Exergy and energy analysis of waste heat recovery options for cooling capacity production

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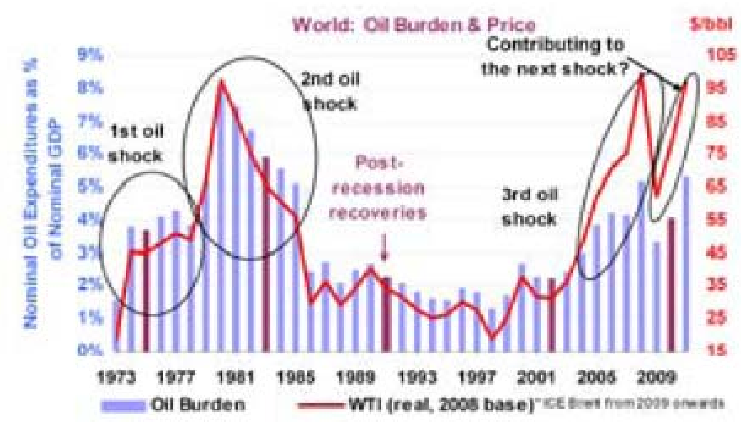
Outline

- Global energy and environmental context in Lebanon
- Case study : Waste heat recovery from hot exhaust gas to produce cooling capacity
- Organic Rankine Cycle coupled with a vapor compression refrigeration cycle
- Dessicant Cycle coupled with a vapor compression refrigeration cycle
- Results
- Conclusions

General context

- Global energy and environmental context
  - Increase of the energy prices
  - Rarefaction of oil resources
  - Climate changes
  - Financial and economics crisis and its energy demand impact



⇒ Need for energy conservation and for developing renewable technologies becomes ever more critical

Lebanon

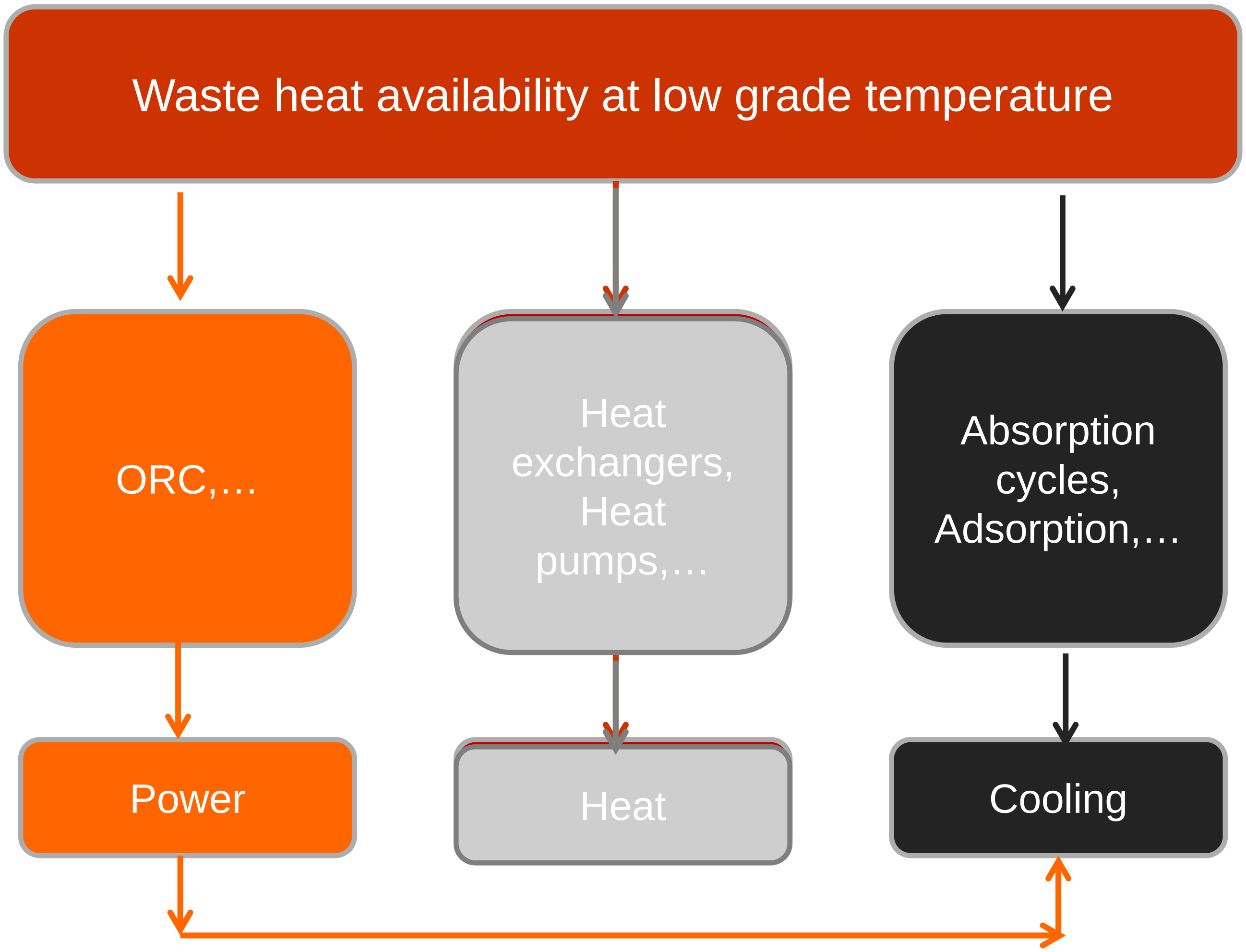
- 10452 km²
- Population : 4.2 millions
- Mediterranean climate (long hot and humid summer)
- Power sector
  - 1500 MW installed capacity
  - 2500 MW demand
- Consequence
  - Installation of large number of small-scale backup generators

Cooling capacity production required all year long especially for tertiary and commercial buildings.

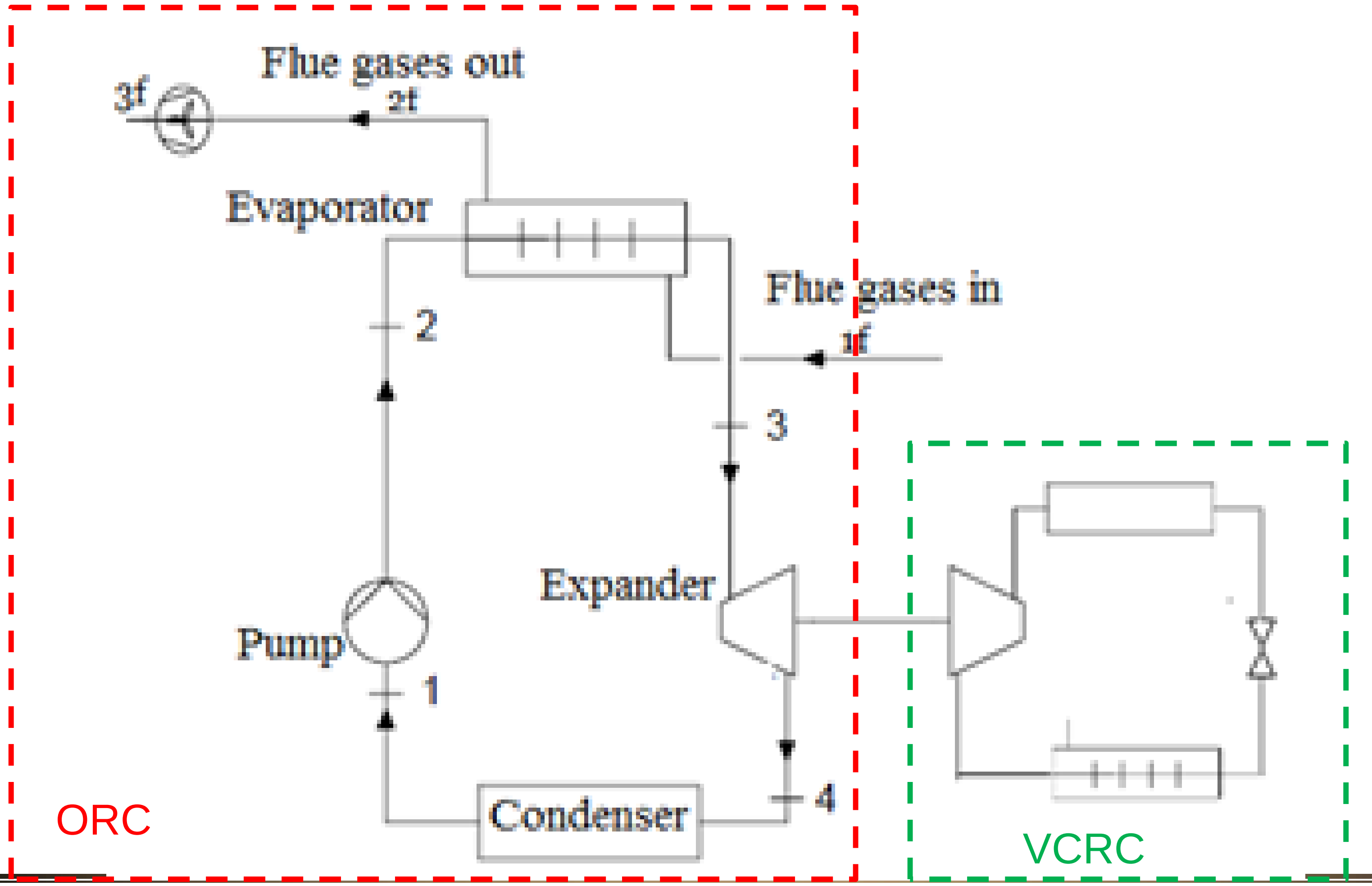
Back up Generators

- Diesel Powered Generating sets
  - Losses through the cooling circuit
  - Losses through exhaust gases
- Enhancement of energy efficiency through recovery of waste heat
- Factors Affecting Waste Heat Recovery Feasibility
  - Rate at which heat is generated,
  - Heat temperature/quality,
  - Composition of the exhaust gas stream,
  - Minimum allowed temperature, and
  - Operating schedules, availability, and other logistics.

End use for recovered heat



Description of ORC with VCRC



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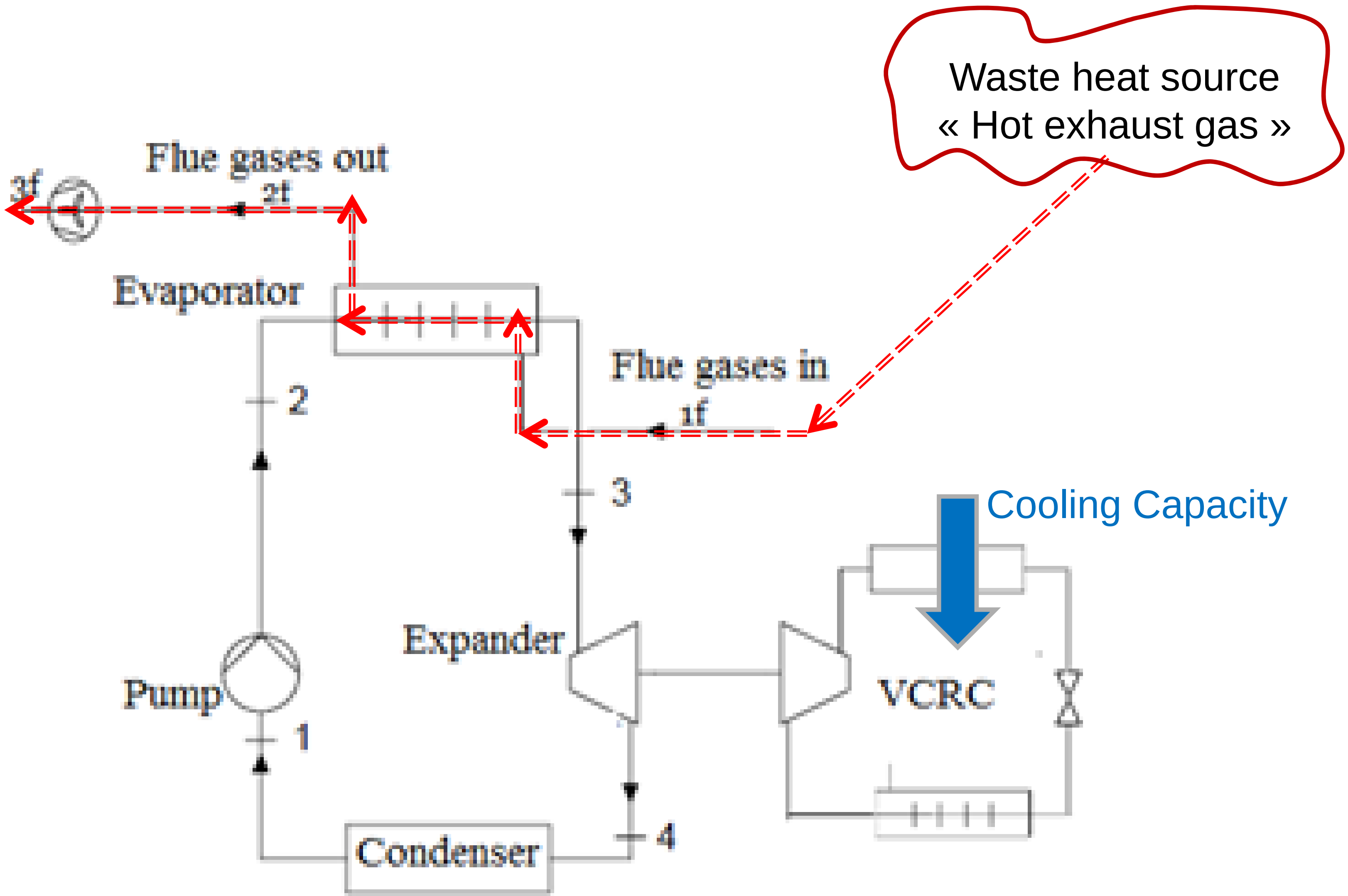


Exergy and Energy analysis

Exergy: ex = h – $T_o s$
T_o: ambient temperature (25°C)
s: entropy ($J.kg^{-1}.K^{-1}$)
h : enthalpy ($J.kg^{-1}$)

Energy and exergy balance for the components of the WHR ORC

Component	*Energy balance*	*Exergy balance*
Evaporator	$\dot{m}_r(h_3 - h_2) + \dot{m}_f(h_{2f} - h_{1f}) = 0$	$\dot{m}_r(ex_3 - ex_2) + \dot{m}_f(ex_{2f} - ex_{1f}) - \dot{E}x_{d,evap} = 0$
Condenser	$\dot{m}_r(h_4 - h_1) + \dot{m}_{air}(h_{out} - h_{in}) = 0$	$\dot{m}_r(ex_4 - ex_1) - \dot{E}x_{d,cond} = 0$
Pump	$W_p = \dot{m}_r(h_2 - h_1)$	$T_0.\dot{m}_r(s_1 - s_2) - \dot{E}x_{d,pump} = 0$
Expander	$W_t = \dot{m}_r(h_3 - h_4)$	$T_0.\dot{m}_r(s_3 - s_4) - \dot{E}x_{d,turbine} = 0$
Blower	$W_b = \dot{m}_f(h_{3f} - h_{2f})$	$T_0.\dot{m}_f(s_{2f} - s_{3f}) - \dot{E}x_{d,blower} = 0$

Exergy destruction for the components of the WHR ORC

Total exergy losses for the ORC system

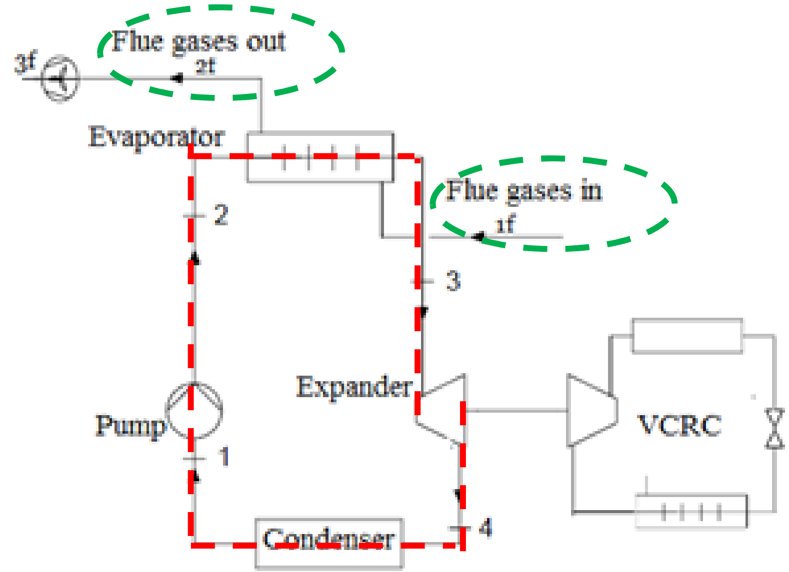
$$\dot{E}x_{d,tot} = \dot{E}x_{d,evap} + \dot{E}x_{d,cond} + \dot{E}x_{d,pump} + \dot{E}x_{d,turbine} + \dot{E}x_{d,blower}$$

Energy and Exergetic efficiency

$$\eta_{en} = \frac{W_t - W_p - W_b}{\dot{m}_f(h_{1f} - h_{2f})} \qquad \eta_{ex} = 1 - \frac{\dot{E}x_{d,tot}}{\dot{E}x_{1f4f}}$$

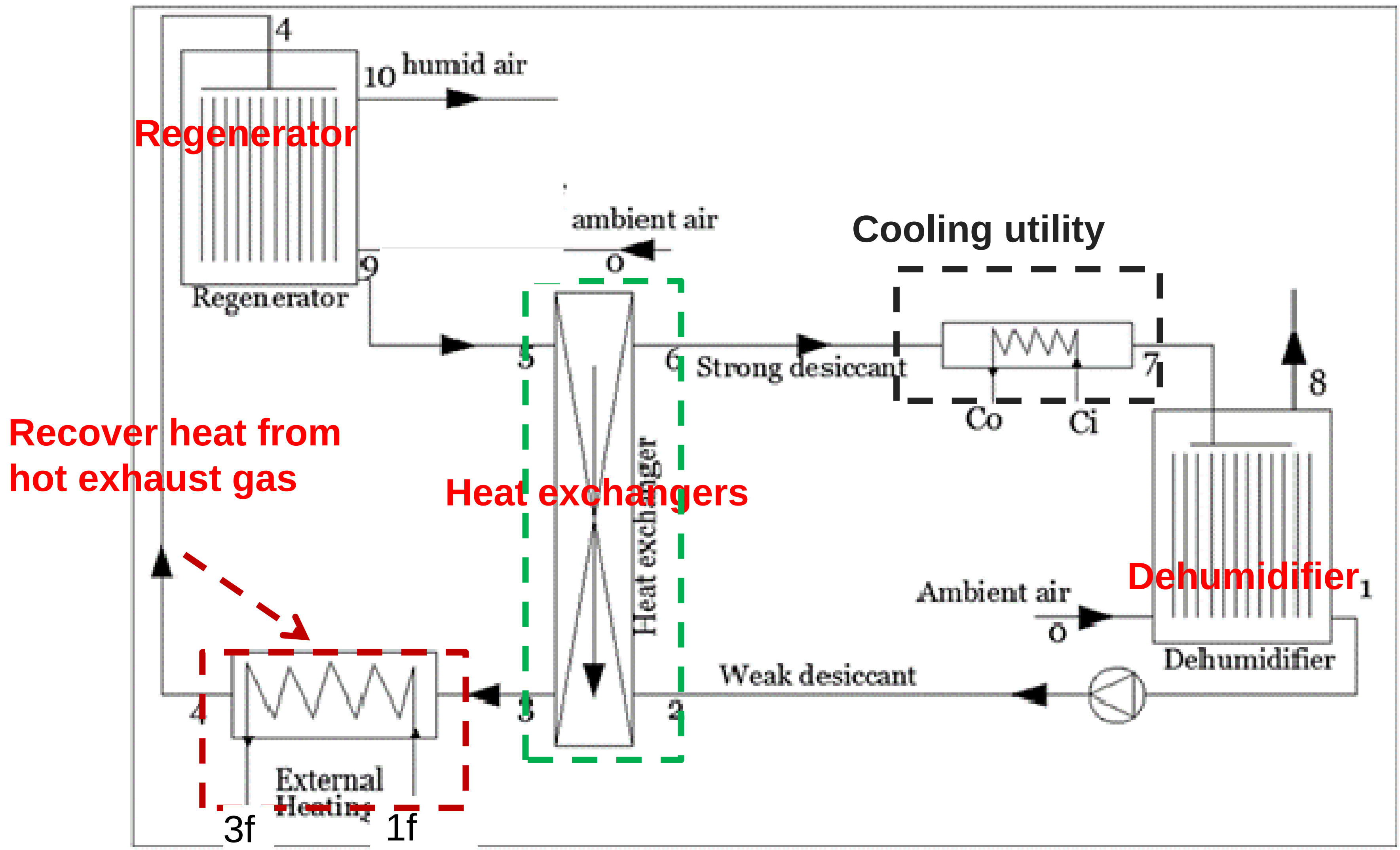
Parametric analysis for ORC + VCRC

- Working fluid
  - R1234yf, R245fa, and R236fa
- T1f: Flue gas inlet T
  - 200, 300 and 400°C
- T2f: Flue gas exit T
  - 150 – 80 °C



- Operating conditions
  - VCRC is modeled by a coefficient of performance equal to 35 % that of a reversed Carnot cycle.
  - Pump efficiency ~ 60%
  - Expander efficiency ~75%

Liquid Desicant Cooling system (LDCS)



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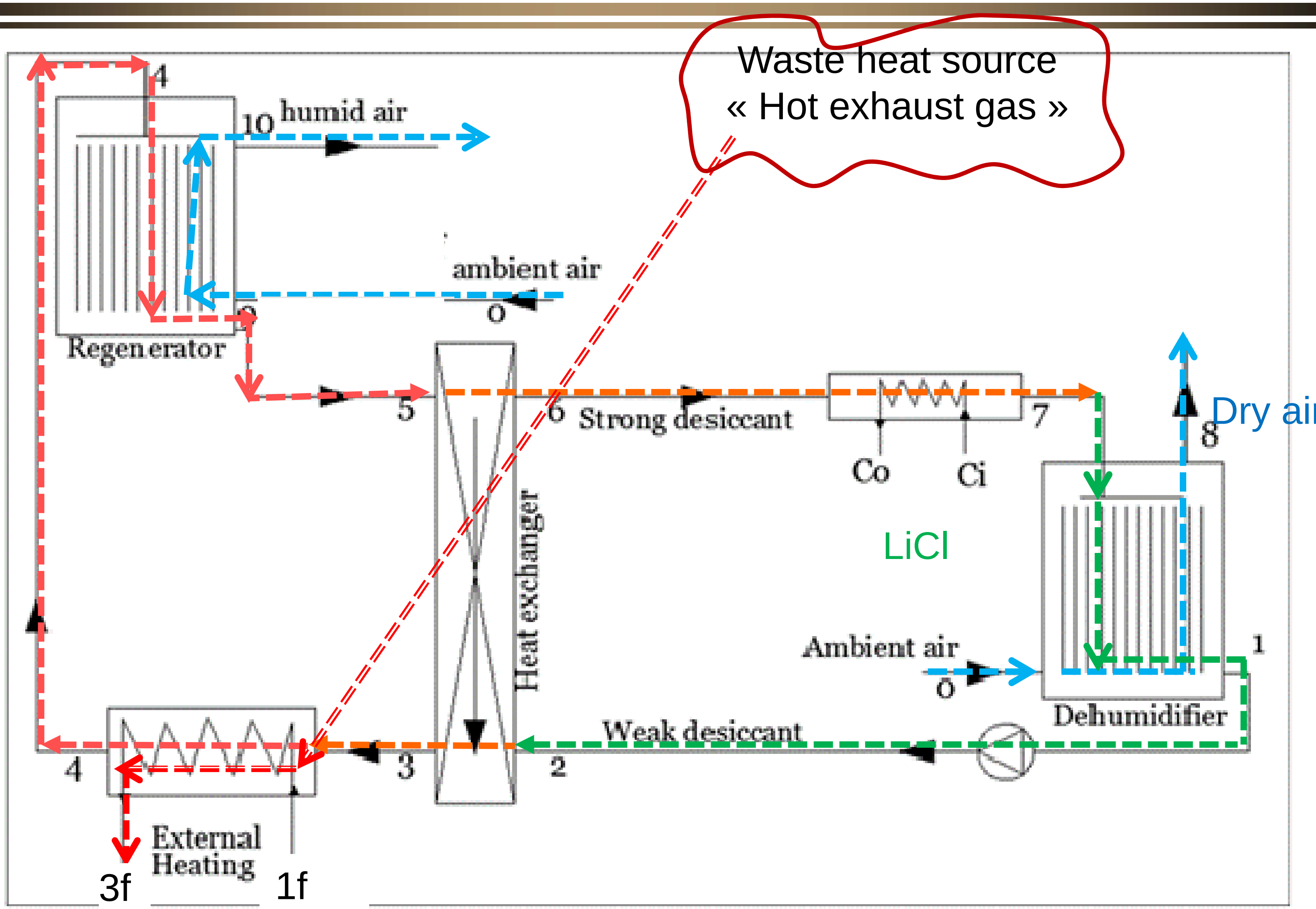


Energy & Exergy analysis

Energy balance for the LDCS components

Component	***Energy balance***
Regenerator	$\dot{m}_{ar}(h_9 - h_{10}) + \dot{m}_w h_4 - \dot{m}_s h_5 = 0$
Dehumidifier	$\dot{m}_{ad}(h_0 - h_8) + \dot{m}_s h_7 - \dot{m}_w h_1 = 0$
Cooling water heat exchanger (CWHX)	$\dot{m}_{cw}(h_{ci} - h_{co}) + \dot{m}_s(h_6 - h_7) = 0$
Solution Heat exchanger	$\dot{m}_w(h_2 - h_3) + \dot{m}_s(h_5 - h_6) = 0$
External Heating of the weak desiccant	$\dot{m}_f\left(h_{2f} - h_{3f}\right) + \dot{m}_w(h_3 - h_4) = 0$

Exergy balance for the LDCS components

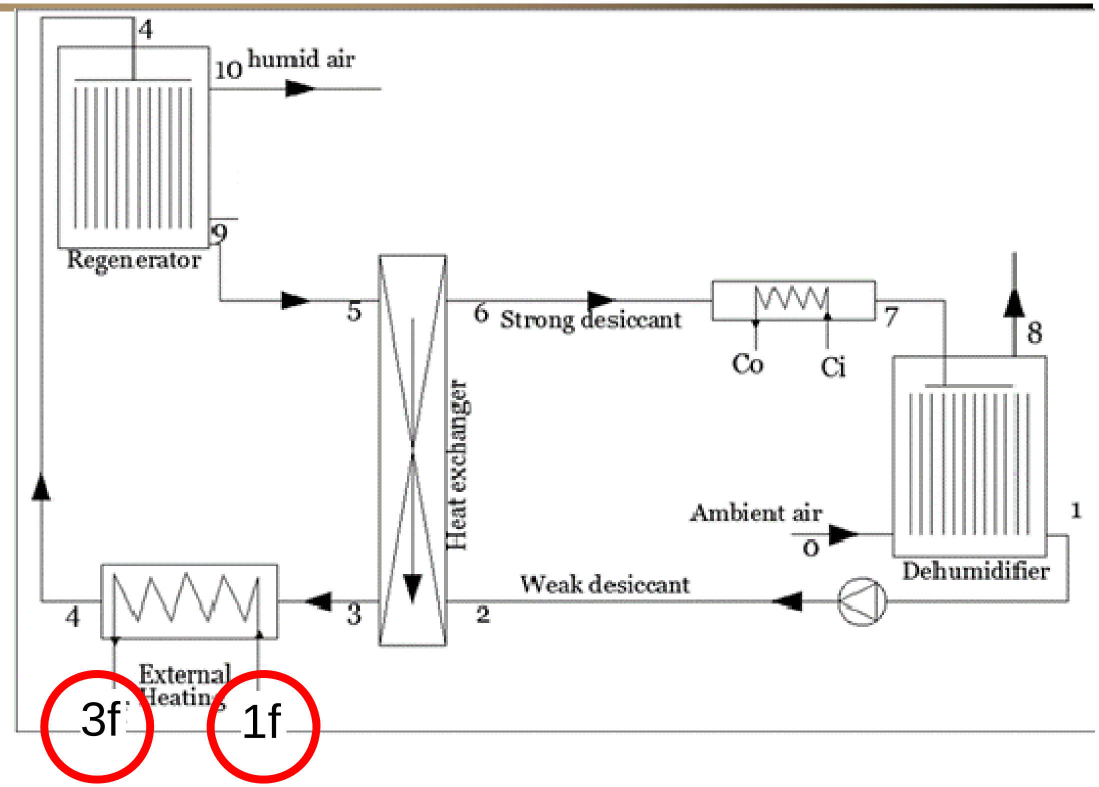
Component	***Exergy balance***
Regenerator	$\dot{E}x_{d,reg} = T_o(\dot{m}_{ar}(s_{10} - s_9) + \dot{m}_s s_5 - \dot{m}_w s_4)$
Dehumidifier	$\dot{E}x_{d,deh} = T_o(\dot{m}_{ad}(s_8 - s_0) + \dot{m}_w s_1 - \dot{m}_s s_7)$
Cooling water Heat exchanger	$\dot{m}_{cw}(ex_{ci} - ex_{co}) + \dot{m}_s(ex_6 - ex_7) - \dot{E}x_{d,CHWE} = 0$
Solution heat exchanger	$\dot{m}_w(ex_2 - ex_3) + \dot{m}_s(ex_5 - ex_6) - \dot{E}x_{d,SHX} = 0$
External Heating of the weak desiccant	$\dot{m}_f\left(ex_{2f} - ex_{3f}\right) + \dot{m}_w(ex_3 - ex_4) - \dot{E}x_{d,EHWD} = 0$

Total exergy losses $\dot{E}x_{d,tot} = \sum \dot{E}x_{d,i} = \dot{E}x_{reg} + \dot{E}x_{deh} + \dot{E}x_{CWHE} + \dot{E}x_{SHX} + \dot{E}x_{EHWD}$

Exergetic efficiency $\eta_{ex} = 1 - \frac{\dot{E}x_{d,tot}}{\dot{E}x_{1f4f}}$

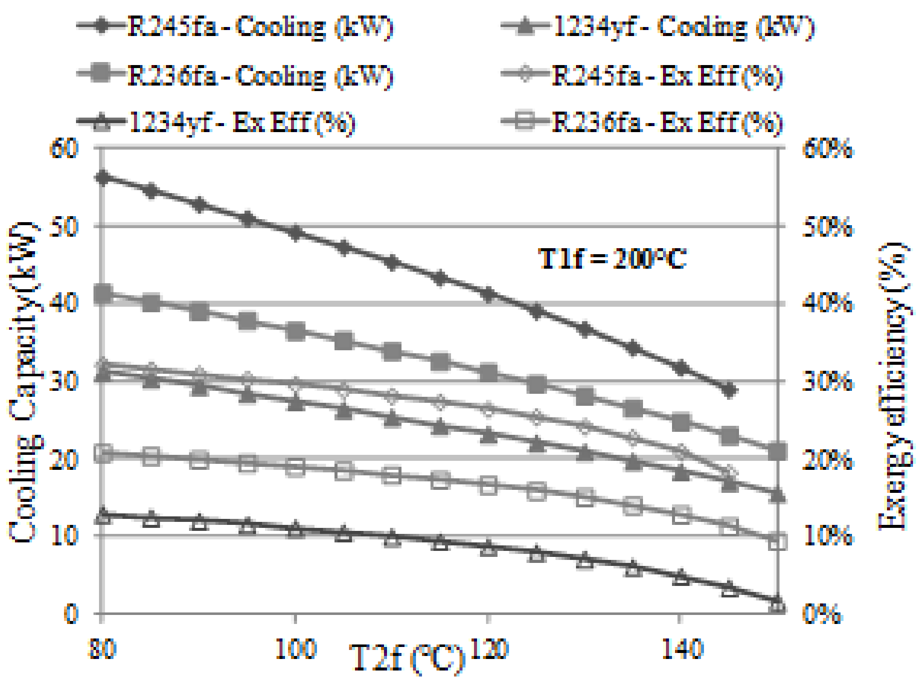
Parametric analysis for LDCS

- T1f: Flue gas inlet T
  - 200, 300 and 400°C
- T2f: Flue gas exit T
  - 105 – 86 °C
- X: LiCl concentration

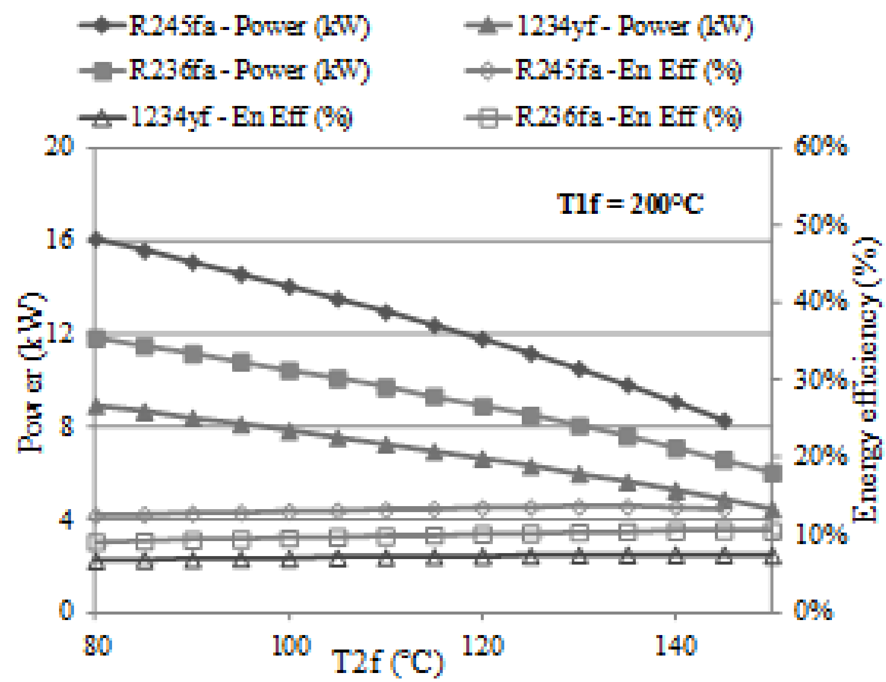


T_0 and T_9 (Ambient conditions)	Mass flow rate of the absorber solution	Mass flow rate of air in the absorber	Efficiency of heat exchangers
30°C, 80%Relative humidity	6 kg/s	1.5 kg/s	60%

Results for ORC + VCRC



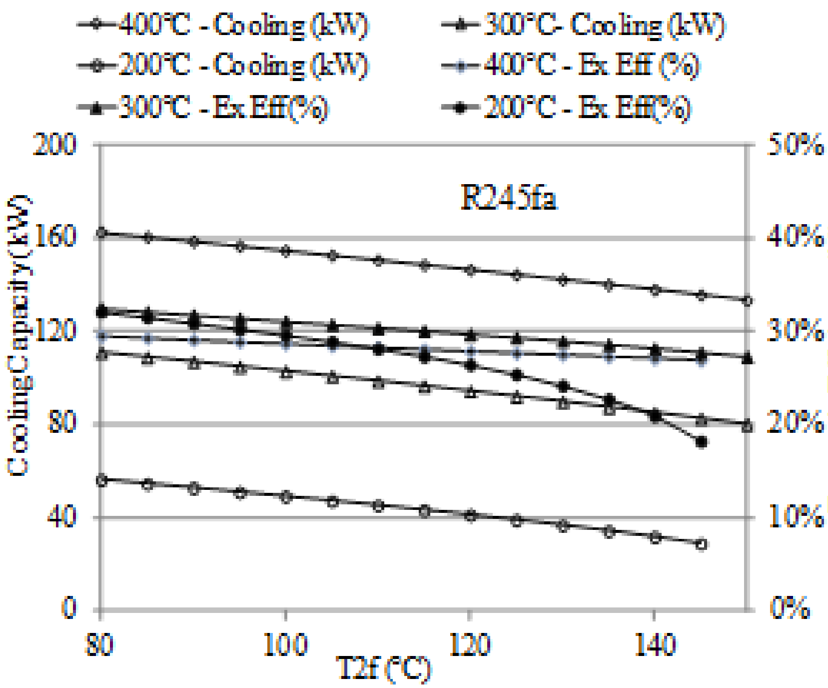
Cooling capacity and exergy efficiency of WHR ORC with R1234yfa, R245fa, and R236fa



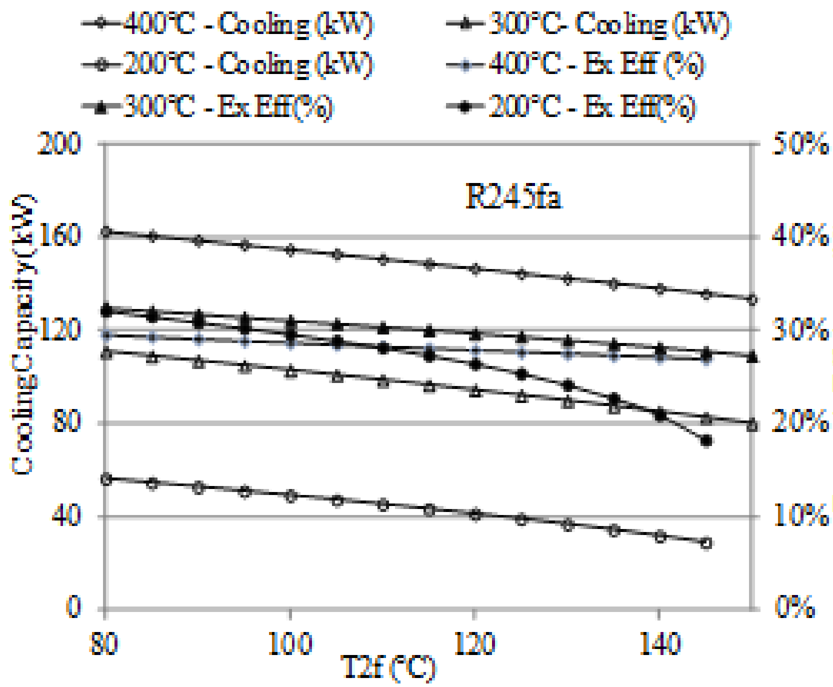
Net power and energy efficiency of WHR ORC with R1234yfa, R245fa, and R236fa

- Flue gas inlet temperature of 200 °C: highest performance achieved with R245fa (energy ,exergy efficiencies, net power delivered and cooling capacity produced).
- Same results were obtained for Flue gas inlet temperature of 300°C and 400°C .

Results for ORC + VCRC



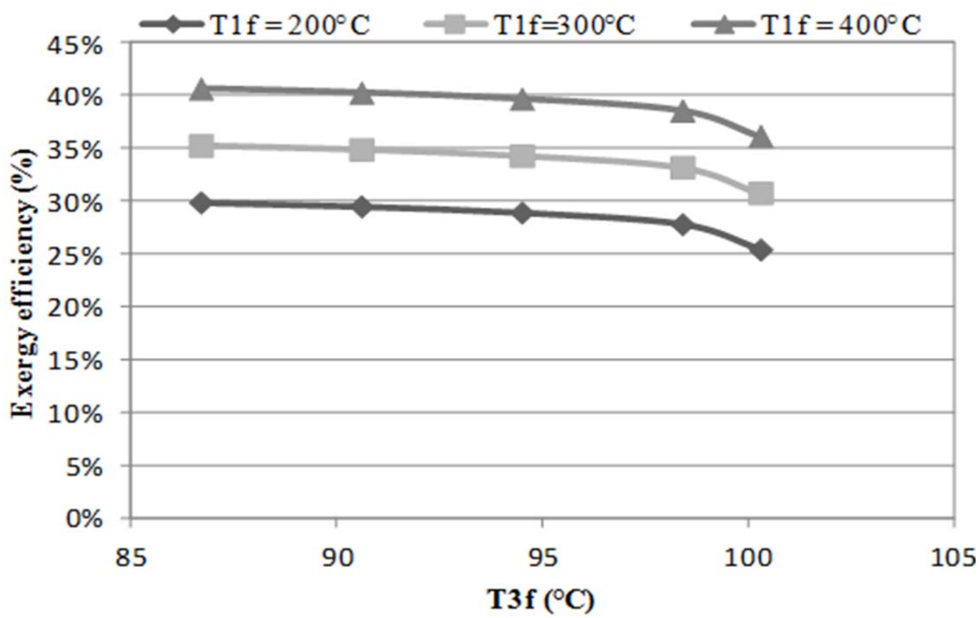
Cooling capacity, exergetic efficiency of WHR ORC for R245fa as function of flue gas inlet and exit T



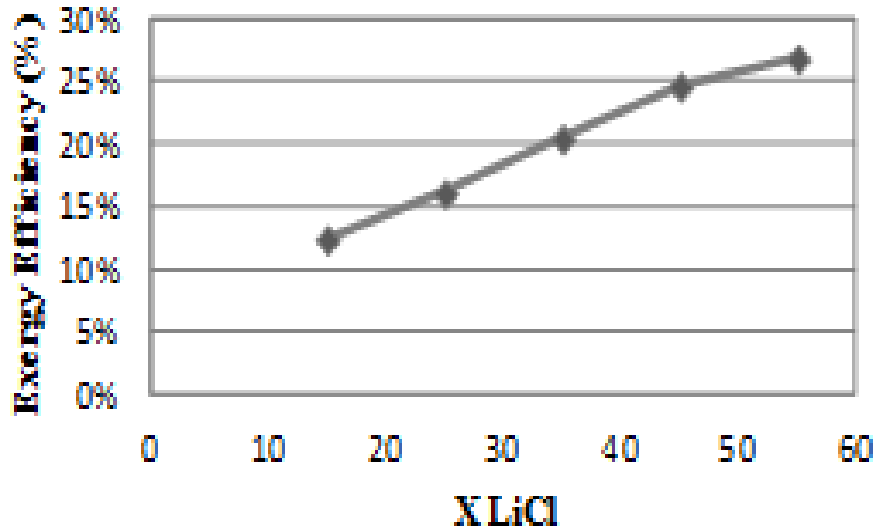
Net power and energy efficiency of WHR ORC for R245fa as function of flue gas inlet and exit T

- For a flue gas inlet temperature of 400°C and mass flow rate of 1kg/s, the WHR ORC using R245fa allows the production of 160 kW of cooling capacity and the delivery of 46 kW with an exergy efficiency of 40% and an energy efficiency of 45%.

Results for LDCS



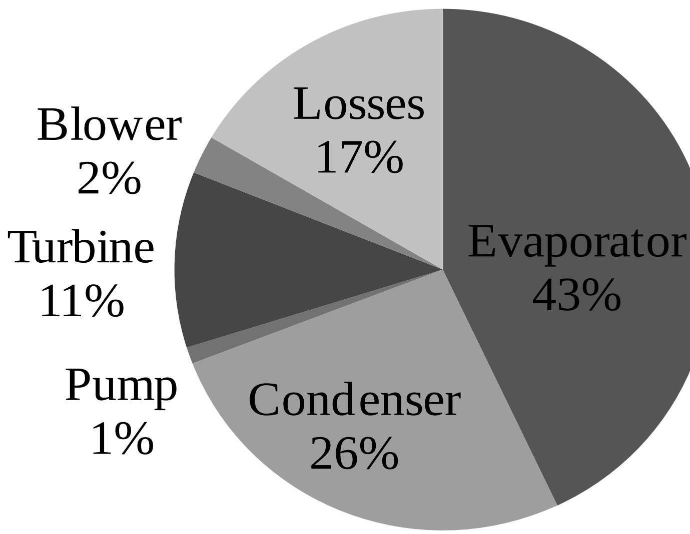
Influence of flue gas inlet and exit T on the LDCS global exergy efficiency



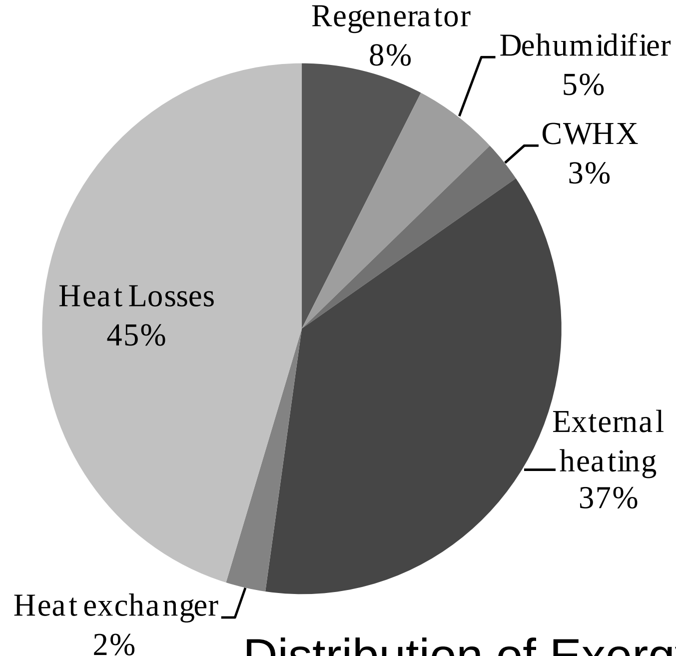
Variation of the exergy efficiency of LDCS with LiCL concentration

- The global exergy efficiency increases with the increase of T_{1f}.
- For a given flue gas inlet temperature, the global exergy efficiency increases as the flue gas exit temperature decreases.
- The global exergetic efficiency increases with the increase of the salt concentration by a slope of 4%/(kg/kg).

Exergy destruction breakdown



Distribution of Exergy destruction in the WHR ORC



Distribution of Exergy destruction in the LDCS

- In the WHR ORC, major losses occur in the evaporator (43% of total exergy losses)
- In the LDCS, major losses are due to partial recovery of energy in the hot flow, and in the external heating heat exchanger .
- From an economical point of view, based on a market study, it was found that LDCS has a PBP less than 5 years where the PBP of the WHR ORC is greater than 20 y.

Summary & conclusions

- The recovery of waste heat by the production of cooling capacity is considered via two systems: an ORC and a LDCS coupled to a conventional VCRC.
- A parametric analysis was carried for both configurations to evaluate the performance of the system as a function of the flue gas inlet and exit temperatures and the working fluid properties.
- The performance of both WHR configurations was evaluated in terms of global exergy efficiency and cooling capacity production.

THANK YOU FOR YOUR ATTENTION

Questions ?