System cost and efficiency optimization by heat exchanger performance simulations

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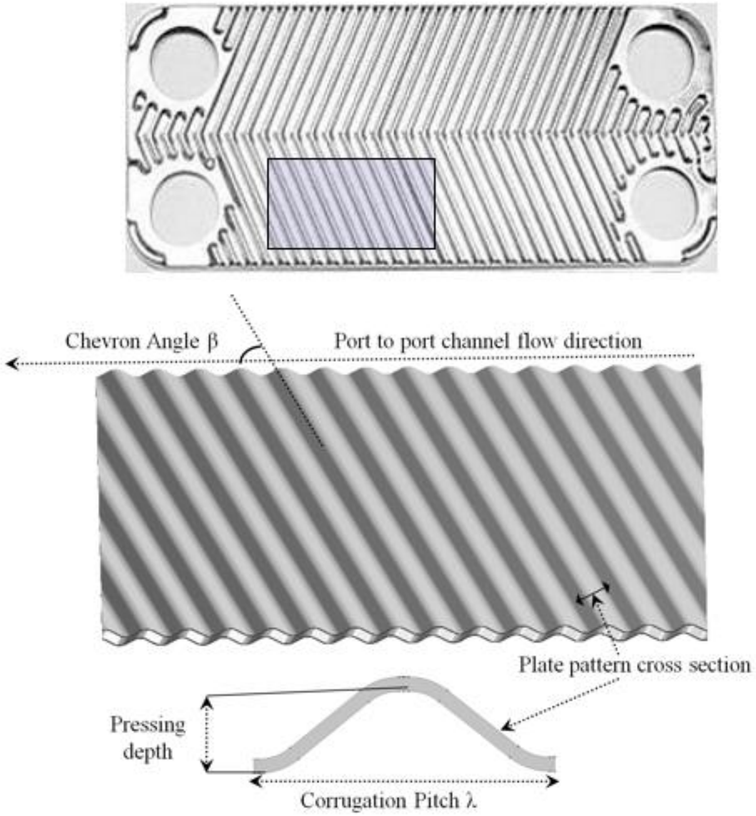
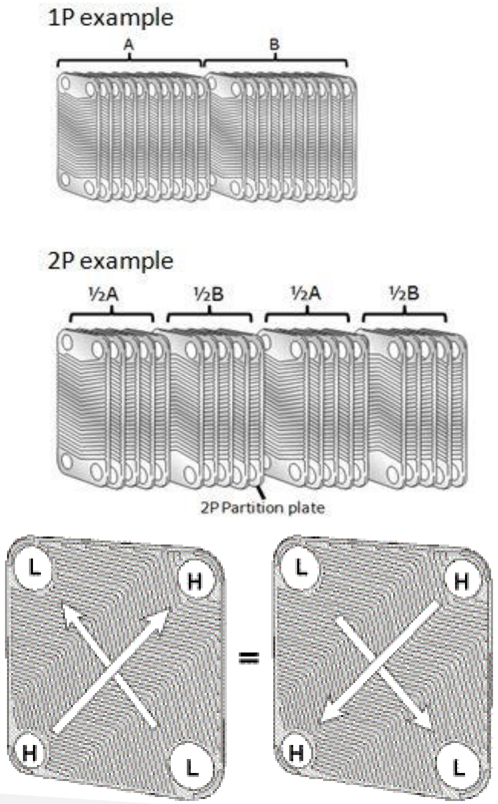
Brazed plate heat exchangers – Plate pattern & executions



Parameters that can be altered in a standard corrugation pattern to obtain desired characteristics include:

- *Chevron angle of the corrugation*
- *Pressing depth*
- *Corrugation pitch*
- *Plate aspect ratio*
- *Design of distribution area*
- *Port location*
- *Flow arrangement*

Execution and **flow arrangement** can be used to obtain desired characteristics



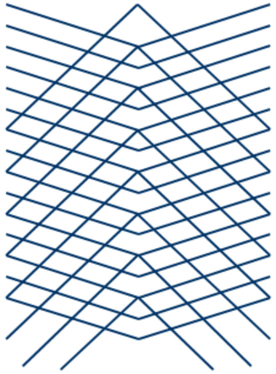


Plate mixing allows to attain **intermediate** thermal and hydraulic characteristics. A wide range of performance/ products can be achieved by mixing plates in various ways

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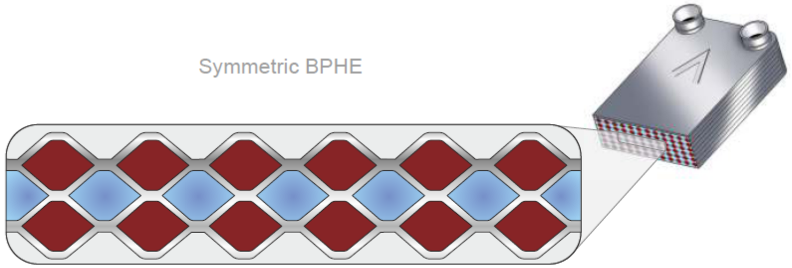
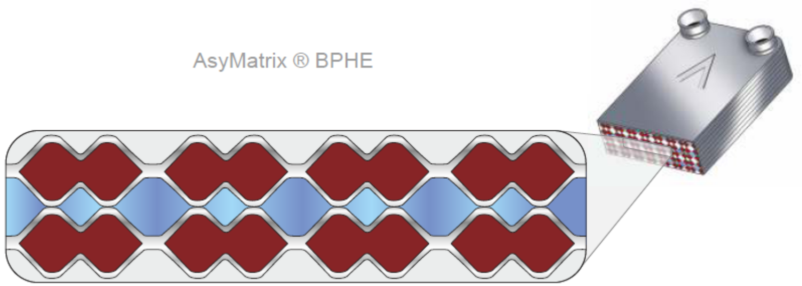
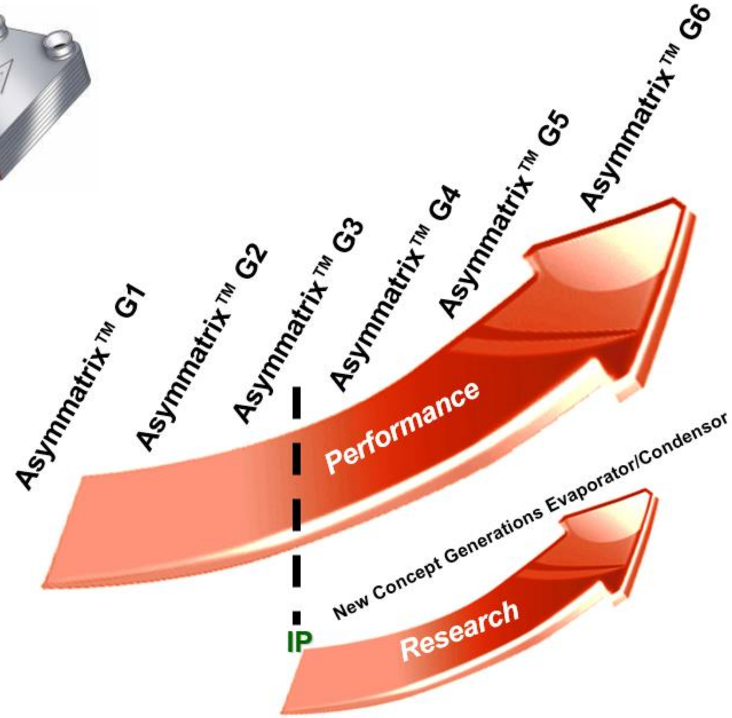
Brazed plate heat exchangers – Asymmetric plate design







Asymmetric plate design allows for **flow channel optimization** based on the characteristics of working media and the thermodynamic process.

For example, the thermal resistance of the working fluid is reduced by utilizing a **narrow flow path** and the flow work of the secondary fluids can be reduced using a **wider channel**.

Various **degree of asymmetry** with varying degree of volume, thermal and hydraulic characteristics are developed and tested at SWEP.

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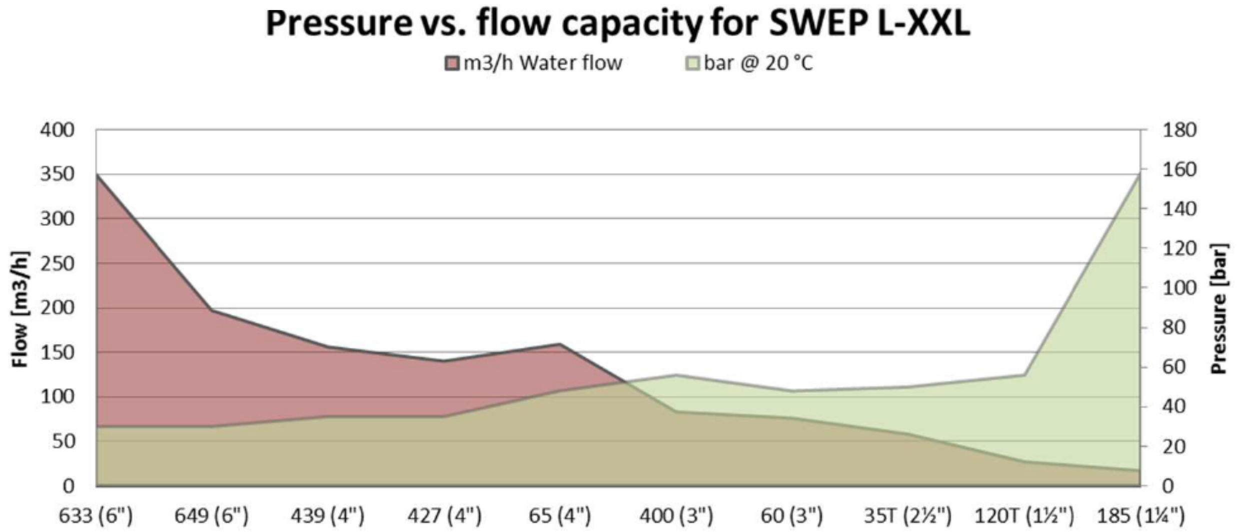
BPHE range for ORC applications



BPHEs can be used as pre-heater, evaporator, recuperator, condenser and sub-cooler. Applicable for modules rated below 200 kWe

16-45 bar pressure rating. Up to 350 m^3/h water capacity, DN 150, 6"

Pressure rating degrades as a function of operating temperature. The derating at 200°C, from 20°C, is up to 25%

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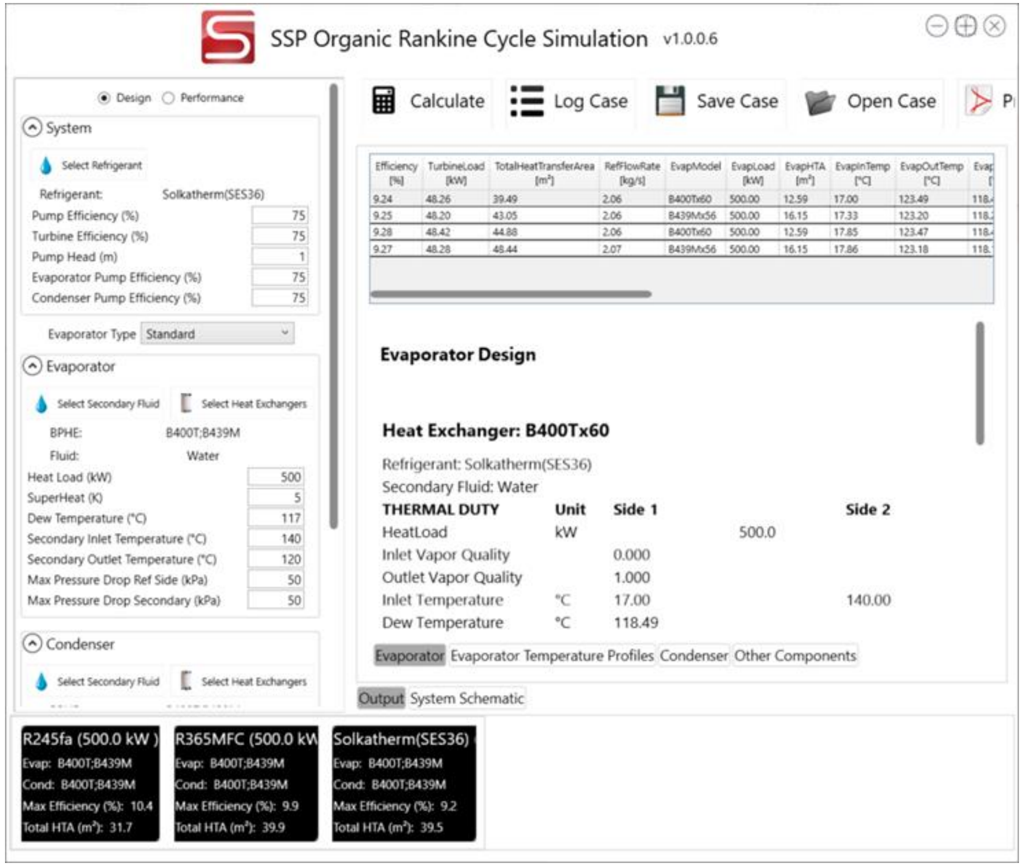
Need for simulation with detailed BPHE calculations



The main goal is to support:

early phase decision making such as choice of thermodynamic cycle, working fluid etc.,
design phase for system design and heat exchanger selection, &
post-launch phase where an existing design might be adopted to use with different heat sources

To identify which heat exchanger positions that are **beneficial operation wise** and add efficiency considering **return of investment.**

Detailed modeling of heat exchangers handles issues such as **internal pinch** with mixed fluid phases, **maldistribution of flow within the heat exchanger at part load conditions** etc., which black-box models don't handle.

Provide a **quick and simultaneous BPHE selection tool** for ORC systems and thus preventing iterative component calculations.

Calculation modes and functional map

Design mode
- Vary working fluid
- Vary thermodynamic cycle
- Add pre-heater
- Add sub-cooler
- Add recuperator

Performance mode
- Vary capacity
- Vary input temperature
- Vary coolant temperature
- Vary working fluid
- Vary secondary fluids

Efficiency vs. Cost

Design mode targets early phase where system design together with heat exchanger selection is conducted. **Performance calculations** target varying operating conditions for selected design.

SSP Organic Rankine Cycle Simulation – Functional Map

Heat input			
Pre-heater	Evaporator		Super-heater
Yes/No	Yes		Yes/No
Design / Performance	Design / Performance	Liquid cooling / Cascaded	Design / Performance

Cycle	
Sub-critical	Trans-critical
Either/or	

Feature
Recuperator
Yes/No
Parametric

Heat output	
Condenser	Sub-cooler
Yes	Yes/No
Design / Performance	Design / Performance

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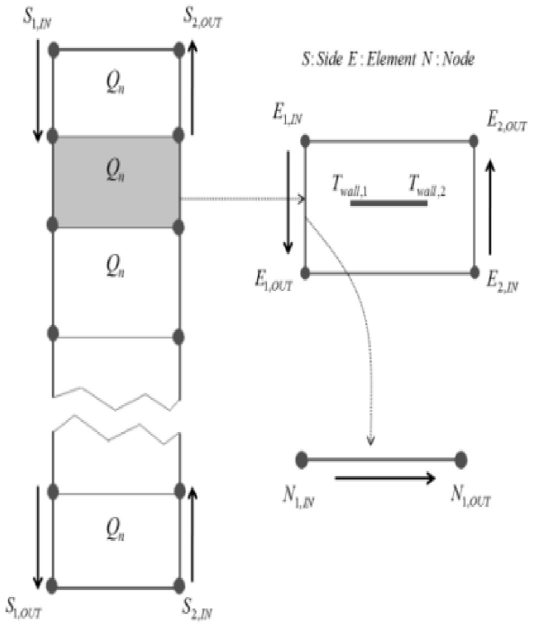
Component calculations and fluid properties

Generalized BPHE rating method

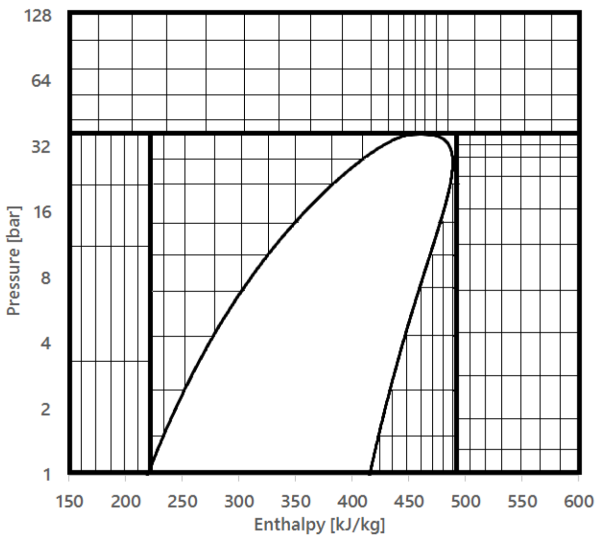


$$T_{Wall,1} = \bar{T}_{E1} - \frac{U_n}{h_{E1}}\left[\bar{T}_{E1} - \bar{T}_{E2}\right]$$

$$T_{Wall,2} = \bar{T}_{E2} - \frac{U_n}{h_{E2}}\left[\bar{T}_{E2} - \bar{T}_{E1}\right]$$

Convergence Criteria:
Wall Temperatures

Refrigerant properties using bi-liner **interpolation** of saved property maps



Simplified **isentropic** efficiency models are used for turbine and pump components (software is prepared to use performance maps)

Initially **21 commonly used refrigerants** in ORC systems are implemented. Super critical properties are available for neo-pentane, pentane, iso-pentane, R245fa, R134a and R507a. A large number of secondary fluids (brines, thermal oils etc.,) are included.

Steady state system solver based on the convergence of saturation points in the system

No heat loss or pressure drop outside specified components

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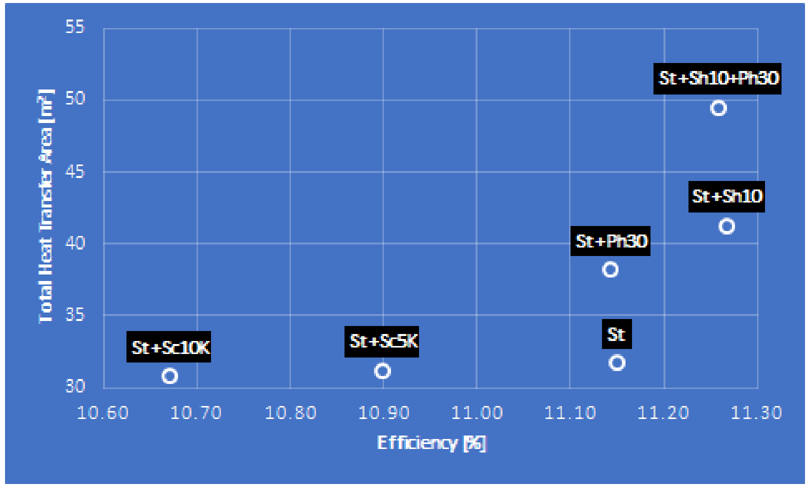
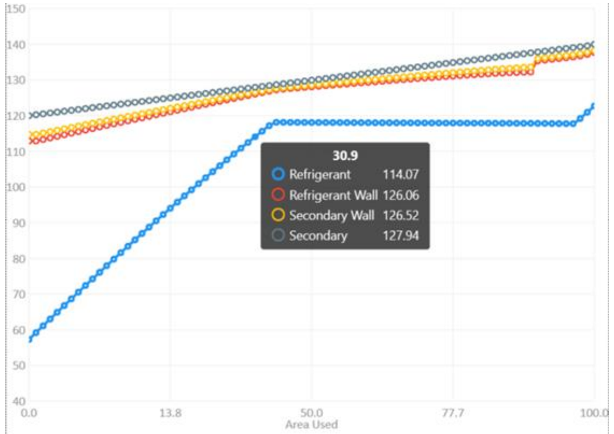
Calculation results – state variables





Evaporator Design

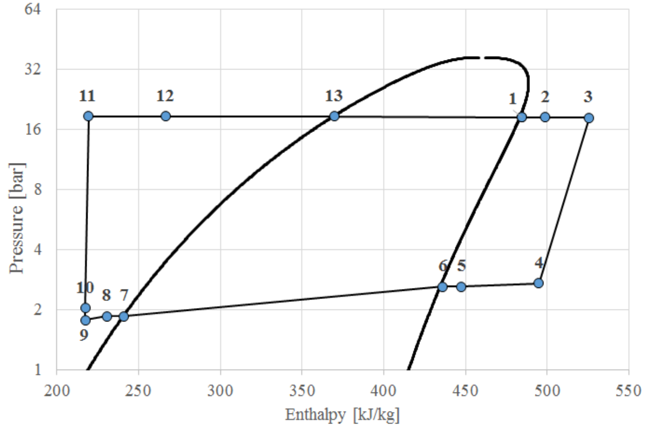
Heat Exchanger: B400Tx60

Refrigerant: R245fa

Secondary Fluid: Water

THERMAL DUTY	**Unit**	**Side 1**		**Side 2**
HeatLoad	kW		500.0	
Inlet Vapor Quality		0.000		
Outlet Vapor Quality		1.000		
Inlet Temperature	°C	49.69		140.00
Dew Temperature	°C	117.53		
SuperHeating	K	10.00		
Outlet Temperature	°C	127.53		120.00

Node [-]	Temperature [°C]	Pressure [bar]	Enthalpy [kJ/kg]	Entropy [kJ/(kg K)]	Density [kg/m³]
1	117.96	18.52	484.77	1.80	113.51
2	122.96	18.52	492.15	1.82	107.83
3	142.96	18.39	519.46	1.89	91.92
4	94.93	2.70	488.95	1.92	12.35
5	51.84	2.60	446.49	1.80	13.85
6	41.06	2.60	436.14	1.76	14.49
7	31.08	1.85	241.05	1.14	1,321.80
8	29.08	1.85	238.39	1.13	1,327.36
9	19.08	1.77	225.24	1.09	1,354.54
10	19.08	1.90	225.24	1.09	1,354.58
11	19.98	18.71	226.95	1.09	1,357.09
12	51.72	18.69	269.41	1.23	1,268.99
13	118.45	18.71	370.65	1.51	1,006.95



Example of BPHE temperature profiles and state variables generated by ORC system simulation program

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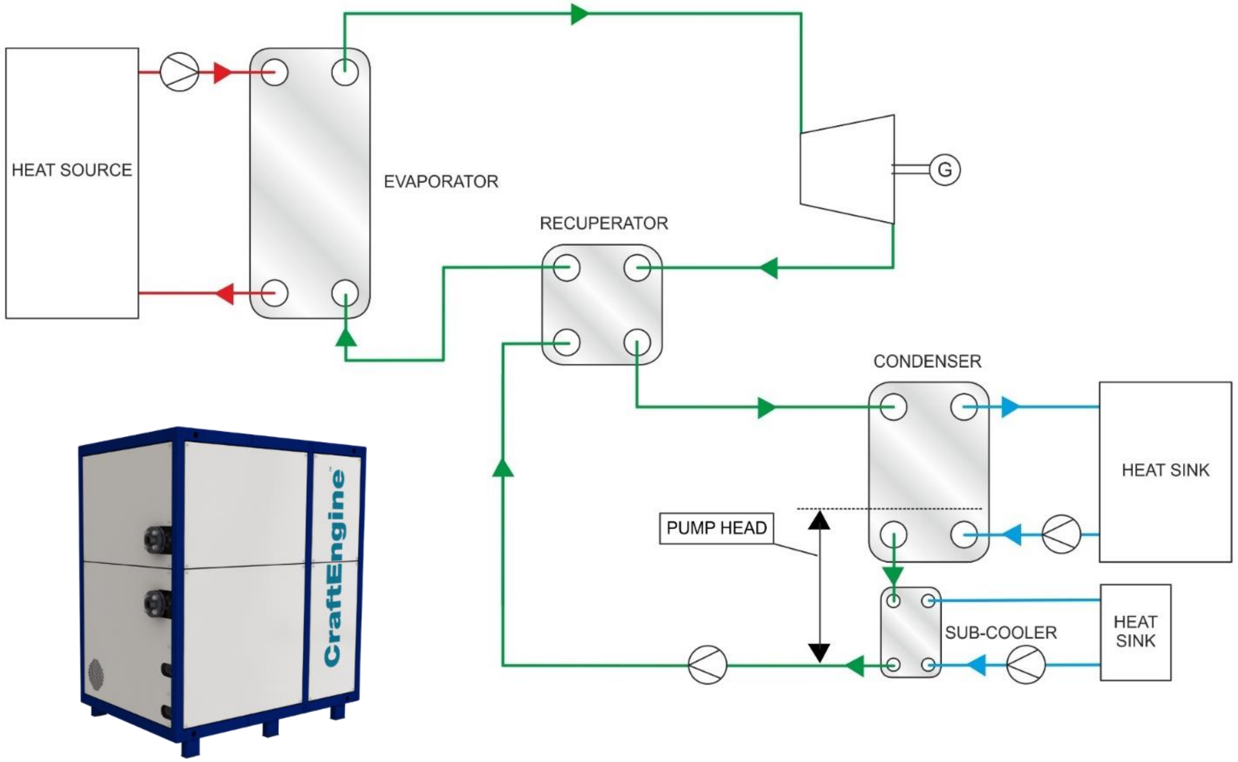
Validation against experimental data

SWEP BPHEs are tested in Viking Heat Engines CraftEngine CE10, a piston based ORC system*

The tested system targets source temperatures in the range of **100°C to 200°C** and heat input of **25 to 150 kW***

The thermal efficiency is in the range of 7-12% and electric efficiency in the range of 6-11%

Variable loads tested using **R134a** and **R245fa.** Heat sink temperatures range from 12°C to 35°C and a heat input of 80-100 kW



CraftEngine CE10
Viking Heat Engines

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* Reference: http://www.vikingheatengines.com

Validation against experimental data

R134a and R245fa operated up to 73% and 82% of the critical pressure respectively.

System efficiency/ output predicted with an accuracy of -4 to 6% for low temperature applications and +5-14% for medium temperature applications.

In evaporator, low temperature cases uses up to 60% area for evaporation and 20% each for pre and super heat. In medium temperature cases, 10% area is used for evaporation and up to 80% area for super heat.

Measured data and deviation in mechanical output from the simulation

Work fluid	Expander speed	p_{evap} [bar]	T_{in} [°C]	Output [kW]	Deviation	
R134a	2/3	23,7	100	7,7	-3 %	
	2/3	23,5	99	6,7	-4 %	
	2/3	23,7	100	6,04	0 %	
	Full	29,4	112	10,17	3 %	
	Full	29,6	112	8,99	6 %	
	Full	29,5	112	8,85	6 %	
	Full	23,4	105	9,09	4 %	
R245fa	Full	29,7	180	16,5	9 %	
	Full	26,0	154	10,3	5 %	
	2/3	21,3	180	10,7	14 %	*

*with correction to evaporator super heat in received data, the deviation is in the range of 10%

R245fa:	p_{crit} = 36,4 bar	T_{crit} = 154,1 C
R134a::	p_{crit} = 40,6 bar	T_{crit} = 101,1 C

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Conclusions

A steady state ORC system simulation program is developed **with focus on brazed plate heat exchanger** components. Detailed modeling is used for heat exchangers and approximate models are used for rest of the components

The developed tool can be used to **optimize efficiency and heat exchanger component cost** by varying thermodynamic cycles and working fluids.

The developed tool **provides the accuracy needed** to replicate the **real operation performance** of the studied ORC system. This can be used to evaluate different operating conditions as long as the performance difference is greater than 5%.

With **further calibration** of the physical models at higher temperatures, combined with handling of **non-converging parameter** setup, the program can provide quick (about 10s per simulation), powerful and reliable system development **support to a wide range of ORC systems**.