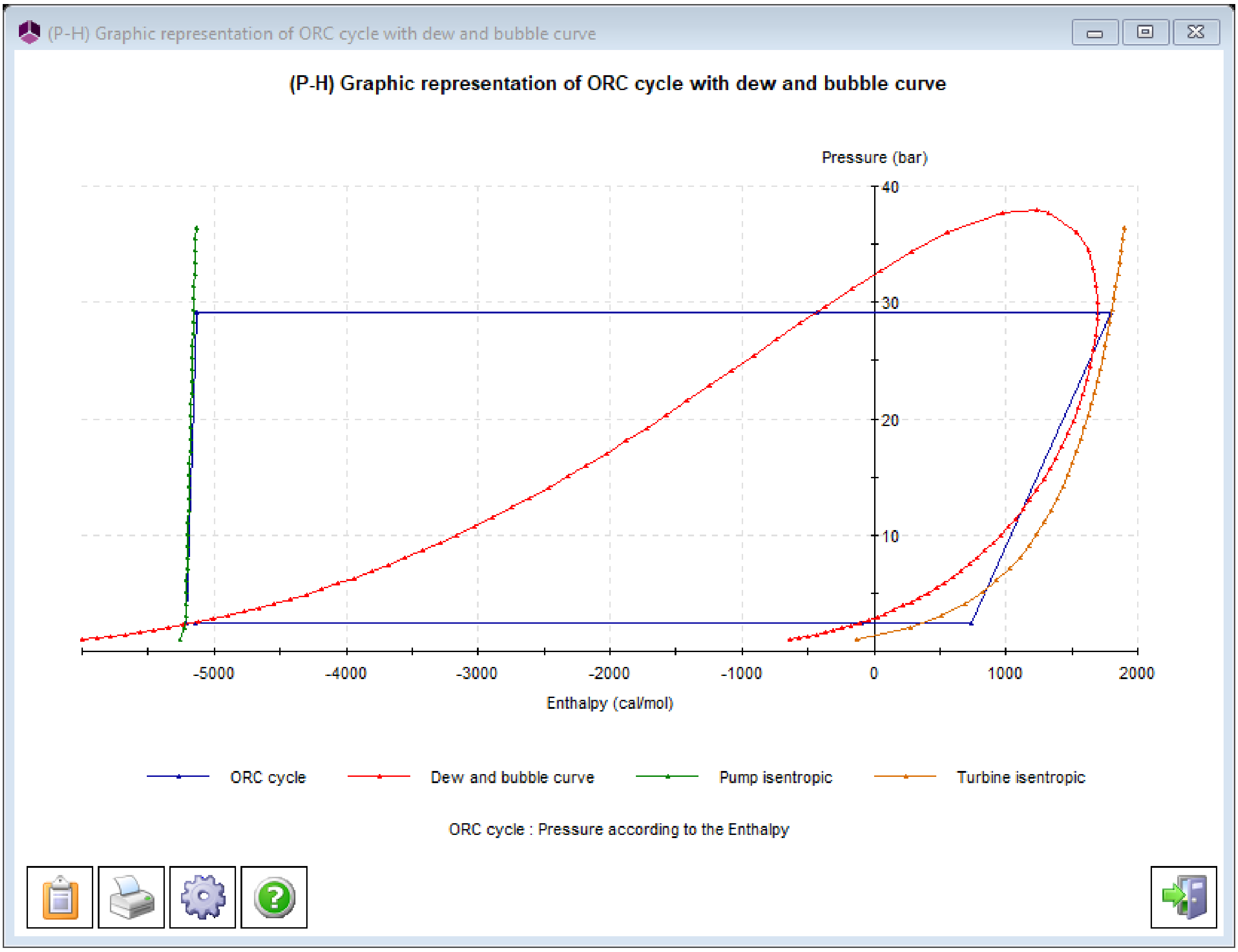


Name: Organic Rankine cycle

Desc:

name	Description
(P-H) Graphic representation of ORC cycle with dew and bubble curve	ORC cycle : Pressure acc
(T-S) Graphic representation of ORC cycle with dew and bubble curve	ORC cycle : Temperature
(H-S) Graphic representation of ORC cycle with dew and bubble curve	ORC cycle : Enthalpy acc
Graphic representation of ORC cycle	ORC cycle : Pressure acc
Temperature profile in the condenser according to the power exchanged	Temperature profile orgar
Temperature profile in the condenser according to the exchange area	NO GRAPHIC WITH USED
Temperature profile in the evaporator according to the power exchanged	Temperature profile orgar
Temperature profile in the evaporator according to the exchange area	NO GRAPHIC WITH USED

The Pressure (P) – Enthalpy (H) diagram of the organic fluid R600 is presented below:

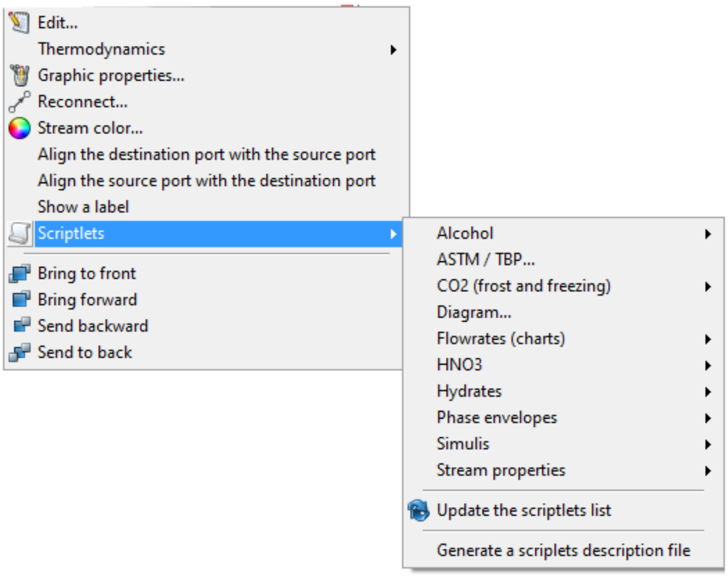


2.5.2. Flashes cycles

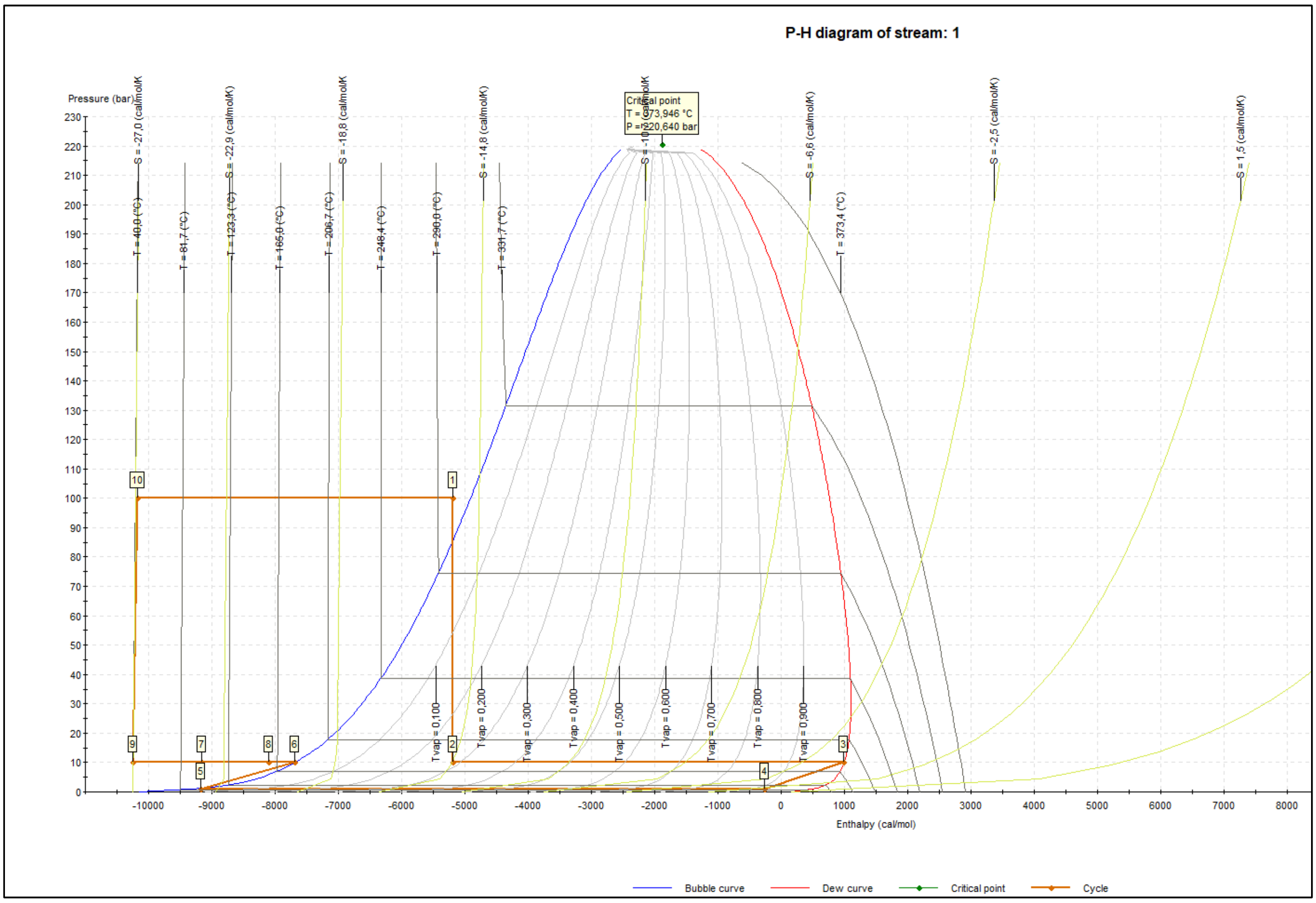
2.5.3.1. <u>Single flash cycle</u>

The scriptlet “Diagram” is used to plot a cycle or different points of the process on a diagram (P-H, P-S, P-T, T-H, T-S) with the phase envelope of the organic fluid.

Select a material stream of the cycle and right-click on “Scriptlets -> Diagram”:

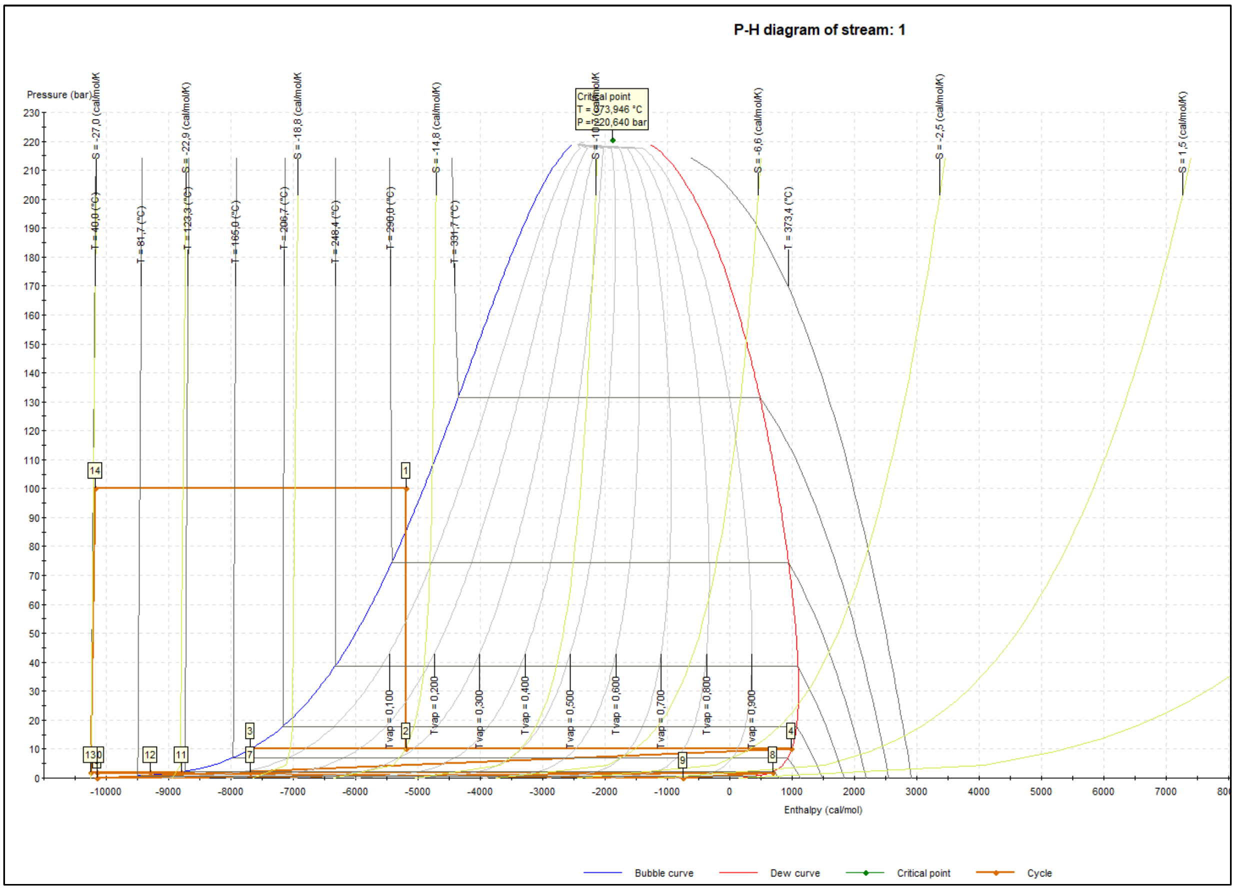


The results of the scriptlet are directly plotted:



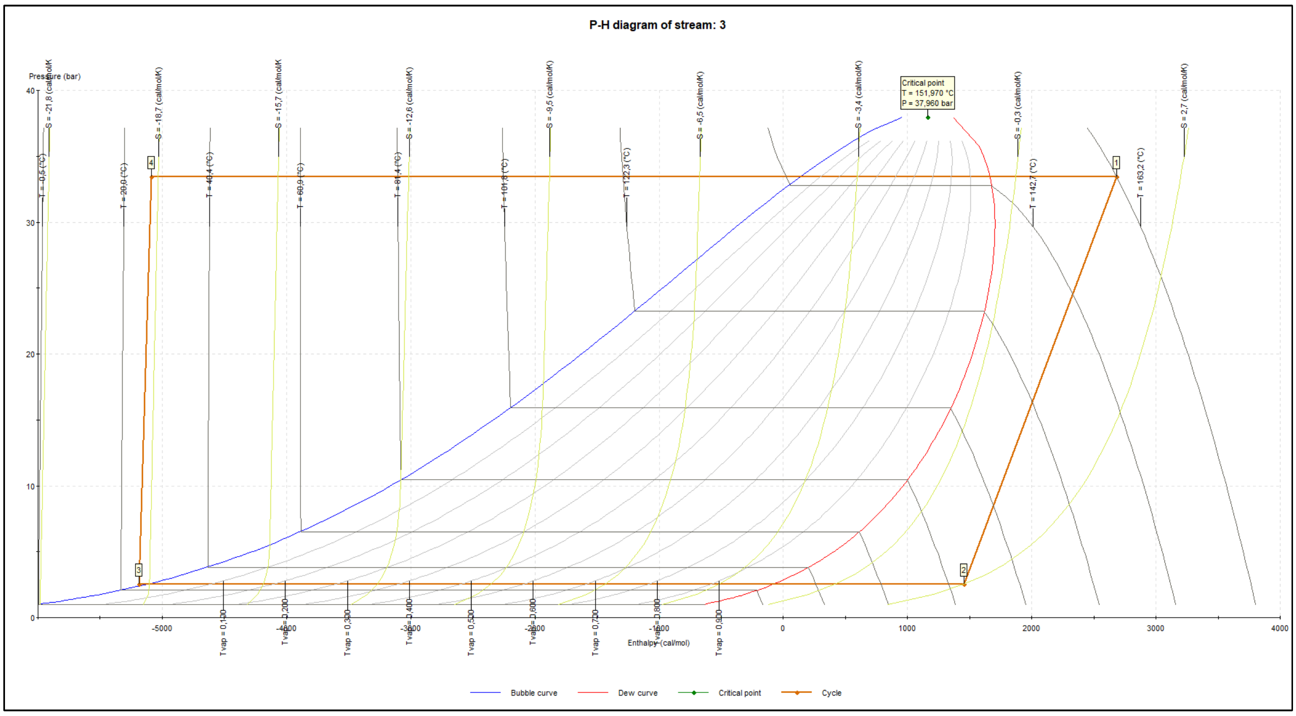
2.5.3.2. Double flash cycle

The Pressure (P) – Enthalpy (H) diagram for the double flash cycle is also plotted with the scriptlet “Diagram":

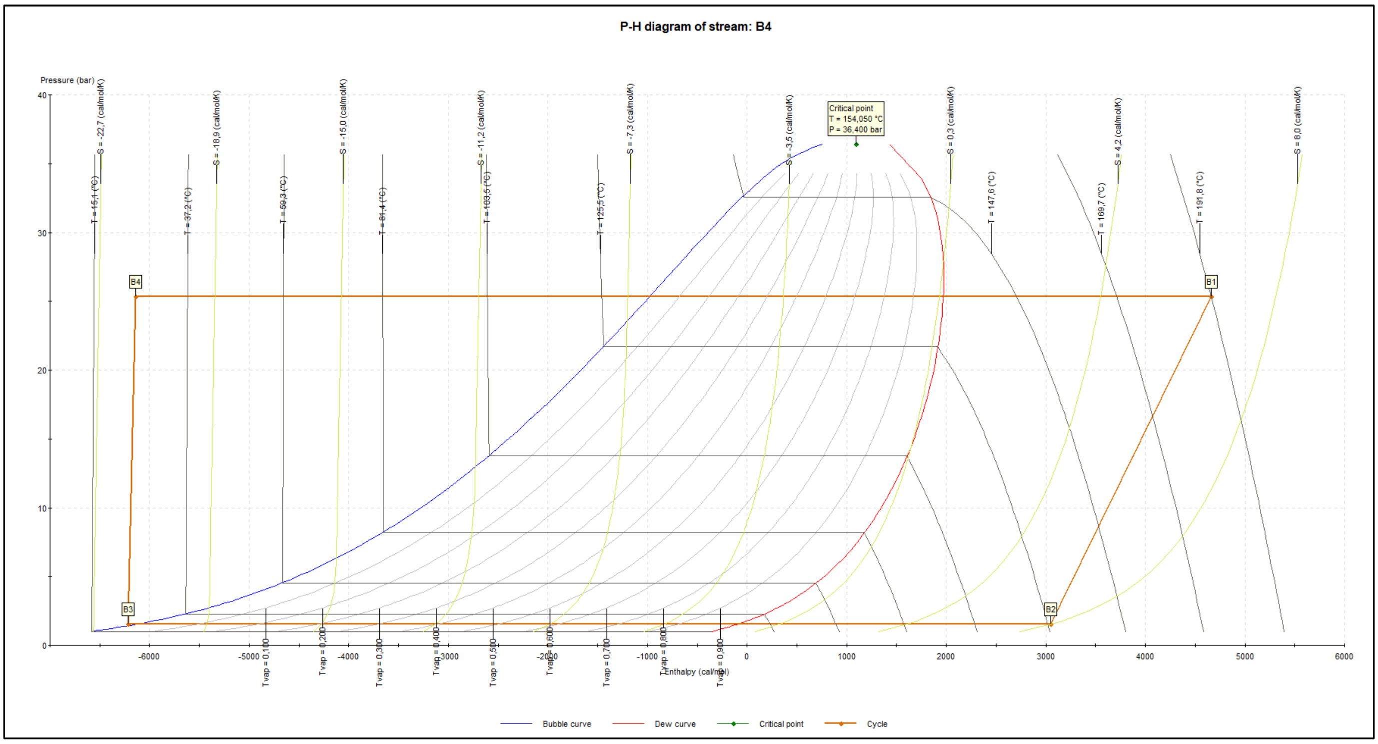


2.5.3. Mixed cycle

The Pressure (P) – Enthalpy (H) diagram of the organic fluid R600 in the first Rankine cycle is presented below:



The Pressure (P) – Enthalpy (H) diagram of the organic fluid R245fa in the second Rankine cycle is presented below:



3. REFERENCES

[VAL11]	Valdimarsson P, “Geothermal Power Plant Cycles and Main Components”, UNU-GTP and LaGeo, Santa Tecla, El Salvador (2011).
[WIL19]	Wilding, W. V.; Knotts, T. A.; Giles, N. F.; Rowley, R. L. DIPPR Data Compilation of Pure Chemical Properties; Design Institute for Physical Properties, AIChE: New York, NY (2019)