Investigating the double-stage expansion in a solar ORC

by

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Presentation Outline

- Activities of our research team relevant to ORC
- Current project description
- Why “double-stage expansion”?
- Design principles of solar ORC
- Performance of solar ORC at various loads
- Control strategies for the selected ORC configuration
- Conclusions

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Activities of our research team relevant to ORC

Research project COOP-CT2003-507997, financed by EC (2004-2006)

- An autonomous small-scale subcritical ORC engine (HFC-134a) has been designed and constructed (~2.5 kW)
- Low-temperature heat (~80 ^{o}C) was produced by evacuated tube solar collectors (~100 kW_{th})
- The power produced by the scroll expander was used to operate a Reverse Osmosis unit for desalination of seawater (~0.3 m^3/h)

Activities of our research team relevant to ORC

Research project COOP-CT2003-507997, financed by EC (2004-2006)

- Extensive simulation and experimental studies were implemented (small-scale unit installed in Greece, near Athens)
- Maximum measured efficiency: 4.3% at maximum heat input
- Efficiency decreases at low-mid solar radiation, mainly due to operation of the scroll expander at low pressure ratios (off-design operation with very low expansion efficiency)

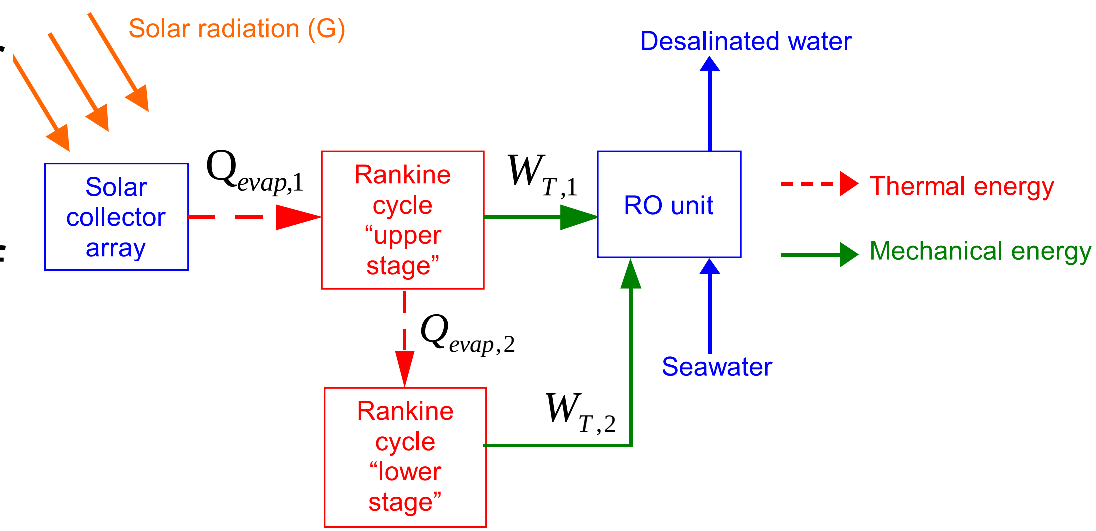
Research project COOP-CT2003-507997, financed by EC (2004-2006)

Due to the low efficiency (especially at low solar radiation), the specific energy cost is high. Additional measures to increase efficiency, without increasing the installation cost:

- Operation at higher temperature (>100 ^oC)
- Efficiency increase at partial load and continual control of the organic fluid mass flow rate

Research project 05NON-EU-219, financed by the Greek government (2006-2008)

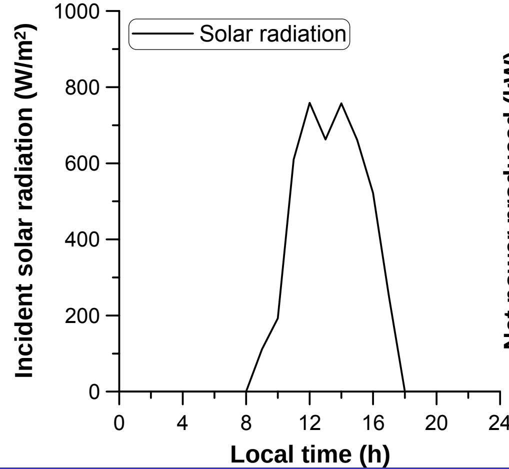
- A similar solar ORC (~10 kW) for RO desalination (~2 m^3/h) was further investigated (only theoretically)
- Max. temperature was increased (~140 ^oC/100 kW_{th}), boosting the ORC efficiency (small decrease of the solar collectors' efficiency)
- A cascade ORC was used (HFC-245fa/HFC-134a) for efficient operation at partial load as well (low variation of the pressure ratio of each scroll expander: ~2-4)

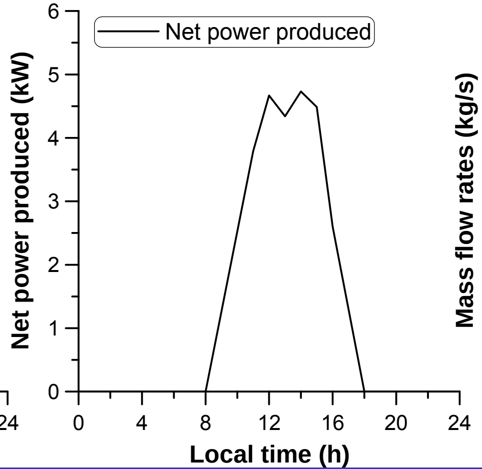


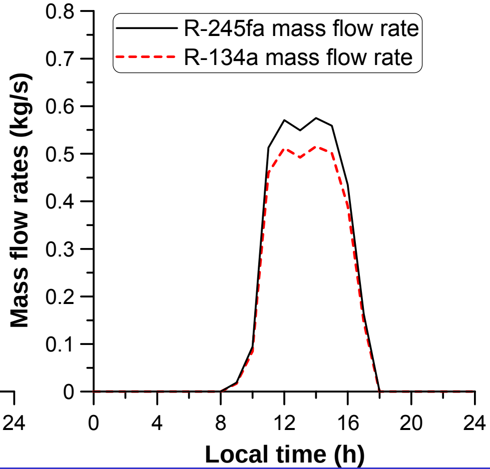
Research project 05NON-EU-219, financed by the Greek government (2006-2008)

Most important outcomes:

- Annual thermal efficiency increased substantially
- Specific energy (and water) cost almost halved
- Annual production of desalinated seawater increased by 160%, due to better performance at low-mid loads (most of the hours per year) and the higher temperature







Further research activities relevant to ORC technology

- Investigation of performance, configuration and components (e.g. expanders, heat exchangers) of low-temperature (~100 ^{o}C), small-scale (few kWs) subcritical / supercritical ORC (*Topic FP7-ENERGY.2012.2.9.1: Power generation in the low temperature range*)
- Exploitation of waste-heat for power production/seawater desalination from:
  - Exhaust gases of internal combustion engines (e.g. heavy-duty Diesel engines)
  - PhotoVoltaic (PV) systems (PV/T)
  - Concentrating PhotoVoltaic (CPV) systems (CPV/T)
  - Geothermal resources
- Collaboration with universities/research centers/SMEs

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Current project description

Research project 09SYN-32-982, financed by the Greek government (2011-2013)

- Design and optimize the operation of:
  - the evacuated tube solar collectors (~100 kW_{th}, max temperature~120-140 ^{o}C)
  - *the double-stage ORC engine* (~10 kW)
  - the RO desalination unit (~2 m^3/h)
- Simulate the annual performance of the integrated system (using weather data for different locations) (end of 2011)
- Select and manufacture all the required components (pumps, scroll expanders, heat exchangers, desalination unit etc.)

Current project description

Research project 09SYN-32-982, financed by the Greek government (2011-2013)

- Construct a prototype system (mid 2012) and extensively measure its performance and the desalinated water produced
  - In the laboratory, using an electric heater to simulate and control the heat input to the ORC (ORC+desalination unit)
  - On-site under real conditions (evacuated tube solar collectors+ORC+desalination unit)
- Implement a cost-analysis (in 2013) to calculate the:
  - specific energy cost (€/kWh)
  - specific water cost (€/m^3)

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Why “double-stage expansion”?

- Scroll expanders are being used in small-scale ORCs, showing good performance close to their design point (mainly depending on the pressure ratio)
- The scroll expanders of the ORC engine under development are selected based on the maximum heat input from the evacuated tube solar collectors (maximum solar radiation: 1000 W/m^2)
- At maximum heat input, the expanders operate with the organic fluid’s volume ratio (outlet/inlet) close to their built-in ratio (~3)
- When the available solar radiation decreases (~600 W/m^2), the ORC evaporation temperature/pressure decrease as well, along with the pressure ratio (P_{in}/P_{out}) of the expanders (~2)
- For low solar radiation (~200 W/m^2), the pressure ratio is very low (~1.4). Therefore, the expansion efficiency radically decreases (~30-40%), bringing a severe decrease to the thermal efficiency of the ORC engine

Why "double-stage expansion"?

- With the use of two expanders, the ORC engine can operate efficiently at a wide range of heat input from the solar collectors
- This control strategy can be accomplished as follows:
  - At mid-high solar radiation, both expanders operate and produce power
  - At low-mid solar radiation, one expander is by-passed and only one operates

↓

- For almost the whole range of incident solar radiation (→evaporation temperature/pressure), the expander(s) operate with high expansion efficiency (>60%), and the thermal efficiency of the ORC engine is not decreased substantially at low loads (depending mainly from the evaporation temperature/pressure)

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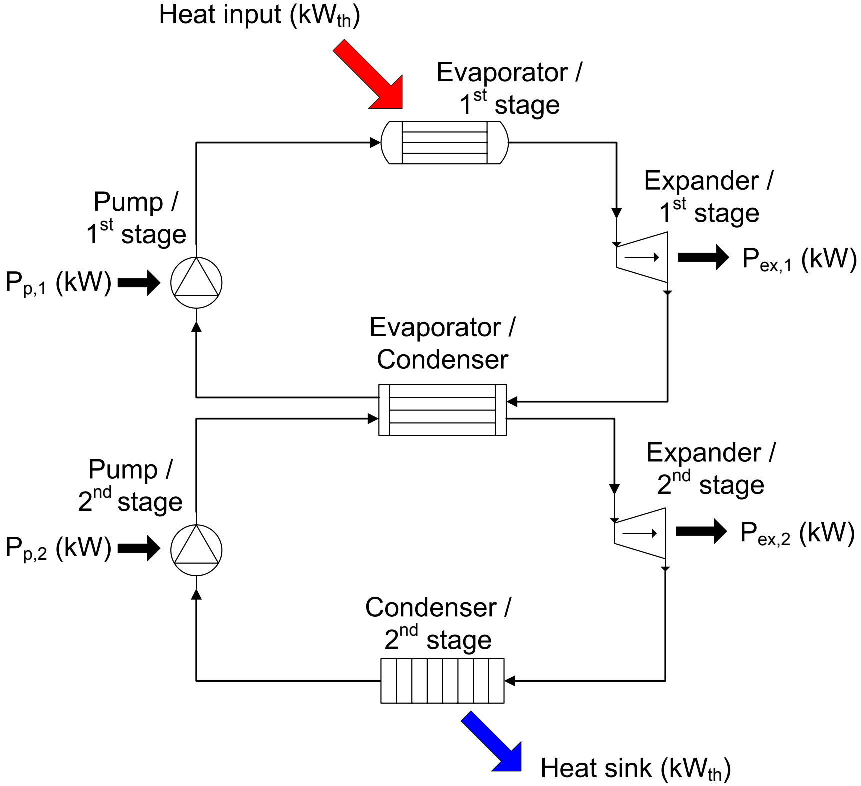
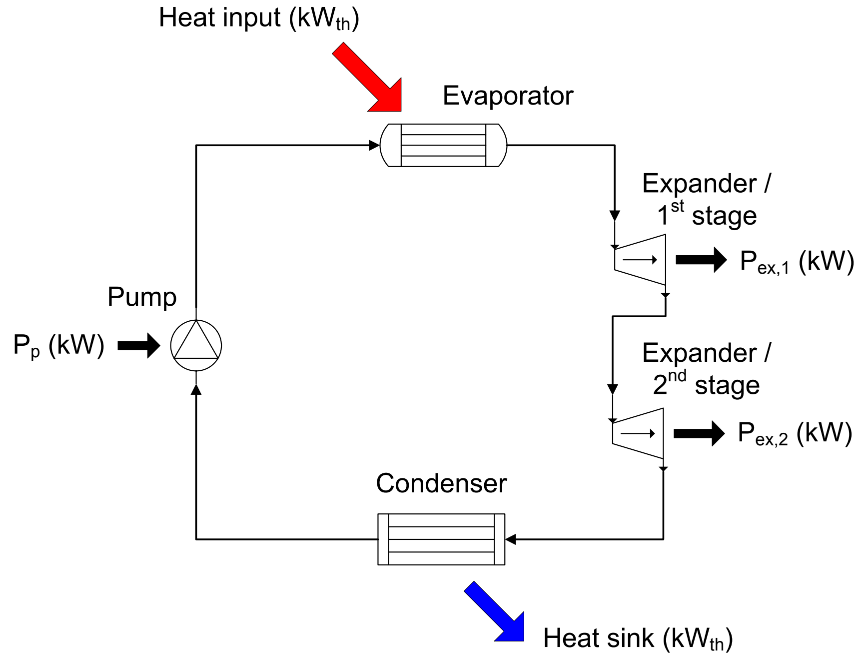
Two major design principles can be identified (except for the single-stage expansion), when the “double-stage expansion” strategy is followed:

- The cascade ORC (upper/lower stage)
- The use of two expanders connected in-series





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Efficiency values and parameters of the analysis (using EES software)

Expansion efficiency	70%
Feed pump efficiency	65%
Organic fluid's superheating (evaporators' outlet)	5 K
Organic fluid's subcooling (pumps' inlet)	5 K
Organic fluid's condensation temperature	40 ^{o}C
Upper/lower stage temperature difference	5 K

Expansion and pump efficiencies include isentropic and mechanical efficiency

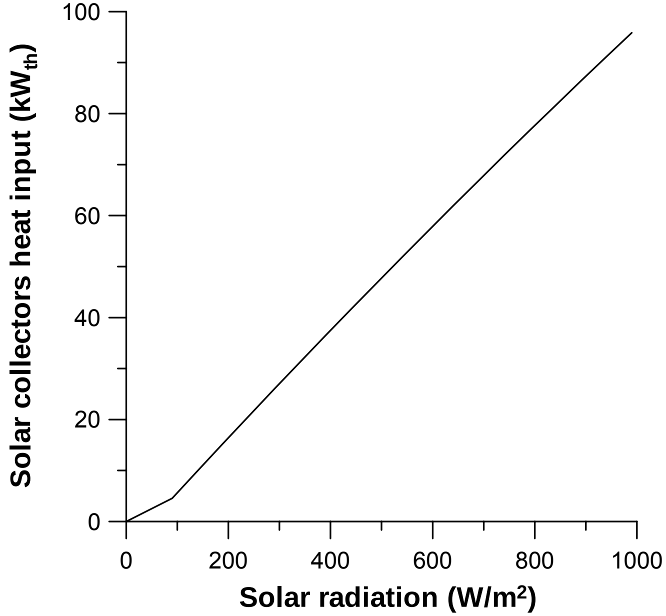
Performance of solar ORC at various loads

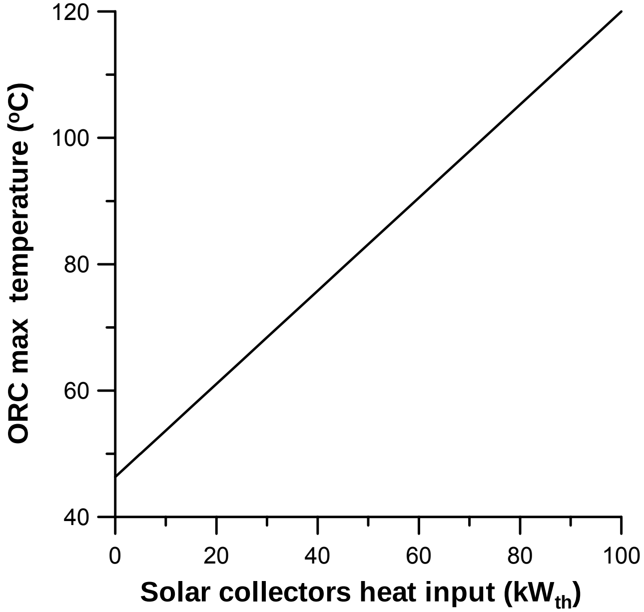
Organic fluids selected, taking into consideration environmental, safety and efficiency criteria:

- Cascade ORC (the pressure ratio and max temperature of each stage have been selected, to maximise thermal efficiency)
  - HFC-245fa for the upper stage (high-temperature stage)
  - HFC-134a for the lower stage (low-temperature stage)

- ORC with two expanders connected in-series (the pressure ratio of each expansion is calculated, in order to maximise thermal efficiency)
  - HFC-245fa

ORC maximum temperature ($T_{max}=T_{evap}$+5 K) for variable heat input from the evacuated tube solar collectors (after a pinch point analysis, dT_{pinch}=10 K) and solar radiation

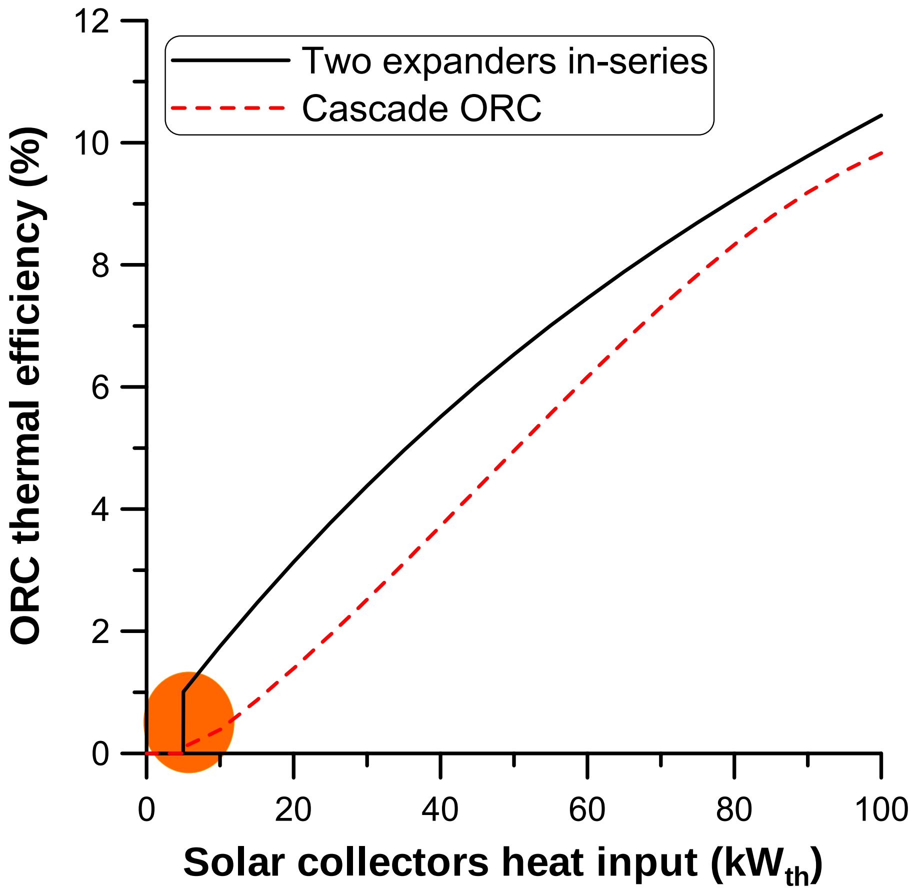




- The heat input is a linear function of the available incident solar radiation
- Also, the max ORC temperature is almost linearly correlated to the heat supply from the solar collectors

The mass flow rates of ORC and solar collectors working fluid are not constant, in order to increase the performance of the system

ORC thermal efficiency for various heat inputs $n_{th} = \frac{W_{ex} - W_p}{Q_{ORC}}$



The system operation is stopped, when the collectors' heat gain is lower than 5 kW$_{th}$ (ORC evaporation temperature ~50 ^{o}C, according to a pinch point analysis)

The thermal efficiency of the ORC with two in-series expanders is higher for the entire range of heat supply, especially at low-mid heat input

The configuration with the two in-series expanders has been finally selected, since its installation cost is also lower (fewer components)

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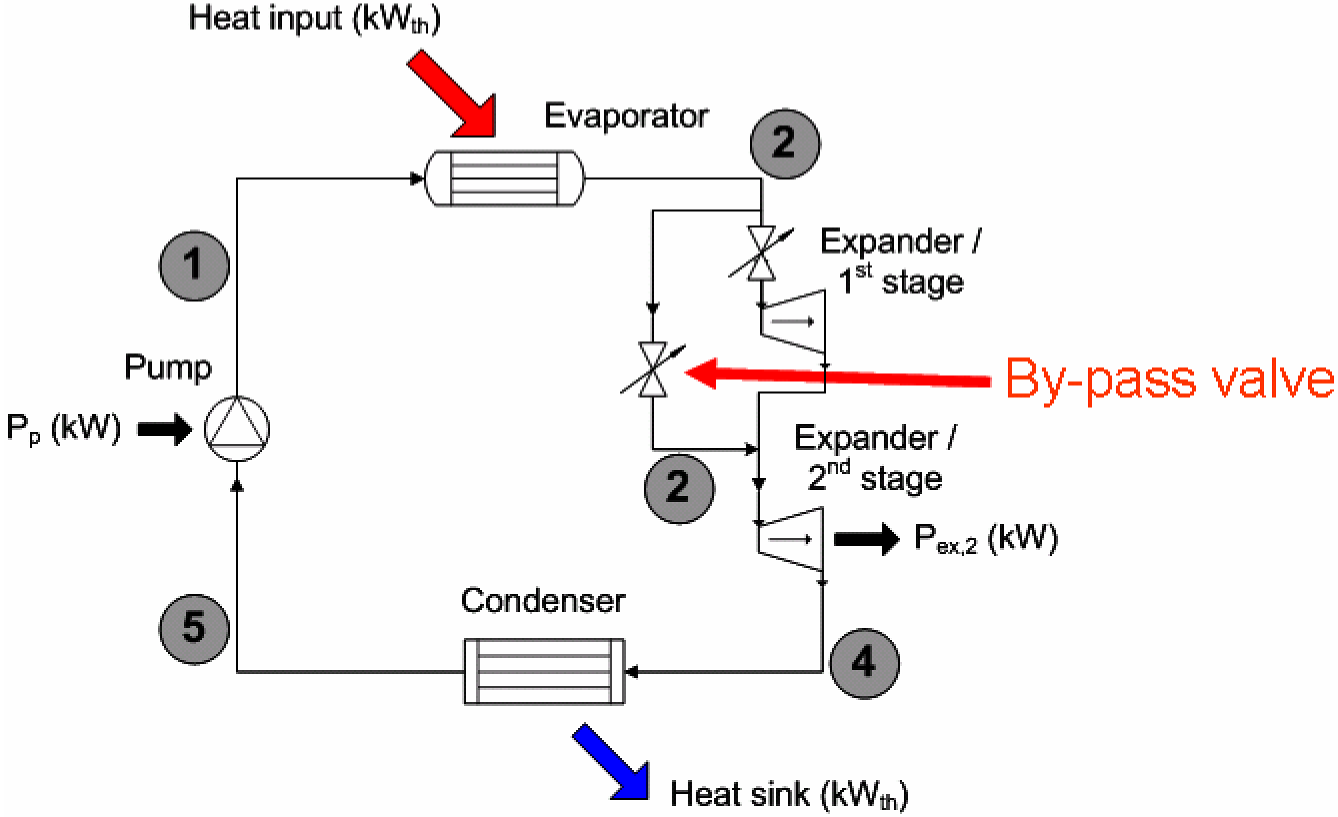
With realistic operating conditions (variable solar radiation) and with the scope to increase/control the system's performance, the rotational speed of the feed pump (variation of mass flow rate) and expanders (variation of inlet pressure) are continually altered

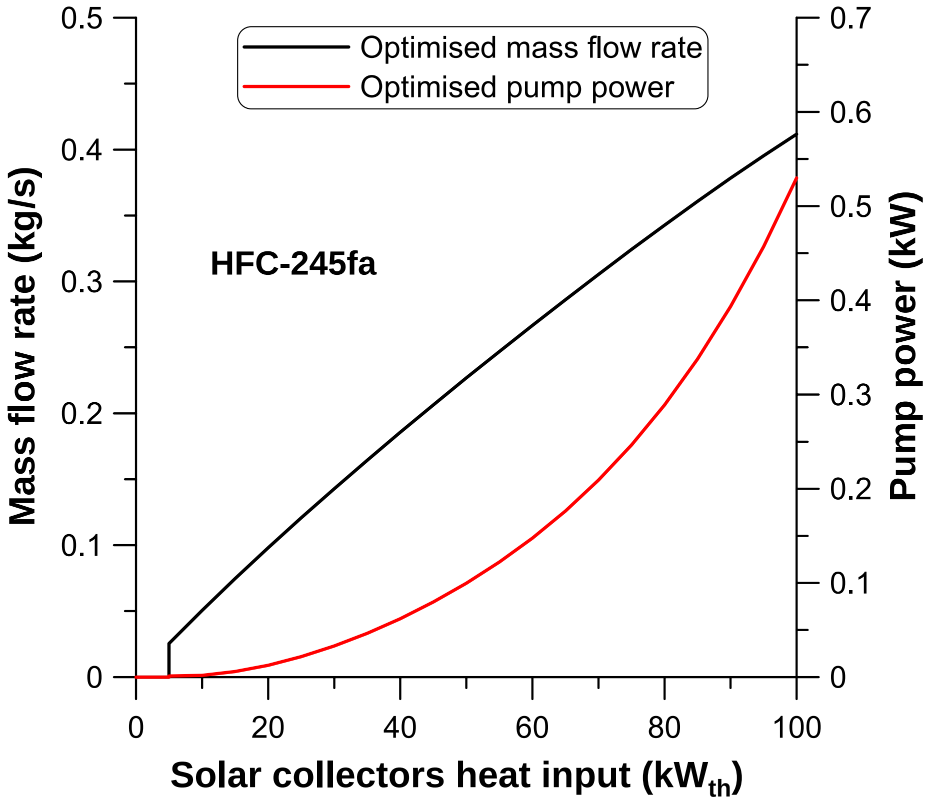


Control strategies for the selected ORC configuration

With realistic operating conditions (variable solar radiation) and with the scope to increase/control the system's performance, the rotational speed of the feed pump (variation of mass flow rate) and expanders (variation of inlet pressure) are continually altered

Feed pump (piston-diaphragm pump):

Control of the pump's rotational speed alters the refrigerant's mass flow rate (together with the pump's power consumption). These optimised parameters are calculated for variable heat input from the solar collectors



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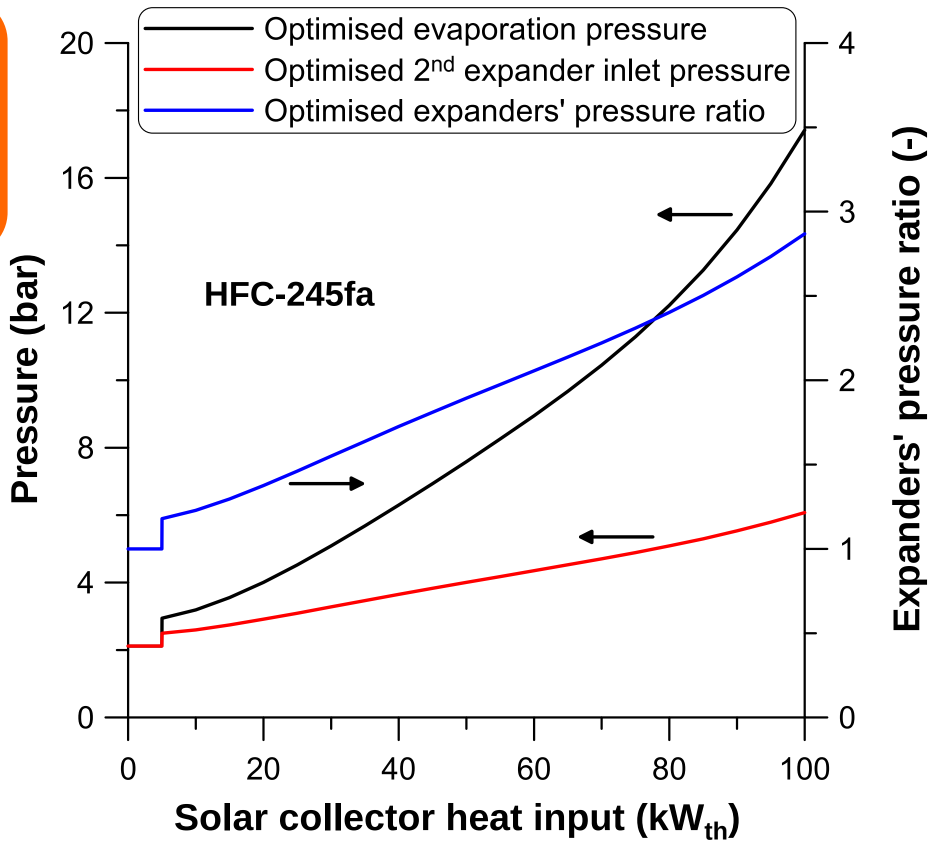
Expanders (scroll type):

Important operating parameter: pressure ratio of each expander (P_{in}/P_{out}), set equal for both expanders (pressure ratio at max load ~ 3)

The evaporation pressure, inlet pressure to the 1st expander, (black line) substantially changes (3-18 bar) for variable heat input (constant superheating=5 K)

The inlet pressure to the 2nd expander (red line) changes within a small range (2.5-6 bar)

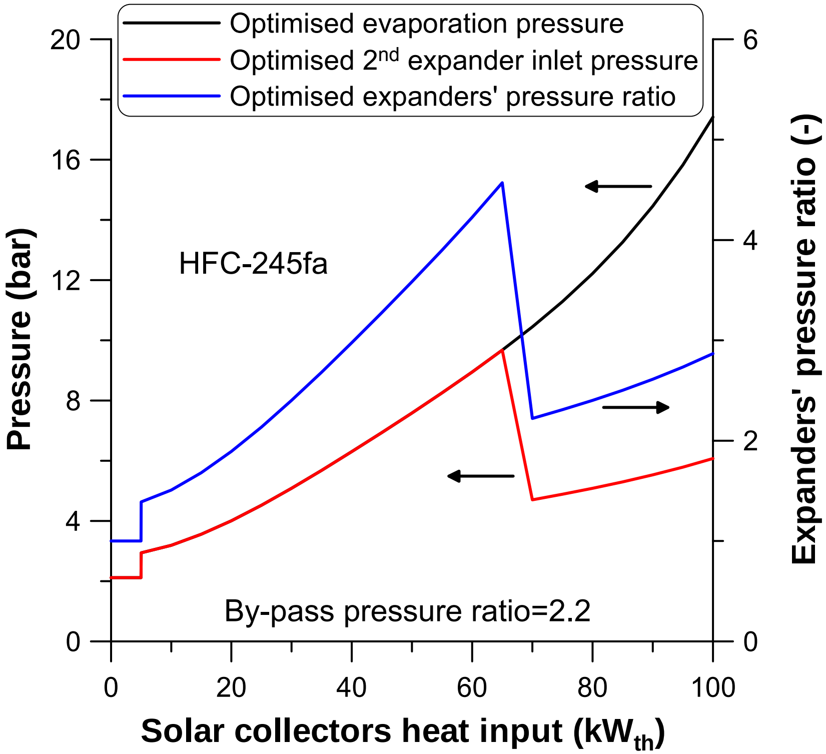
The expanders' pressure ratio (blue line) is rapidly decreased at low loads (~1.4), reaching off-design conditions, where the expansion efficiency is extremely low



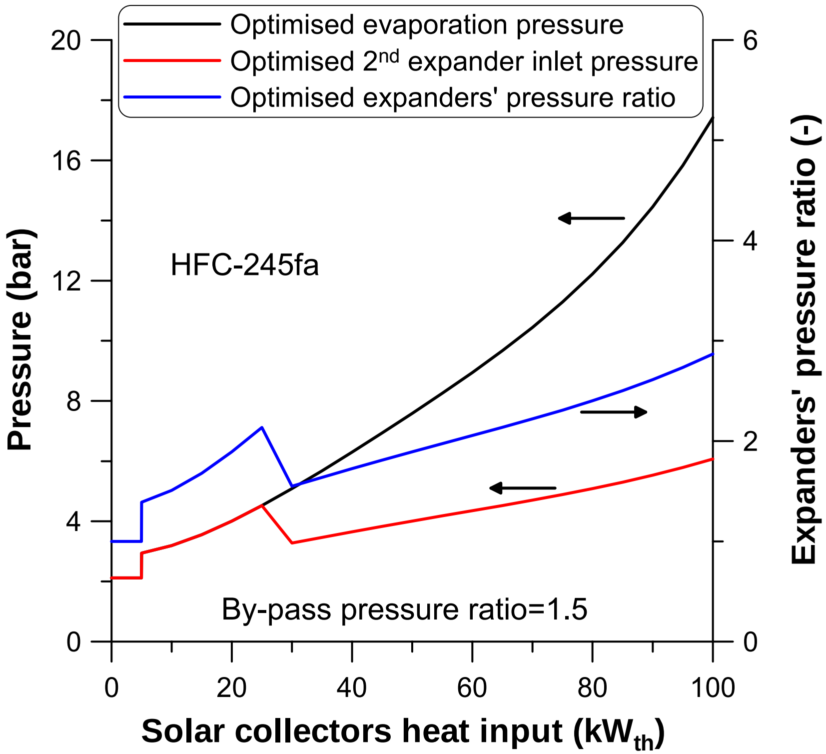
Expanders (scroll type):

Important operating parameter: pressure ratio of each expander (P_{in}/P_{out}), set equal for both expanders (pressure ratio at max load ~ 3)

Early by-pass (pressure ratio=2.2) at 70 kW_{th} (~1.5-4.5)



Late by-pass (pressure ratio=1.5) at 30 kW_{th} (~1.5-3)



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Conclusions

Main conclusions drawn so far from the investigation of the "double-stage expansion"

- For solar applications a different ORC configuration is needed (except for the single-stage expansion), in order to have high performance for every solar radiation level
- Two "double-stage expansion" configurations have been investigated, appropriately selecting the organic working fluids
- An ORC with two in-series expanders shows higher thermal efficiency for the whole range of solar collectors' heat gain (especially at low-mid loads), in comparison to the cascade ORC (e.g. 10.4% instead of 9.8% at max load), having also a lower installation cost (fewer components needed)
- The 1st expander is by-passed at low-mid loads, according to its operating pressure ratio (optimisation parameter → critical pressure ratio)
- The control of the feed pump and the expanders is required (regulation of their rotational speed), in order to achieve high performance

Thank you for your attention

Acknowledgement: The current project is financed by the Greek government (contract No. 09SYN-32-982)