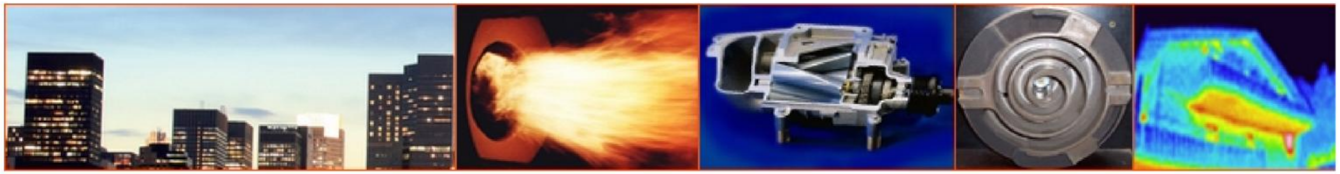


Sizing and parametric optimization of a waste heat to power plant based on Trans-ORC

Van Long Le[1], Michel Feidt[2], Abdelhamid Kheiri[2], Vincent Lemort[1]

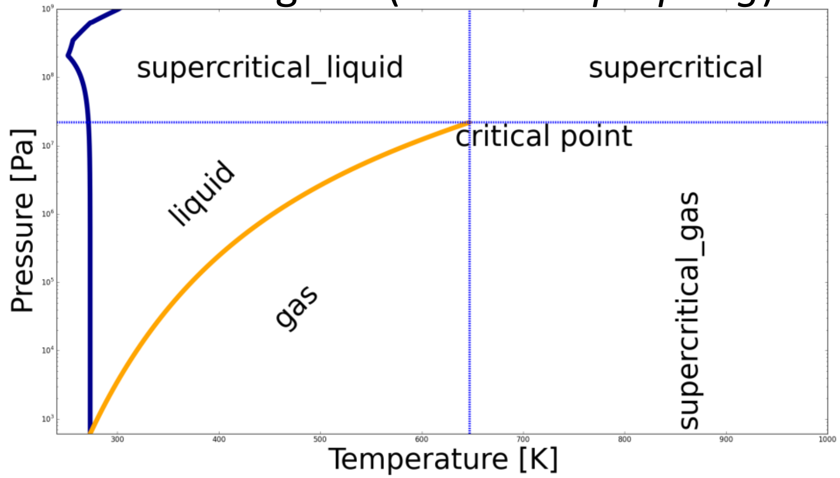
[1] Thermodynamic Laboratory, University of Liège
[2] LEMTA, University of Lorraine

Outline

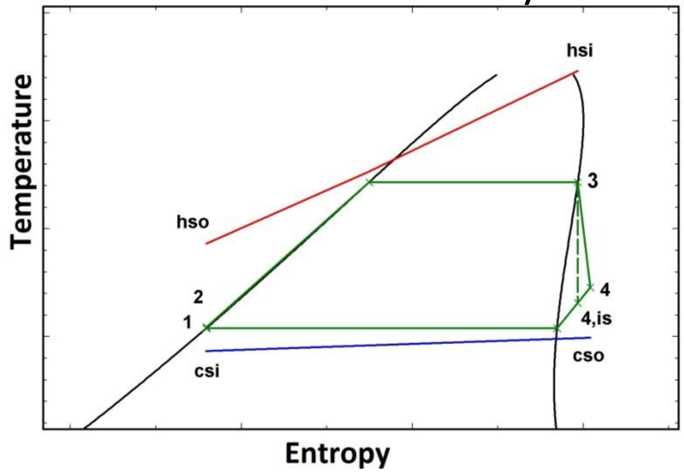
- What is a Trans-ORC?
- Why Trans-ORC?
- Equipment sizing and capital cost estimation
- Parametric optimization
- Conclusions

Trans-ORC: Transcritical Organic Rankine Cycle

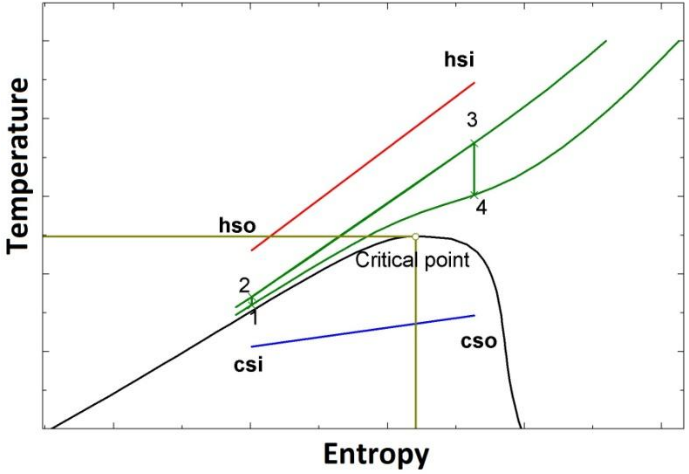
P-T diagram (*www.coolprop.org*)



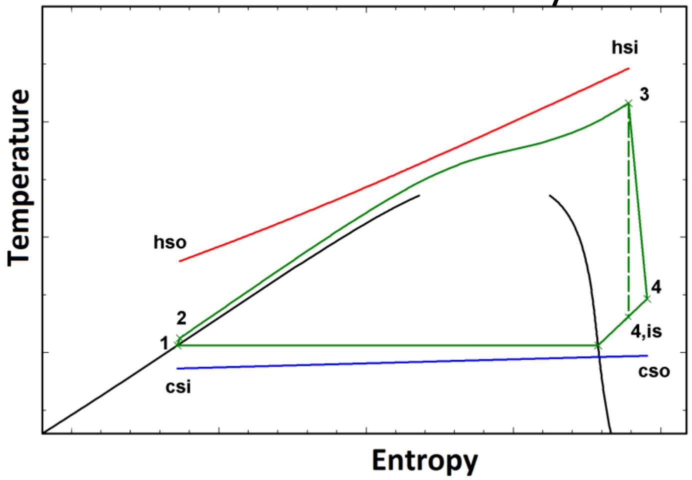
Subcritical Rankine cycle



Supercritical Rankine cycle



Transcritical Rankine cycle



Trans-ORC benefits and challenges

- **Benefits:**
  - Better match between resource cooling curve & working fluid heating curve → greater utilization of the heat source → More power with higher efficiency
  - Single primary heat exchanger
  - Components are compact and the cost of both components and connecting piping can possibly be lower

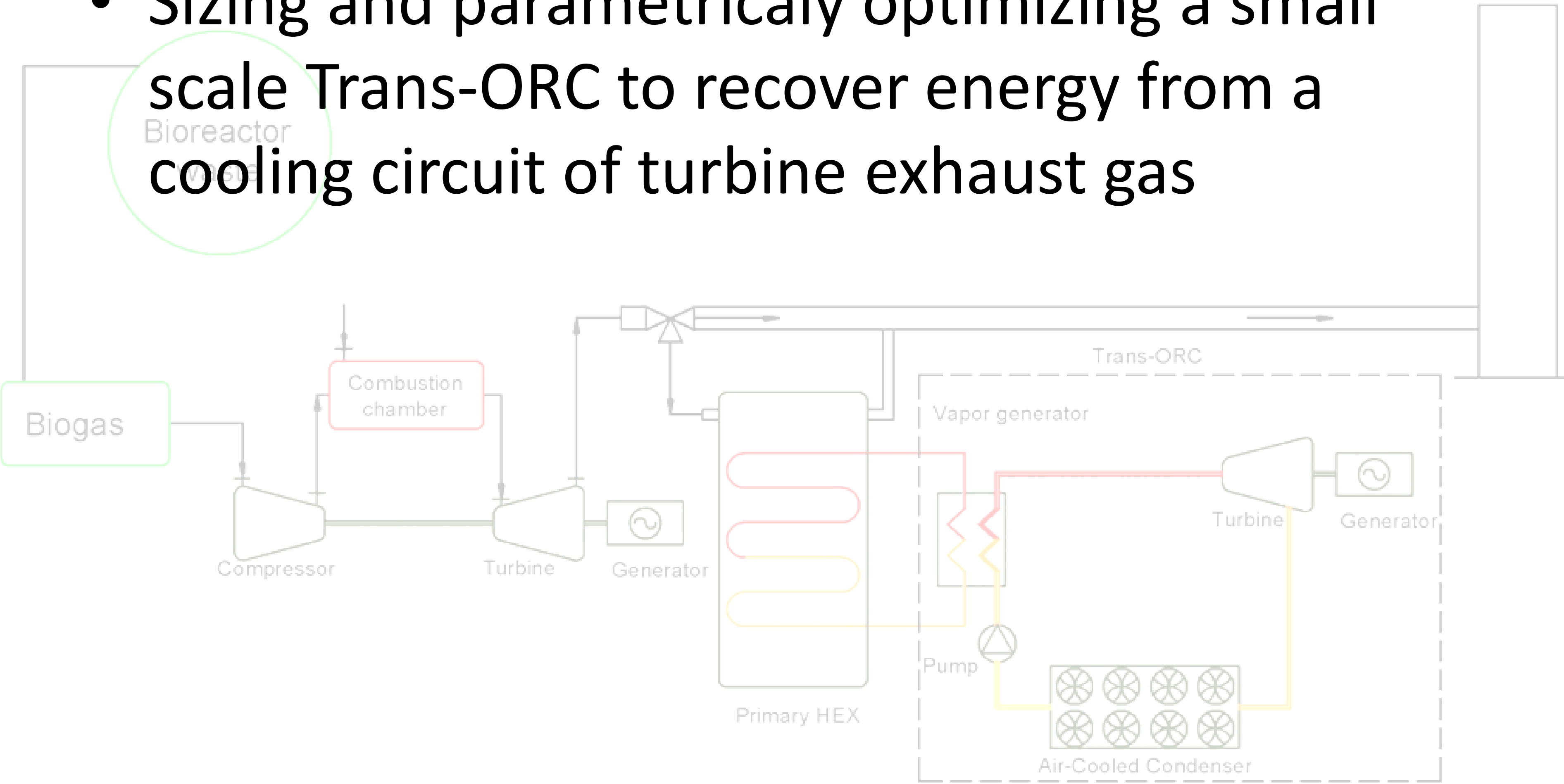
- **Challenges:**
  - Higher cost and more pump power required
  - Additional engineering on supercritical heat exchangers and special attention paid to the pressure ratio limits on the expander

Trans-ORC References

- **Geothermal – Kirchweidach (Germany)**
  - Cryostar Trans-ORC (T_{source}: 130°C, working fluid: refrigerant, Cryostar TG-700: 8.1 MW)
- **Geothermal – Livorno (Italia)**
  - Turboden Trans-ORC (T_{source}: 150°C, working fluid: refrigerant, net power: 500 kWel)
- **Geothermal – TAS Trans-ORCs** (working fluid: R134a)
  - 13.2 MW Gumuskoy power plant
  - ~3 MW TAS Trans-ORC (Net San Emidio power plant)
  - 22 MW Neal Hot Springs Power Plant

Objective

- Sizing and parametricaly optimizing a small scale Trans-ORC to recover energy from a cooling circuit of turbine exhaust gas

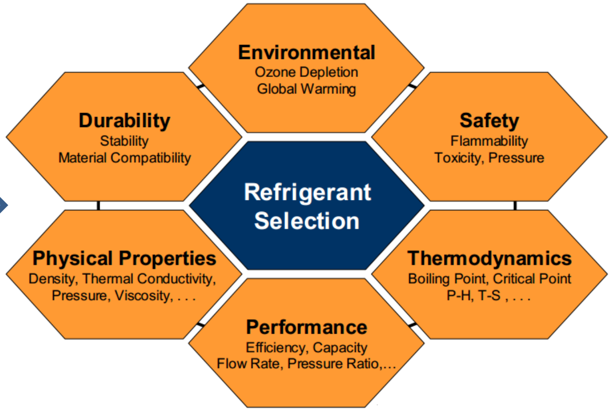


Working fluid properties

Available compounds → **Screening criteria** → **Selected fluids**

HFCs
HCs
HFOs
…

Heat source available temperature



Factors influencing working fluid selection (*Horn, 2011*)

R134a
R152a
R32
Propane
R1234ze

Working fluid properties

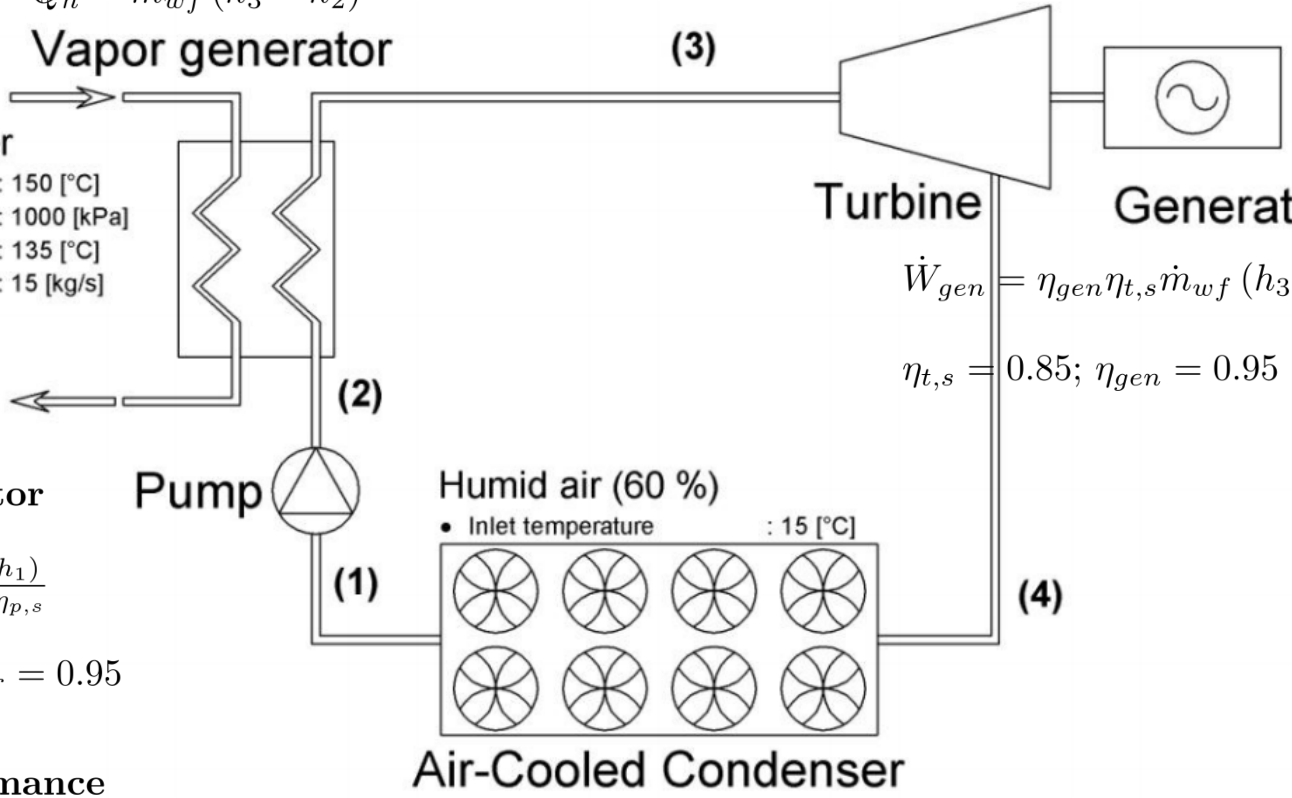
	R134a	R152a	R32	Propane	R1234ze (E)
GWP	☹☹	☺	☹	☺☺	☺☺
Toxicity	☺☺	☺☺	☺☺	☺☺	☺☺
Flammability	☺☺	☹	☺	☹☹	☺
Materials	☺	☺	☺	☺	☺
Pressure	☺	☺	☹	☺	☺
Cost	☺	☺	☺	☺☺	☹
Availability	☺☺	☺☺	☺☺	☺☺	☹
Familiarity	☺	☺	☺	☺	☹

Equipment sizing and cycle performance

- Power consumed by ORC feed pump
- Heat transfer surface area of heat exchangers
- Power consumed by fan
- Power produced by turbine/generator
- Working fluid quantity
- Net cycle power and thermal efficiency

Equipment sizing and cycle performance

$$\dot{Q}_h = \dot{m}_{wf}\left(h_3 - h_2\right)$$



Presurized hot water

- Inlet temperature : 150 [°C]
- Inlet pressure : 1000 [kPa]
- Outlet temperature : 135 [°C]
- Mass flow rate : 15 [kg/s]

$$\dot{Q}_h = 964.5\ [\mathrm{kW}]$$

Humid air (60 %)

- Inlet temperature : 15 [°C]

$$\dot{W}_{gen} = \eta_{gen}\eta_{t,s}\dot{m}_{wf}\left(h_3 - h_{4,s}\right)$$

$$\eta_{t,s} = 0.85;\ \eta_{gen} = 0.95$$

Pump and motor

$$\dot{W}_p = \dot{m}_{wf}\frac{\left(h_{2,s} - h_1\right)}{\eta_{motor}\eta_{p,s}}$$

$$\eta_{p,s} = 0.7;\ \eta_{motor} = 0.95$$

System performance

$$\dot{W}_{net} = \dot{W}_{gen} - \dot{W}_p - \dot{W}_{fan}$$

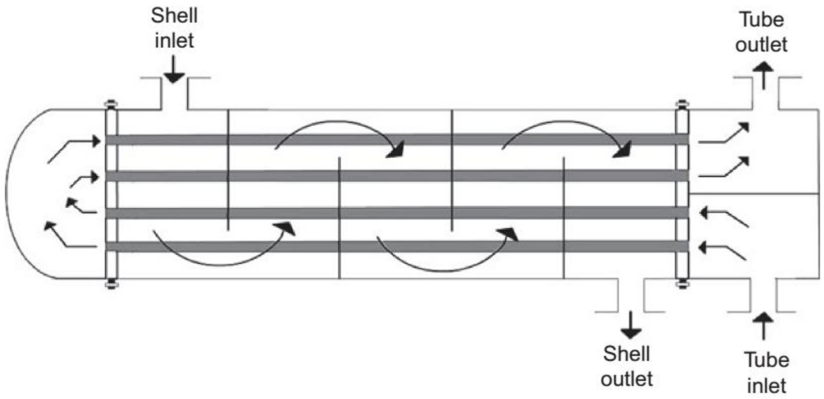
$$\eta_{ORC} = \dot{W}_{net}/\dot{Q}_h$$

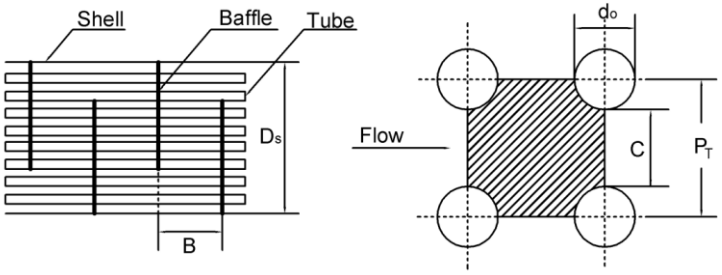
$$\dot{Q}_c = \dot{m}_{wf}\left(h_4 - h_1\right)$$

$$\dot{W}_{fan} = \frac{\Delta P_{air}\dot{m}_{air}}{\rho_{air}\eta_{fan}\eta_{motor}};\ \eta_{fan} = 0.7$$

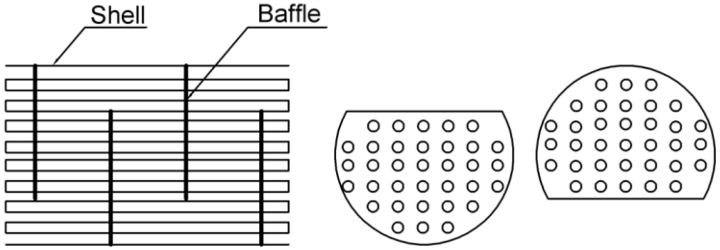
Vapor generator

Shell and tube heat exchanger





Simple geometry of shell and tube hex



Single-segmental cut baffle

$$\dot{Q} = UA\Delta T_{ln}$$

$$U = \left[\frac{D_o}{D_i h_i} + \frac{D_o ln(D_o/D_i)}{2k_w} + \frac{1}{h_o}\right]^{-1}$$

Heat transfer and pressure drop in shell side: Kern method

Heat transfer inside tube: Jackson correlation (2002)

Optimized variables: baffle spacing, number of tube

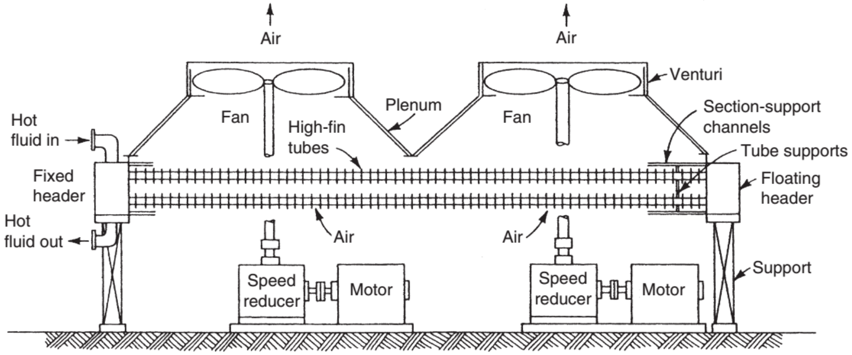
Contraintst for the optimization: pressure drops, tube length

Air-cooled condenser

$$\dot{Q} = UA\Delta T_{ln}$$

$$U = \frac{A_{tot}}{A_i h_i} + \frac{A_{tot} ln(D_o/D_i)}{2L\pi k_w} + \frac{1}{\eta_w h_o}$$

A_{tot}: Total external surface of finned tube



Air-cooled heat exchanger (*Kraus et al., 2001*)

Horizontal finned tube bundle

Air side heat transfer & pressure drop: Ganguli correlations (Ganguli et al., 1985)

Single phase heat transfer inside tube: Gnielinski correlation (Gnielinski, 1976)

Two phase heat transfer inside tube: Shah correlation (Shah, 2009)

Optimized variables: tube pass number, tube number

Optimization constraints: pressure drop, tube length

Equipment costing

Free-on-board (f.o.b) purchase cost of equipment, C_P

$$C_B = e^{\{A_0 + A_1 \ln(S) + A_2 [\ln(S)]^2 + \ldots\}}$$

$$C_P = C_B F_P F_M$$

$$C_P^{2013} = C_P \frac{\mathrm{CEPCI}_{2013}}{500}$$

C_B: Equipment base cost

S: Equipment size or capacity

F_P: Pressure factor

F_M: Material factor

CEPCI: Chemical Engineering Plant Cost Index

Capital investment

$$C_{TCI} = \sum C_P + C_{wf} + C_{sp} + C_{sf} + C_{CCF}$$

C_{TCI}: Capital investment

C_{wf}: Cost for working fluid

C_{sp}: Cost for site preparation

C_{sf}: Cost for service facility

C_{CCF}: Cost for contigencies and contractor's fee

Values of constant A_0, A_1 and A_2 can be found in (*Seider et al., 2010*)

Parametric optimization

Goal function: SIC (Specific Investment Capital)

$$\text{SIC} = \frac{C_{TCI}}{\dot{W}_{net}}$$

Opimization variables:

- Inlet turbine temperature, pressure
- Condensation temperature (or pressure)
- Fluid velocity inside tube of vapor generator and condenser
- Baffle spacing of shell-and-tube heat exchanger
- Tube pass number of air-cooled condenser

Optimization constraints:

- Pressure drops of fluids throug heat exchangers
- Heat exchanger tube lengths
- Minimum temperature diferences between hot and cold fluid

Genetic algorithm optimization(EES)

Number of individual: 16

Number of generation: 64

Results

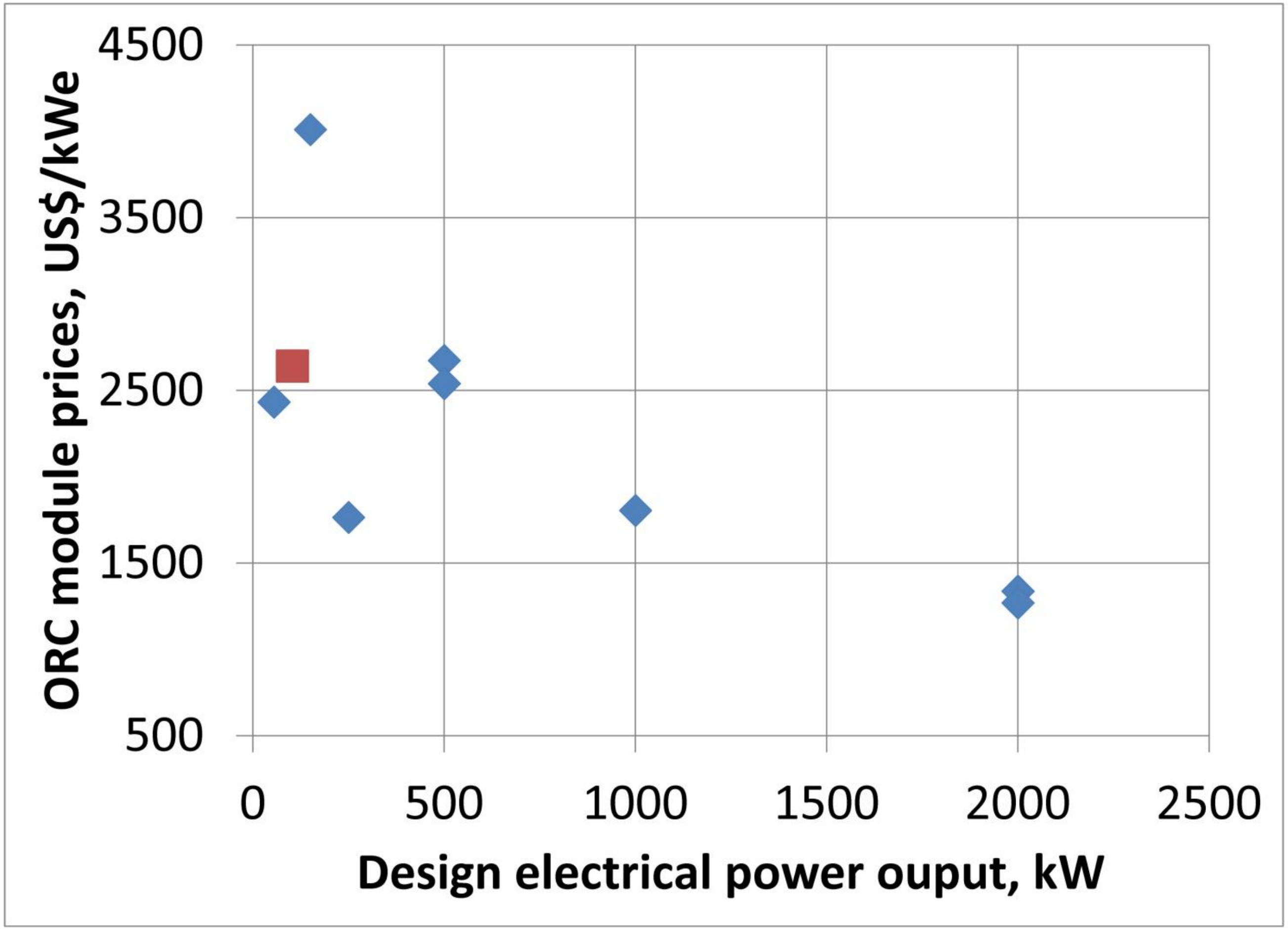
Parameters	R134a	R152a	R32	Propane	R1234ze (E)
Electrical power output, kWe	88.7	102.9	93.1	89.3	95.6
Thermal Efficiency, %	9.2	10.7	9.7	9.3	9.9
TIT, °C	140	139.6	140	140	140
TIP, kPa	5420	5014	9253	6087	4206
T_{cond}, °C	48.1	44.4	40.5	43.8	43.5
P_{cond}, kPa	1257	1022	2509	1494	842.7
T_{cso}, °C	29.8	29.9	28.9	29.5	29.9
SIC, US$/kWe	2937	2641	3155	3075	3059
Avoided CO_2 emission*, t/year	131.5	268.5	243	258.9	249.5

Lowest SIC

* Annual operating hours is assumed to be 7884 h/year at full load with specific CO_2 emissions for electricity generation of 331g/kWh (Clément, 2014)

Results

- ◆ Sub-ORC module (data adapted from *Vanslambrouck et al., 2011*)
- 🟥 SIC of R152a-based Trans-ORC



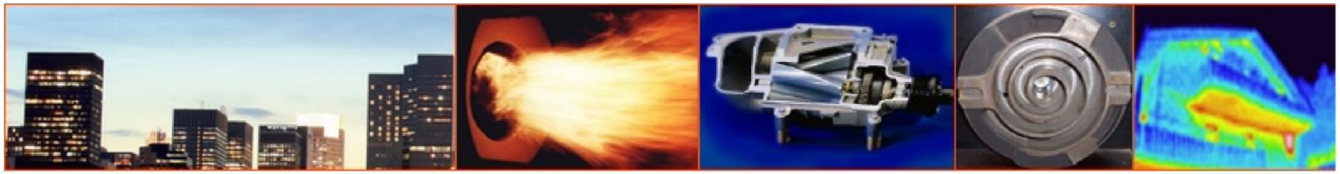
Conclusions – Perspectives

- Sizing and minimizing Specific Investment Capital of a Trans-ORC for WHR
- Trans-ORC presents a real potential to improve performance and reduce investment of small-scale waste heat to power plant
- Thermo-hydraulic and economic models should be considered in more detail
- Other improvements should be considered for Trans-ORC power plant

LABORATOIRE DE THERMODYNAMIQUE UNIVERSITE DE LIEGE

References

- Kim YM, Kim CG, Favrat D. *Transcritical or supercritical CO2 cycles using both low- and high-temperature heat sources*. Energy. 2012;43(1):402-15.
- Horn BV. *A primer on HFOs Hydrofluoro-olefins Low-GWP refrigerants*. Las Vegas, NV2011.
- Kern DQ. *Process Heat Transfer*: McGraw-Hill, 1950.
- Jackson JD. *Consideration of the heat transfer properties of supercritical pressure water in connection with the cooling of advanced nuclear reactors*. Shenzhen City, China2002.
- Ganguli A, Tung SS, Taborek J. *Parametric study of air-cooled heat exchanger finned tube geometry. Conference Parametric study of air-cooled heat exchanger finned tube geometry*. p. 122-8.
- Gnielinski V. *New equations for heat and mass transfer in turbulent pipe and channel flow*. International Chemical Engineering. 1976;16:359-68.
- Shah MM. *An Improved and Extended General Correlation for Heat Transfer During Condensation in Plain Tubes*. HVAC&R Research. 2009;15(5):889-913.
- Seider WD, Seader JD, Lewin DR, Widagdo S. *Product and process design principles: synthesis, analysis, and evaluation*: John Wiley, 2010.
- Clément L. *Final report LIFE08 ENV/B/000040 CLIM-WASTENER*. Bierges, Belgium: VERDESIS SA; 2014.
- Vanslambrouck B, Vankeirsbilck I, Gusev S, De Paepe M. *Turn waste heat into electricity by using an Organic Rankine Cycle*. 2nd European Conference on Polygeneration. Tarragona, Spain2011. p. nn-mm.
- Kraus A, Aziz A, Welty J, Sekulic D. *Extended Surface Heat Transfer*. Applied Mechanics Reviews. 2001;54(5).



Thank you for your attention!