PERFORMANCES OF AN ORC POWER UNIT FOR WASTE HEAT RECOVERY ON HEAVY DUTY ENGINE

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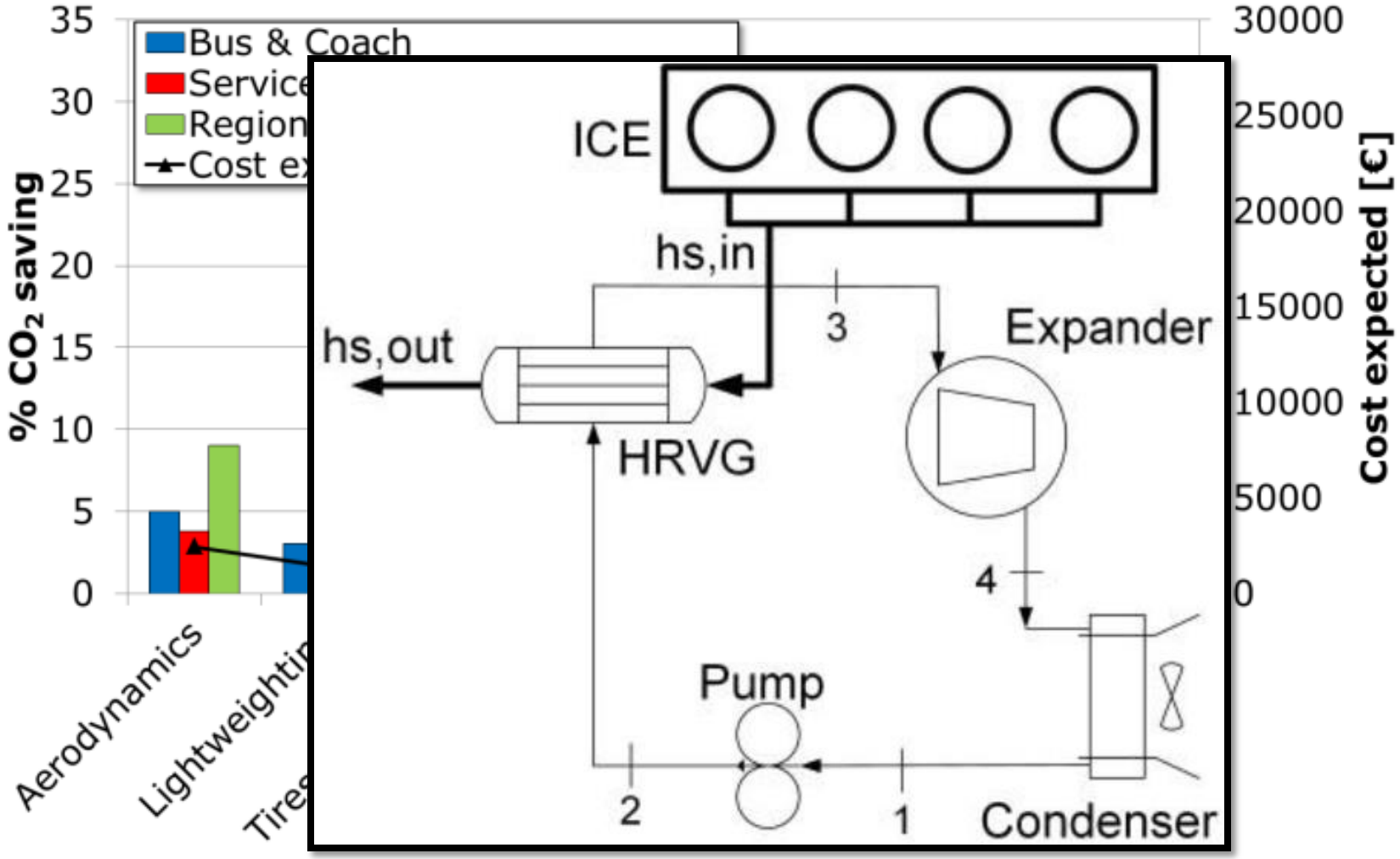
CRF CENTRO RICERCHE FIAT

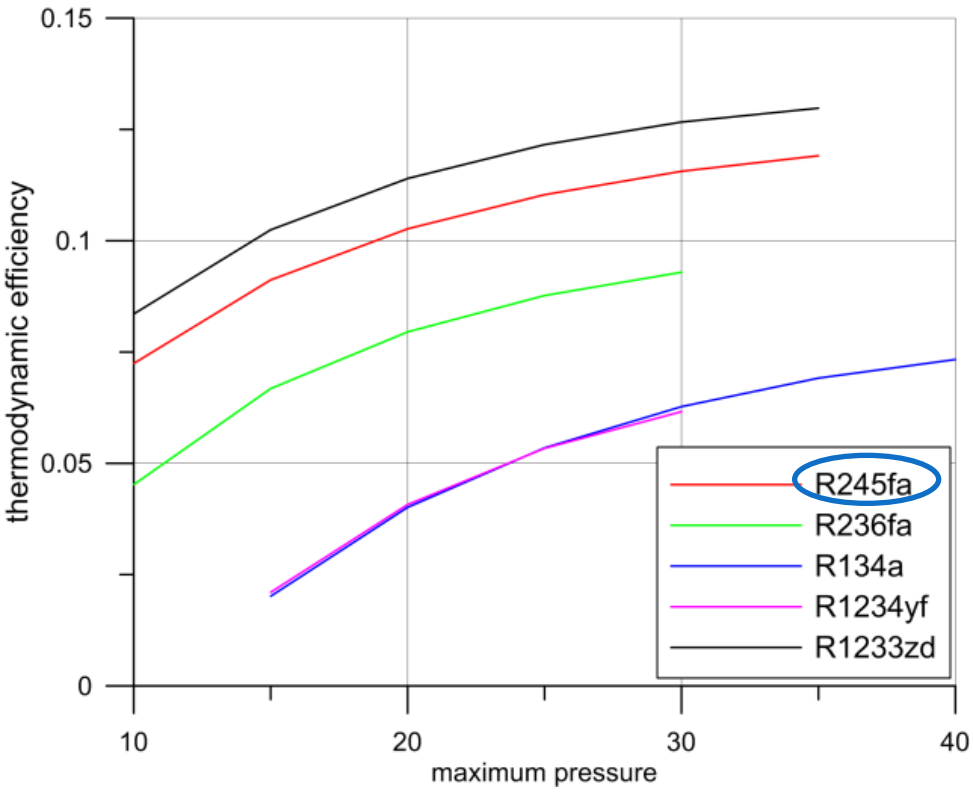
Summary

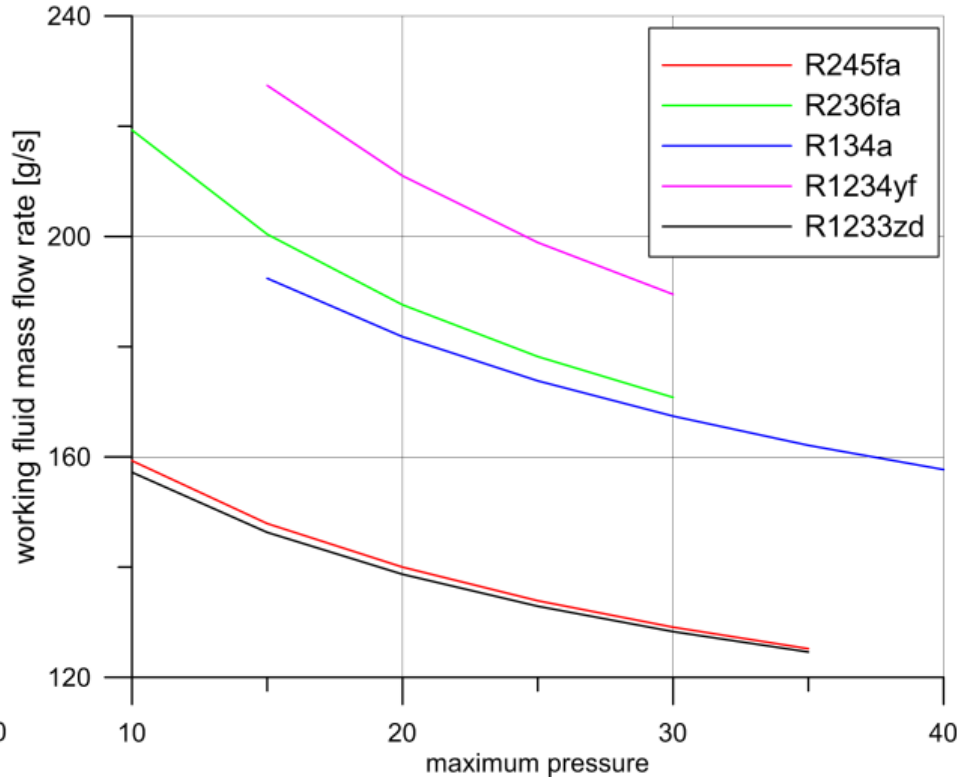
- **Waste Heat Recovery opportunity for emission savings**
- **Experimental test bench development**
  - Fluid choice
  - Hot thermal source characterization (Heavy Duty ICE)
  - Heat recovery vapor generator
  - Turbine characterization
  - Pump
  - Condenser
- **Overall plant performances**
  - Energetic and exergetic analyses
- **Conclusions**

Cultural Motivation



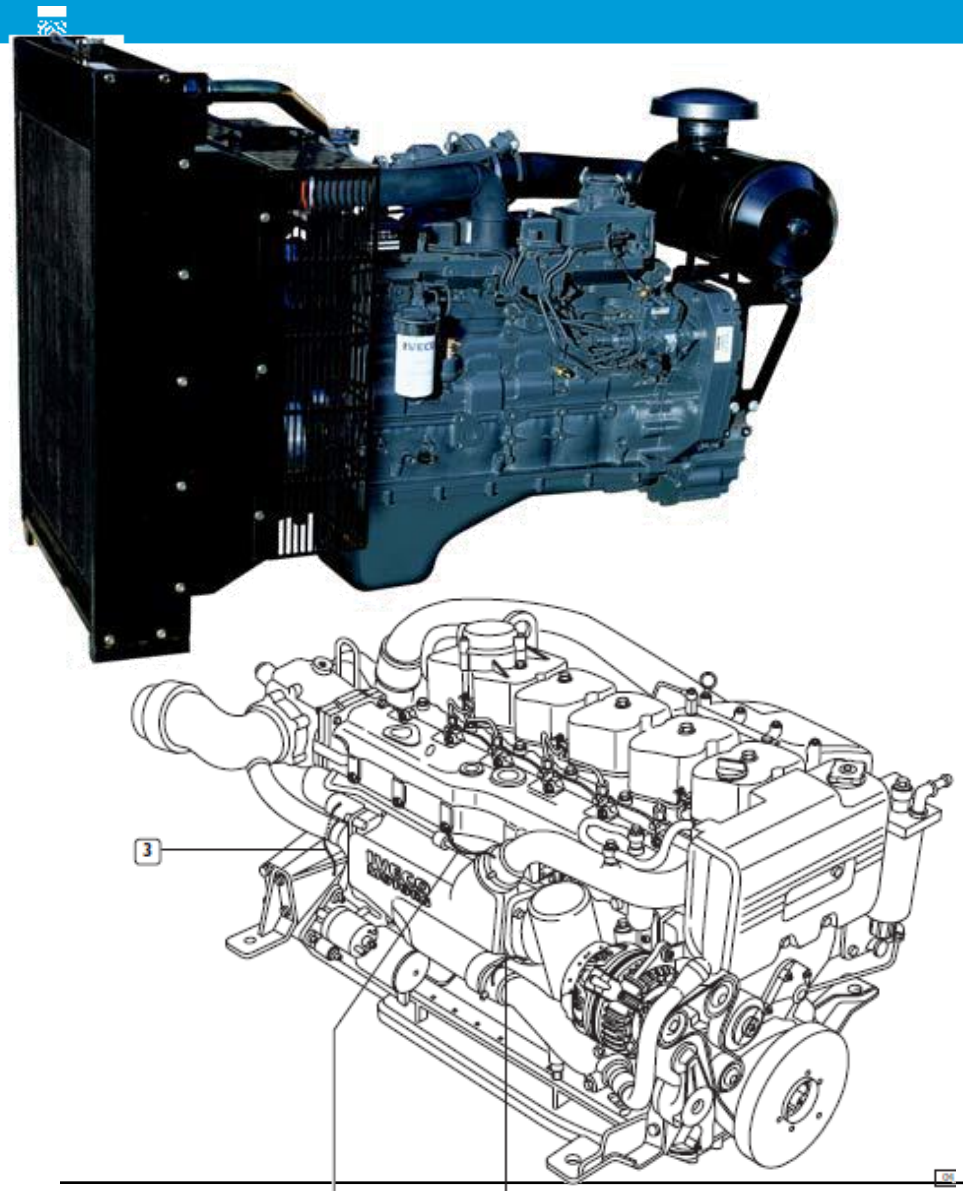
Fluid choice





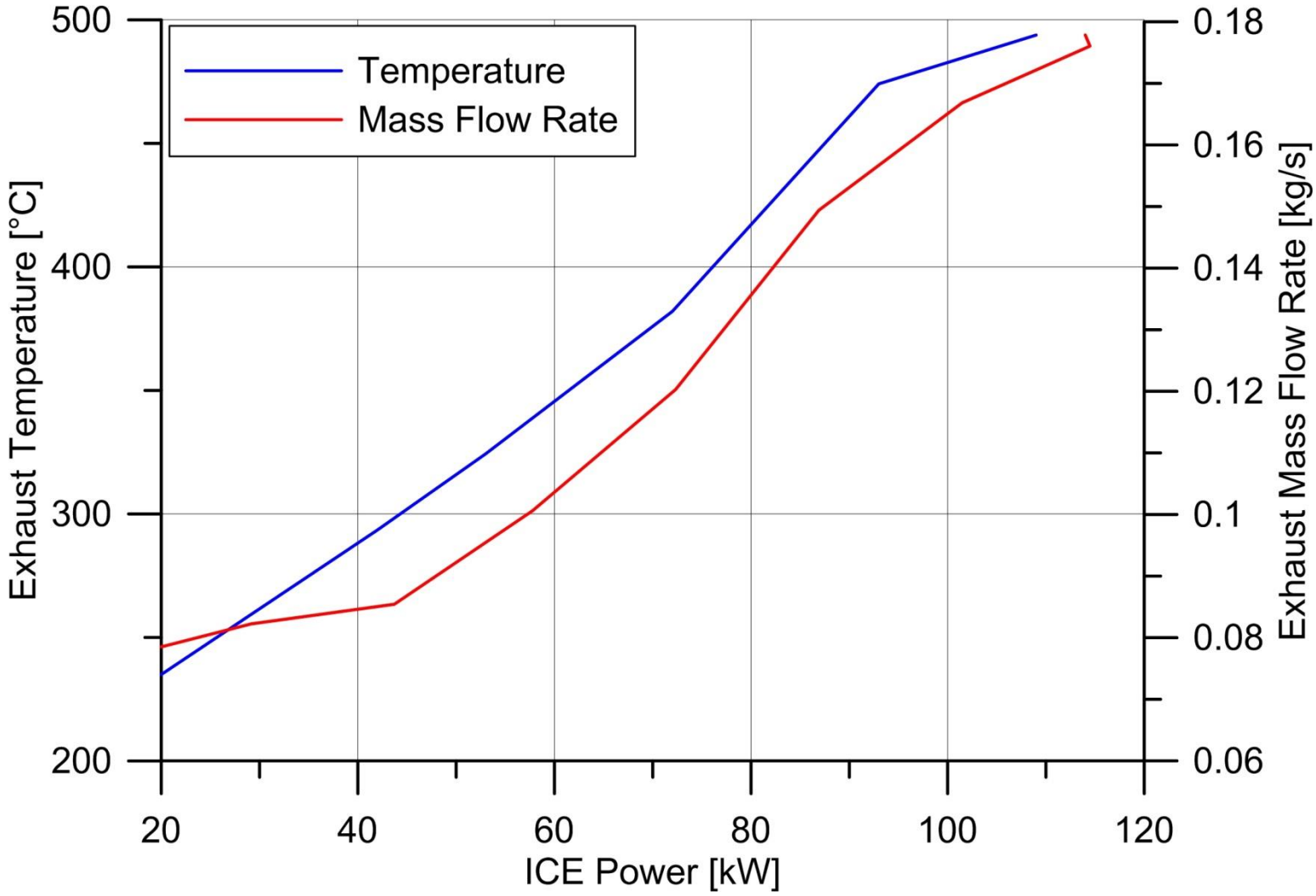
Exhaust gas inlet temperature	390 °C
Exhaust gas outlet temperature	160 °C
Condensing temperature	45 °C
Pump efficiency	0.85
Expander adiabatic isentropic efficiency	0.75

Hot source characterization

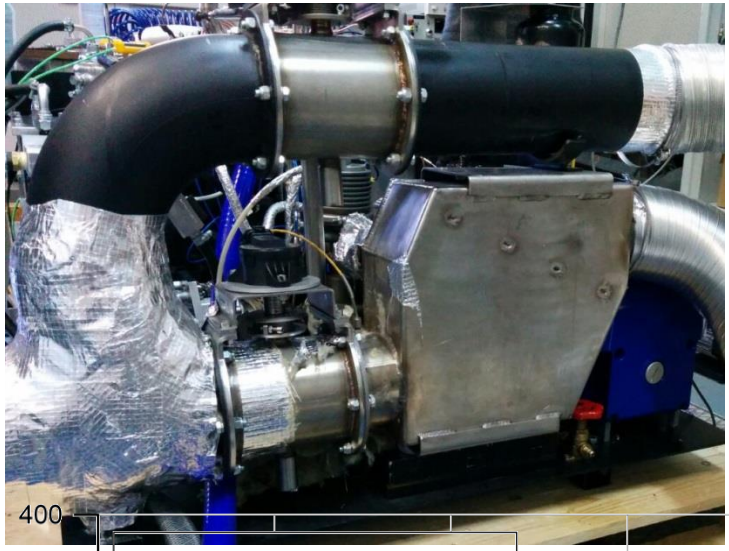


Engine model	NEF67 TM2.1
Number cylinders	6
Firing order	1-5-3-6-2-4
Cylinder arrangement	In line
Valves per cylinder	2
Cycle	Diesel 4 Strokes
Injection system	Direct
Induction System	Turbocharged after cooled air/air
Bore	104 mm
Stroke	132 mm
Total displacement	6.7 liters
Peak Power	118 kW@1500 RPM

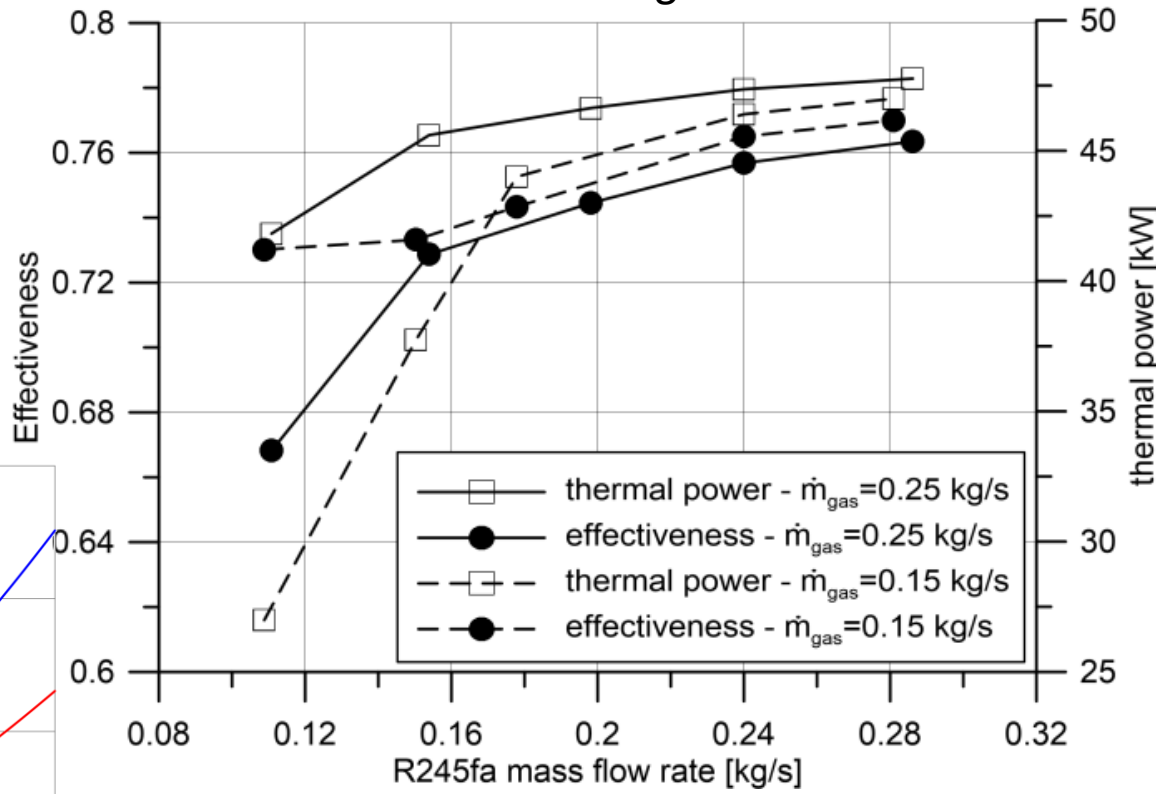
Hot source characterization

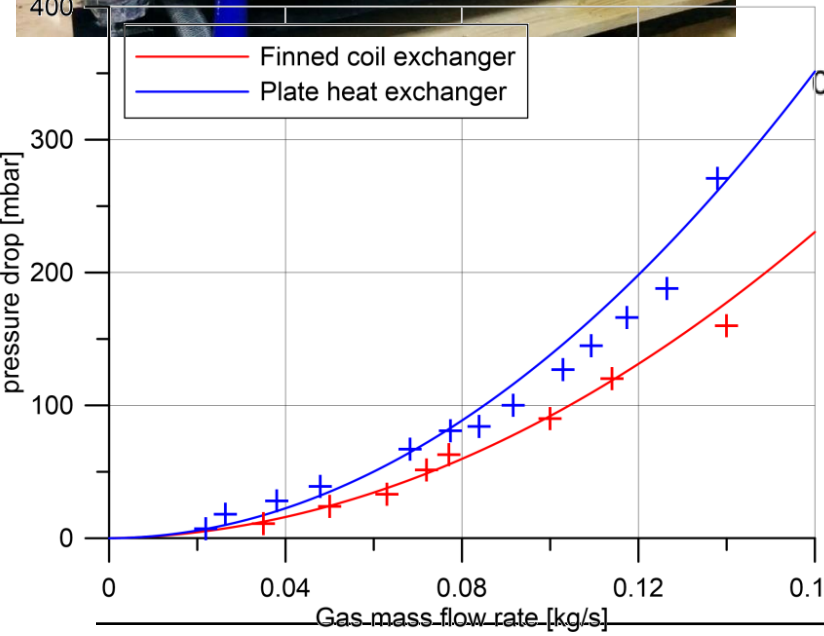


Heat Recovery Vapor Generator characterization



Steel finned coil heat exchanger



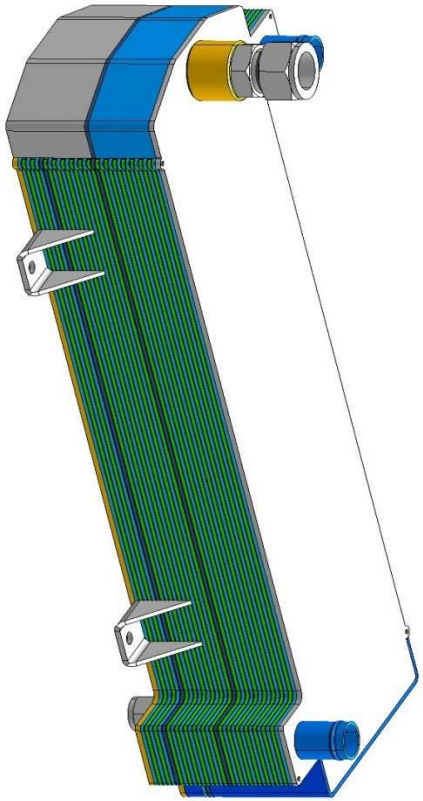


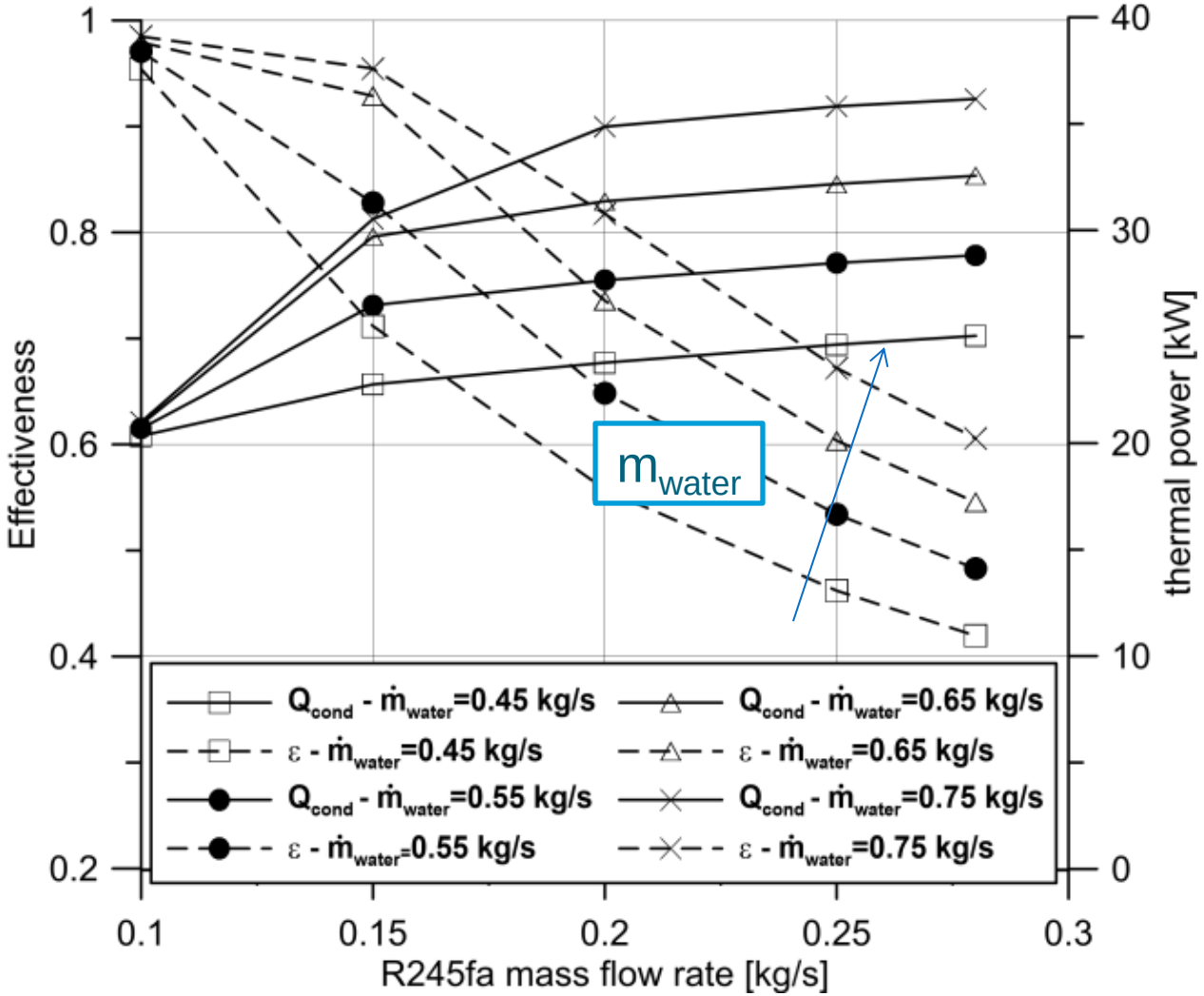
- Effectiveness close to 0.8
- Low gas side pressure drop

$$\varepsilon = \frac{Q}{C_{\min}(T_{h,i} - T_{c,i})}$$

Condenser characterization

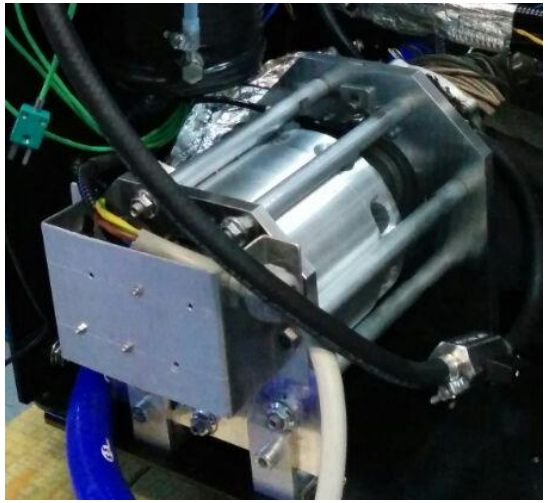
Plate heat exchanger



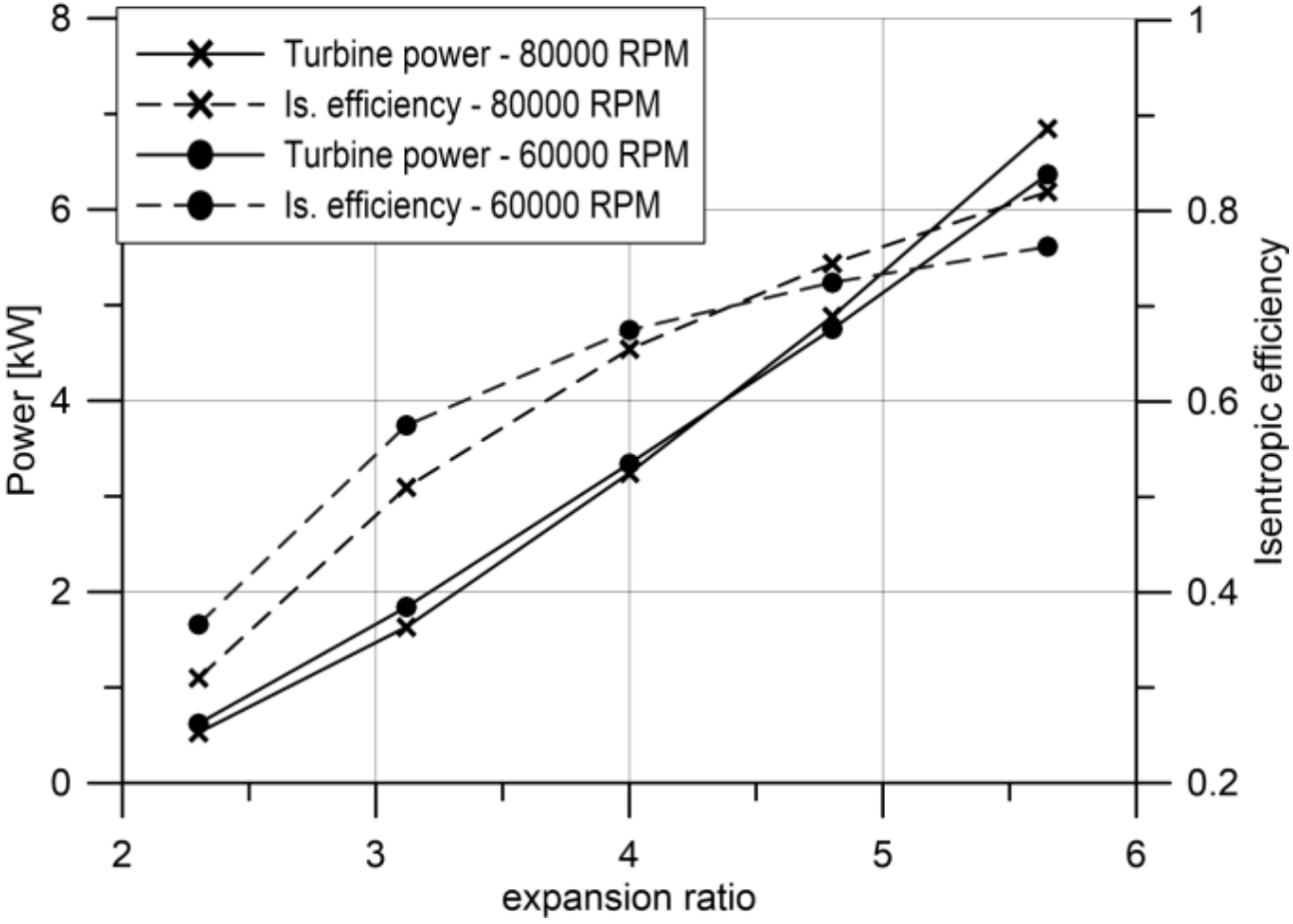


- Cooling water is at 50° C
- R245fa at 5 bar and 90° C inlet temperature

Turbine characterization



Axial turbine

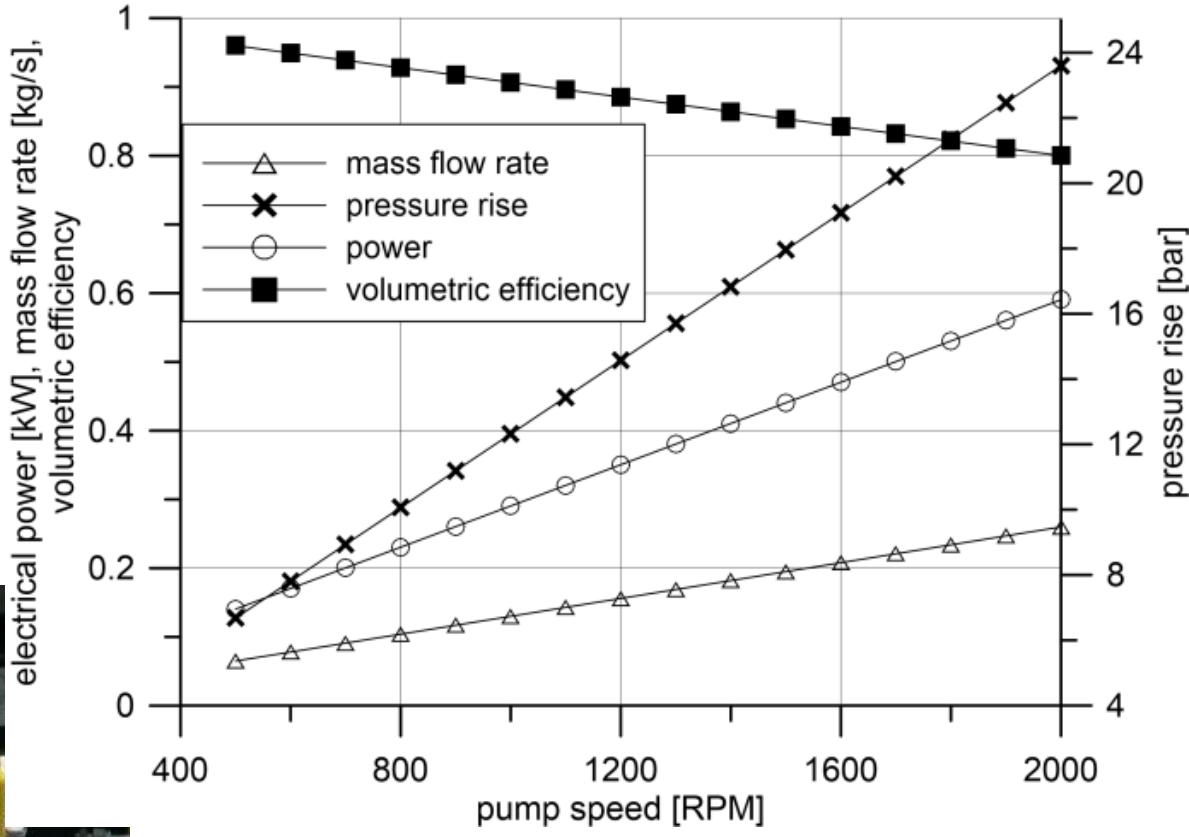


- *Oil circuit for gear lubrication*
- *Syncronous electric generator*
- *24 V DC current rectifier*

Pump characterization

Internal gear pump

- Oil free
- DC brushless motor
- Magnetic clutch

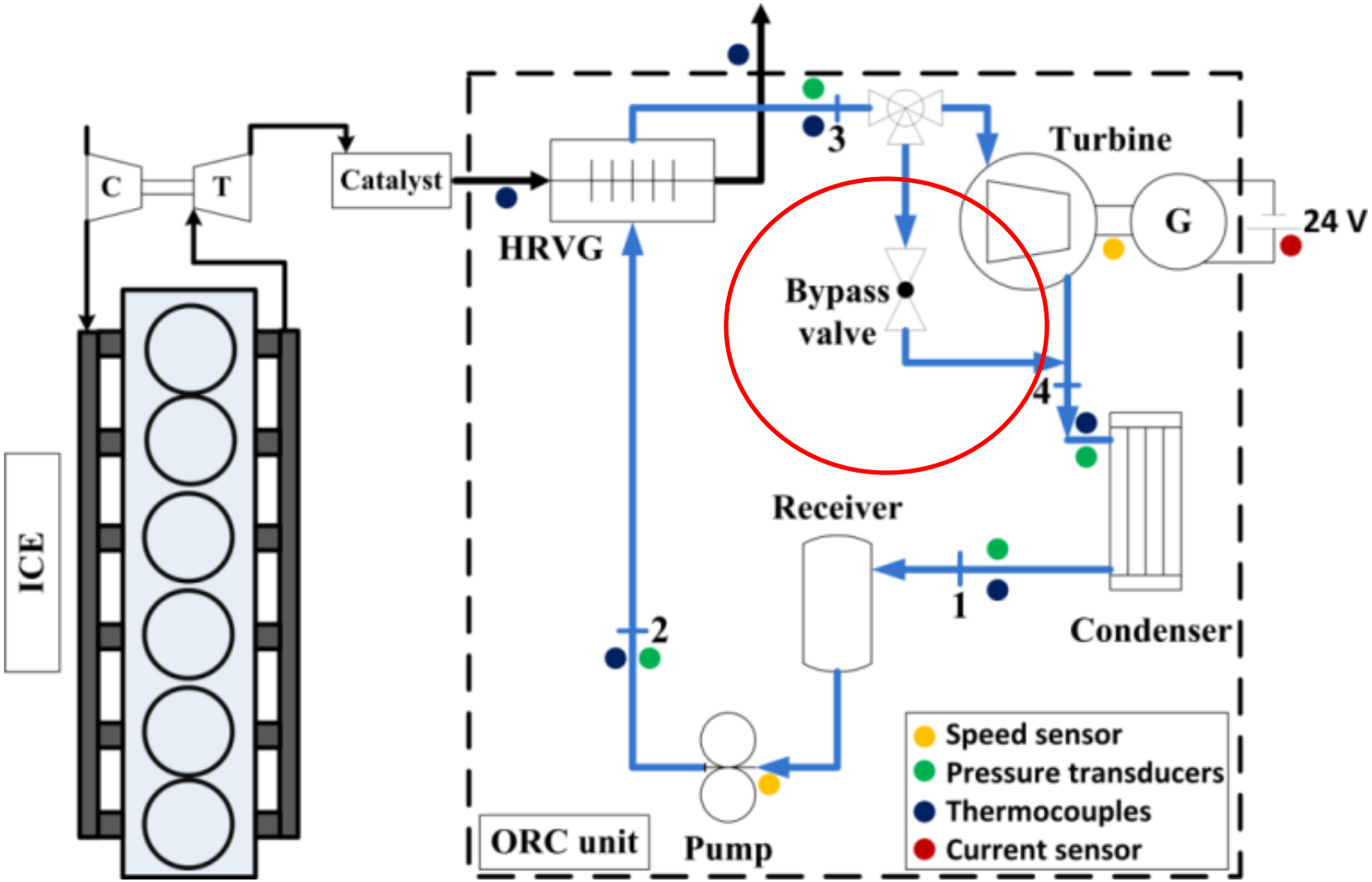


-High volumetric effficiency

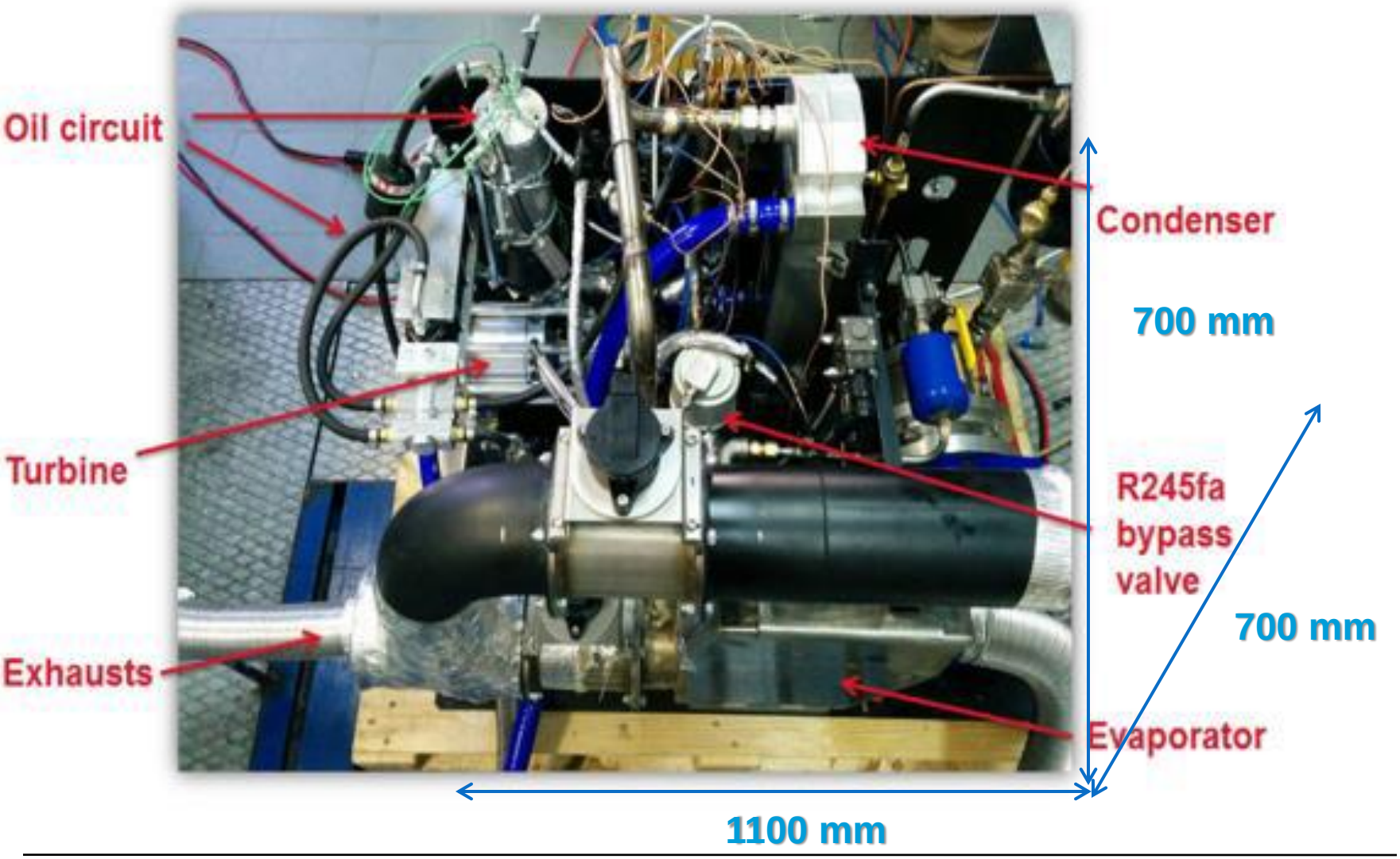
-Low electric absorption

- 100 – 300 g/s mass flow rate

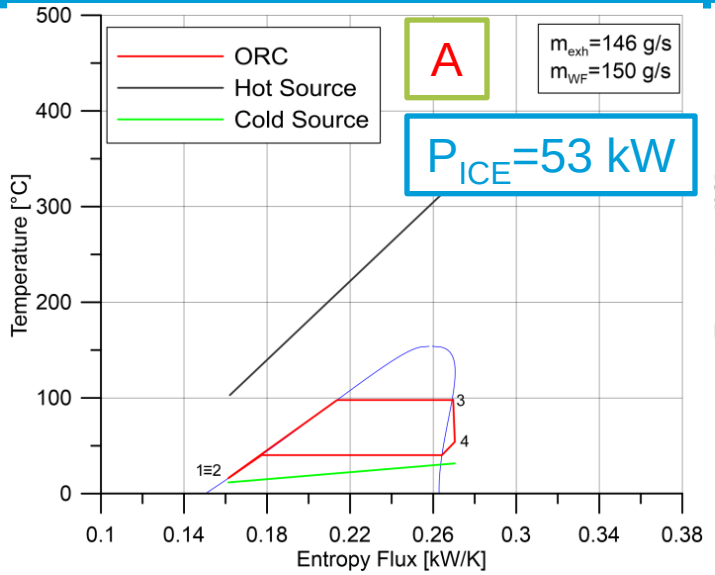
Test bench description

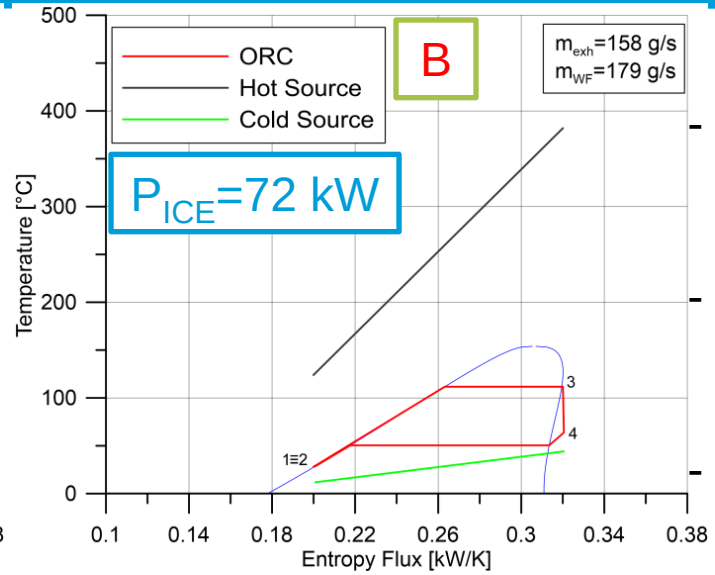


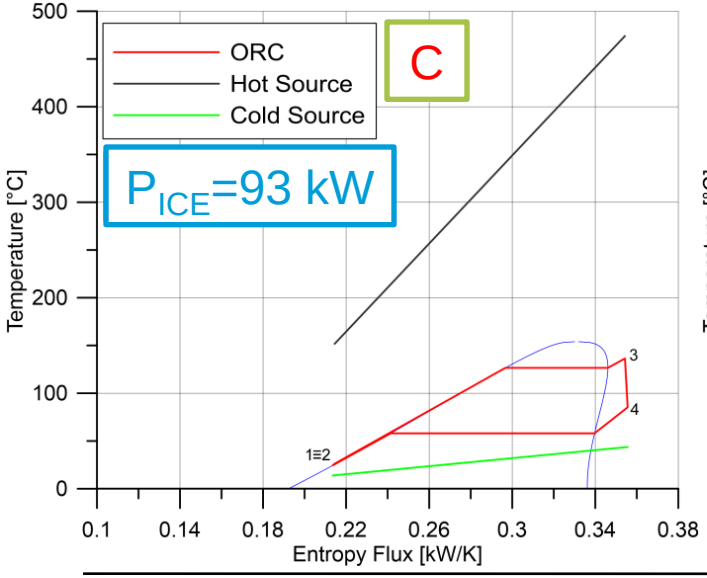
Test bench description

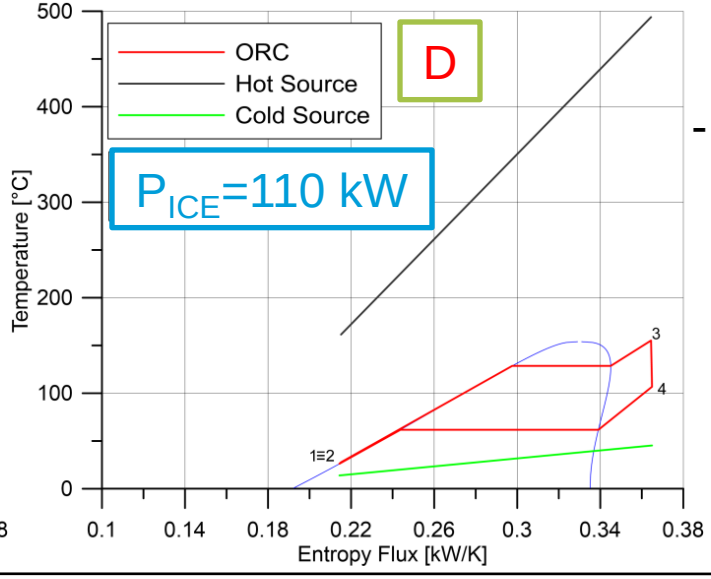


Selected tests – Entropy diagrams



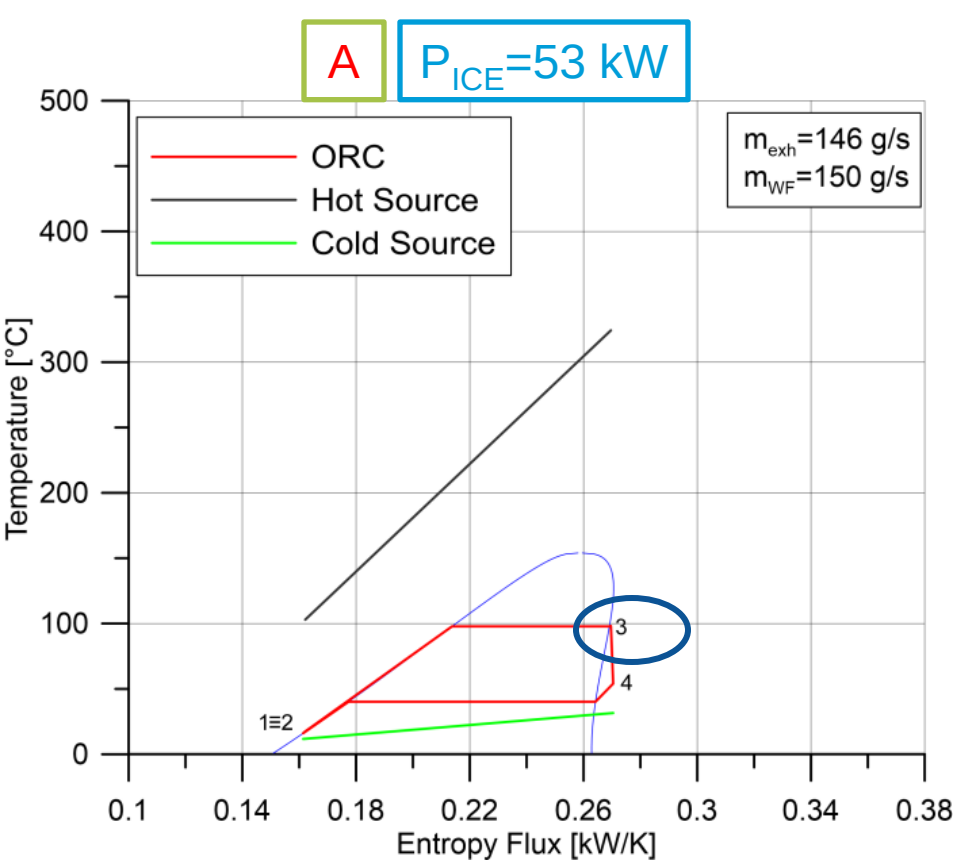


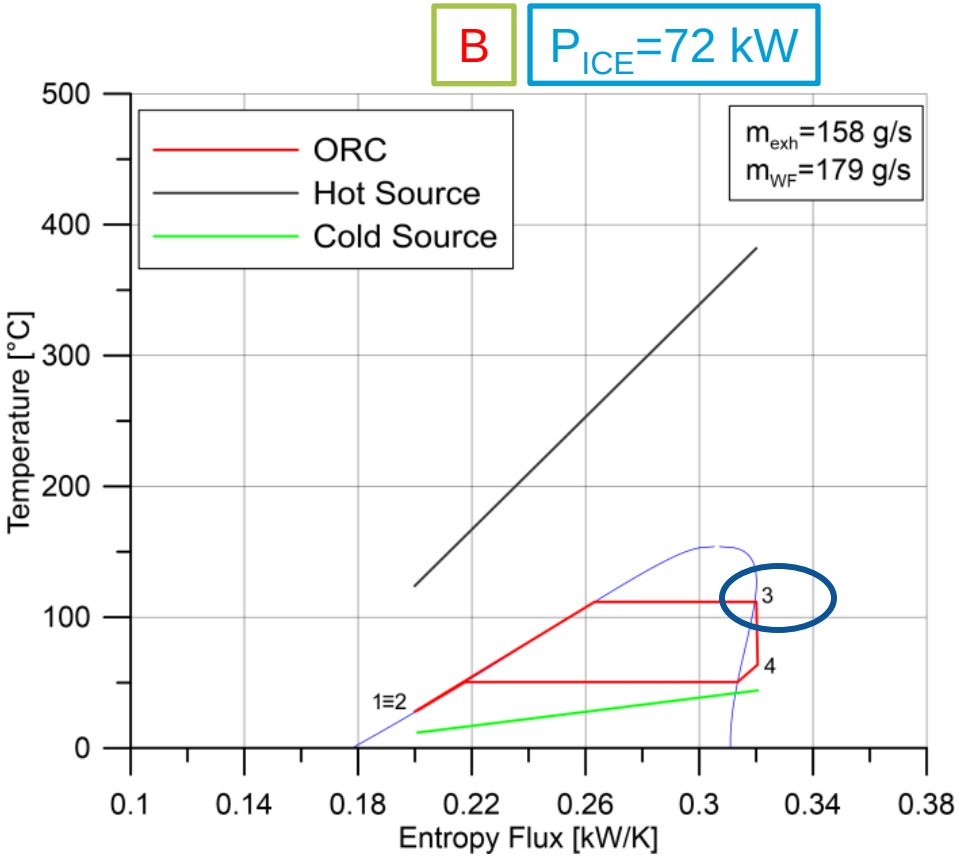




- High distance from hot source
- High condenser undercooling
- Low superheating value in lower loads conditions
- Higher desuperheating
  → Regeneration opportunity

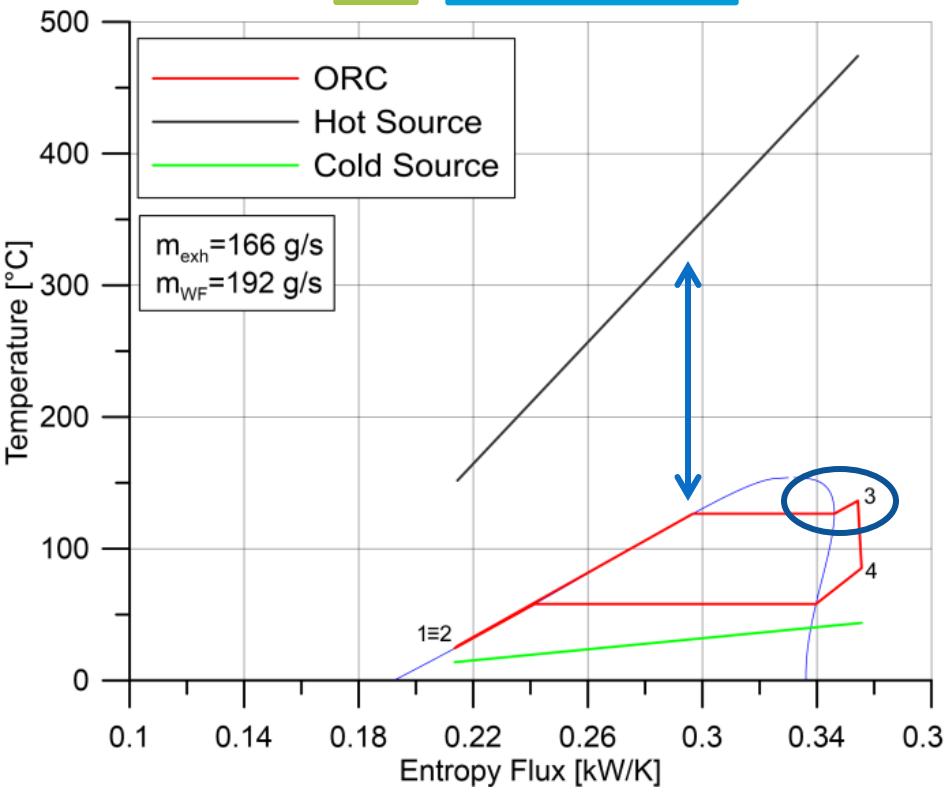
Selected tests – Entropy diagrams



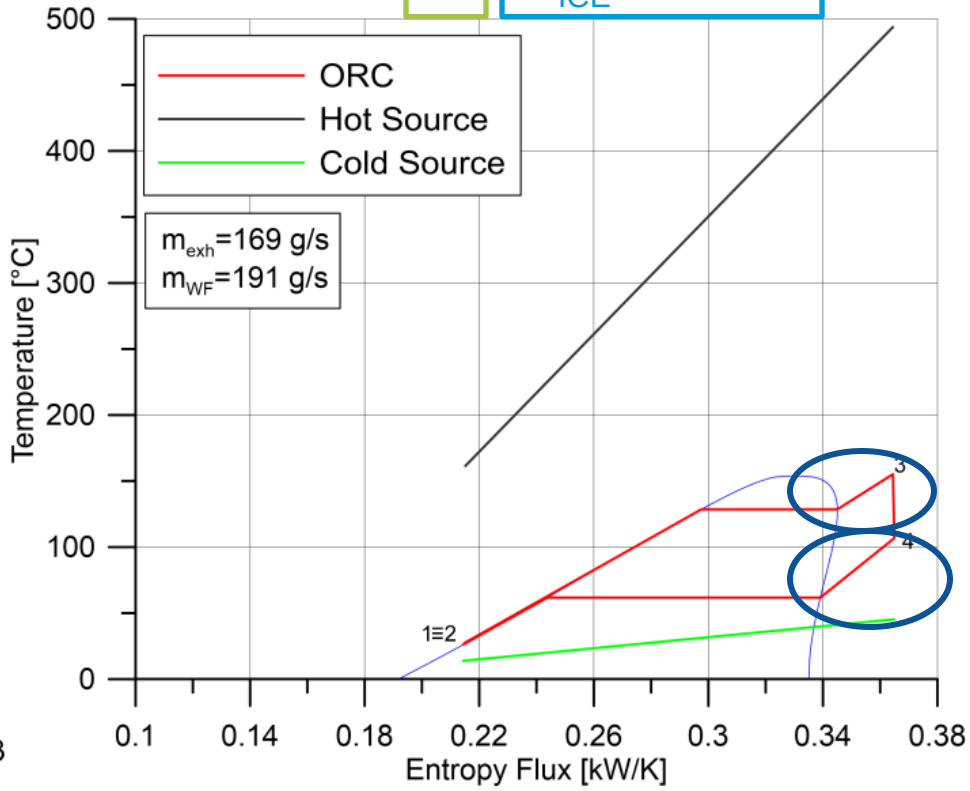


Selected tests – Entropy diagrams

C P_{ICE}=93 kW

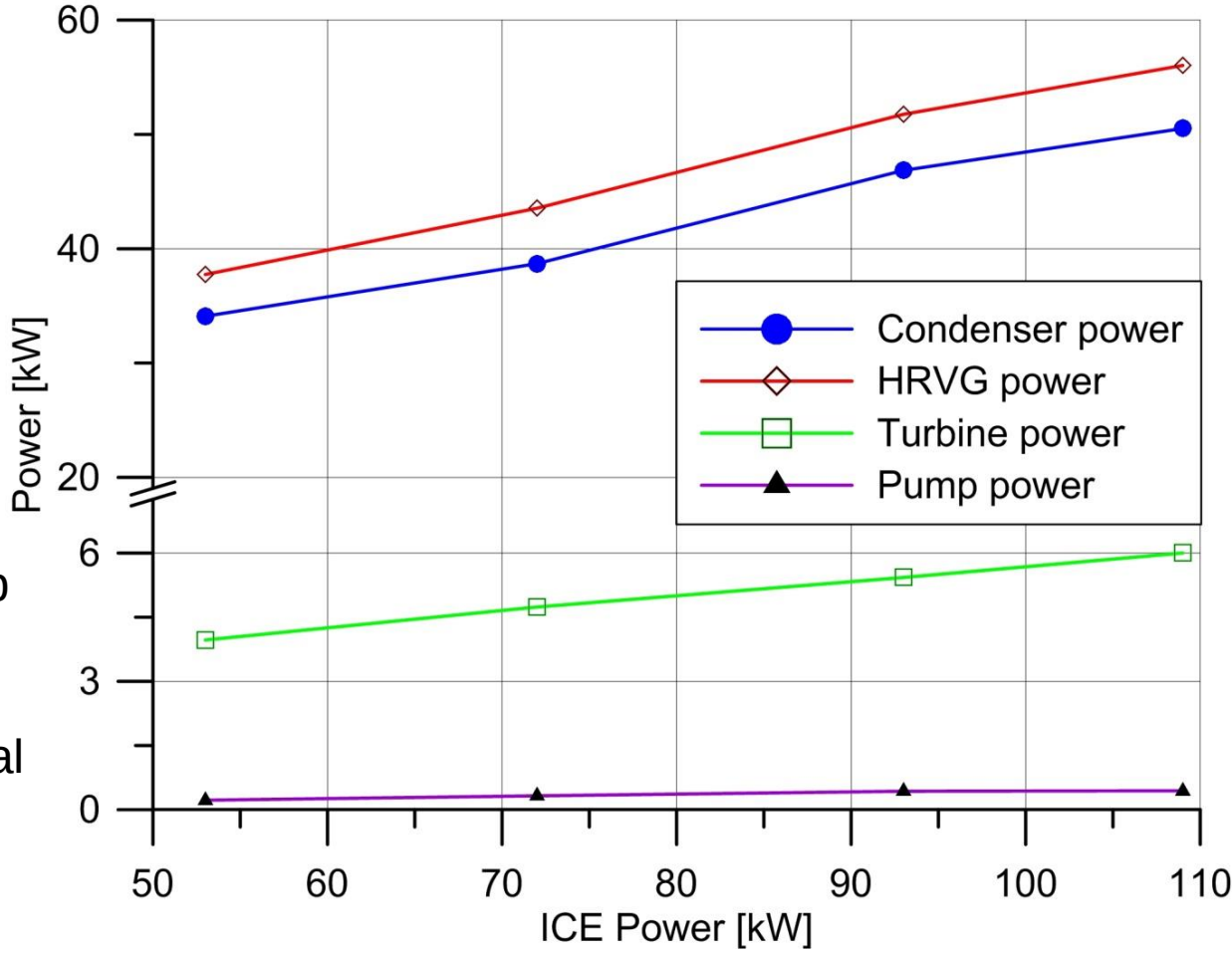


D P_{ICE}=110 kW



Plant energy balance

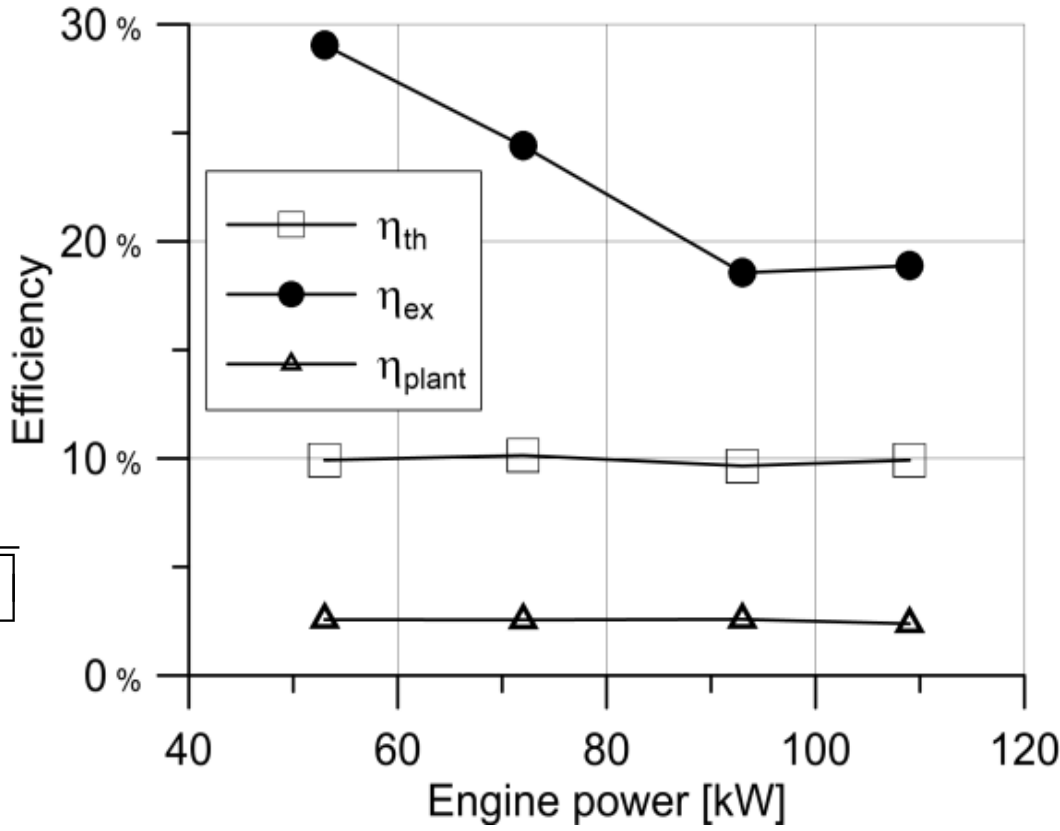
$$\begin{cases} Q_{HRVG} = \dot{m}_{WF}(h_3 - h_2) \\ P_{pump} = \dot{m}_{WF}(h_2 - h_1) \\ P_{turb} = \dot{m}_{WF}(h_3 - h_4) \\ Q_{cond} = \dot{m}_{WF}(h_4 - h_1) \end{cases}$$



- Thermal power recovered up to 55 kW
- Max turbine thermodynamical power = 6 kW @ full engine load (110 kW)
- Negiglible pump power

Efficiencies analysis

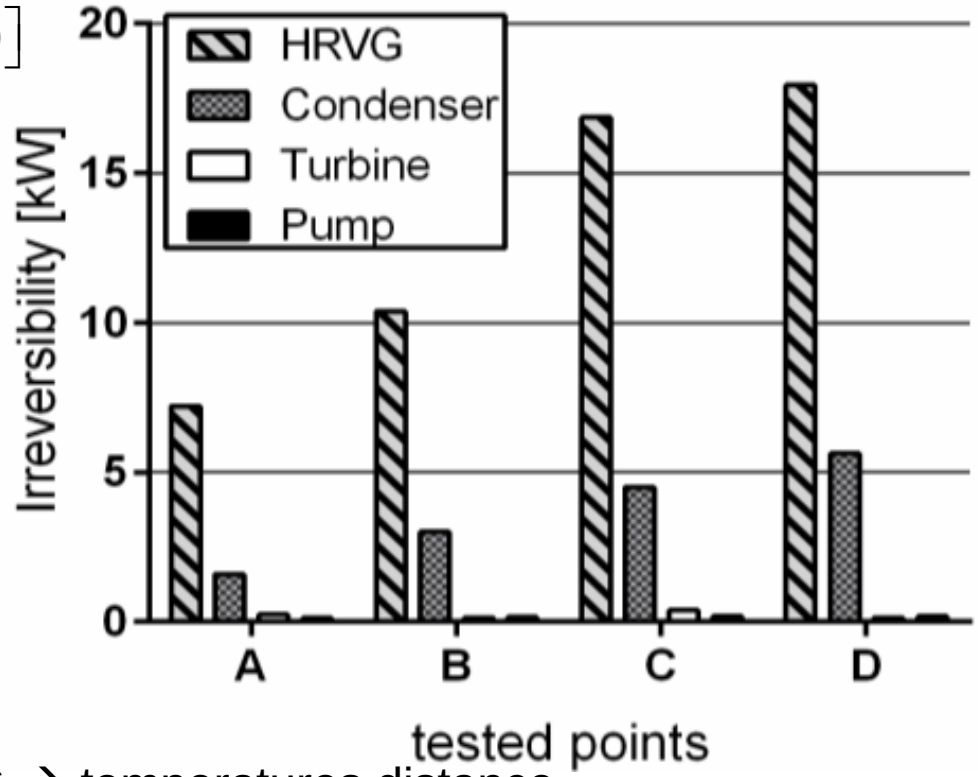
$$\begin{cases} \eta_{plant} = \dfrac{P_{el,turb} - P_{el,pump}}{Q_{hs}} \\ \eta_{th} = \dfrac{\Delta h_T - \Delta h_{pump}}{h_3 - h_2} \\ \eta_{ex} = 1 - \dfrac{I_{HRVG} + I_{turb} + I_{cond} + I_{pump}}{\dot{m}_{hs}\left[h_{hs,in} - h_{hs.out} - T_{ref}\left(s_{hs,in} - s_{hs.out}\right)\right]} \end{cases}$$



- Thermodynamic efficiency around 10 %
- Overall plant efficiency only 3%
- Exergetic efficiency is 30 % in lower loads and under 20% in higher load cases

Exergy analysis

$$\begin{cases} I_{HRVG} = T_{ref}\left[\dot{m}_{WF}(s_3 - s_2) - \dot{m}_{hs}(s_{hs,in} - s_{hs,out})\right] \\ I_{pump} = P_{pump} - \dot{m}_{WF}\left[(h_2 - h_1) - T_{ref}(s_2 - s_1)\right] \\ I_{turb} = \dot{m}_{WF}[(h_3 - h_4) - T_{ref}(s_3 - s_4)] - P_{turb} \\ I_{cond} = \dot{m}_{WF}\left[(h_4 - h_1) - T_{ref}(s_4 - s_1)\right] \end{cases}$$



- Higher irreversibilities related to HRVG → temperatures distance (in particular in higher load cases)
- Neglibile irreversibilities on turbine and pump
- Condenser ones also high
- Exergetic efficiency from 30 % to 20 %

Conclusions

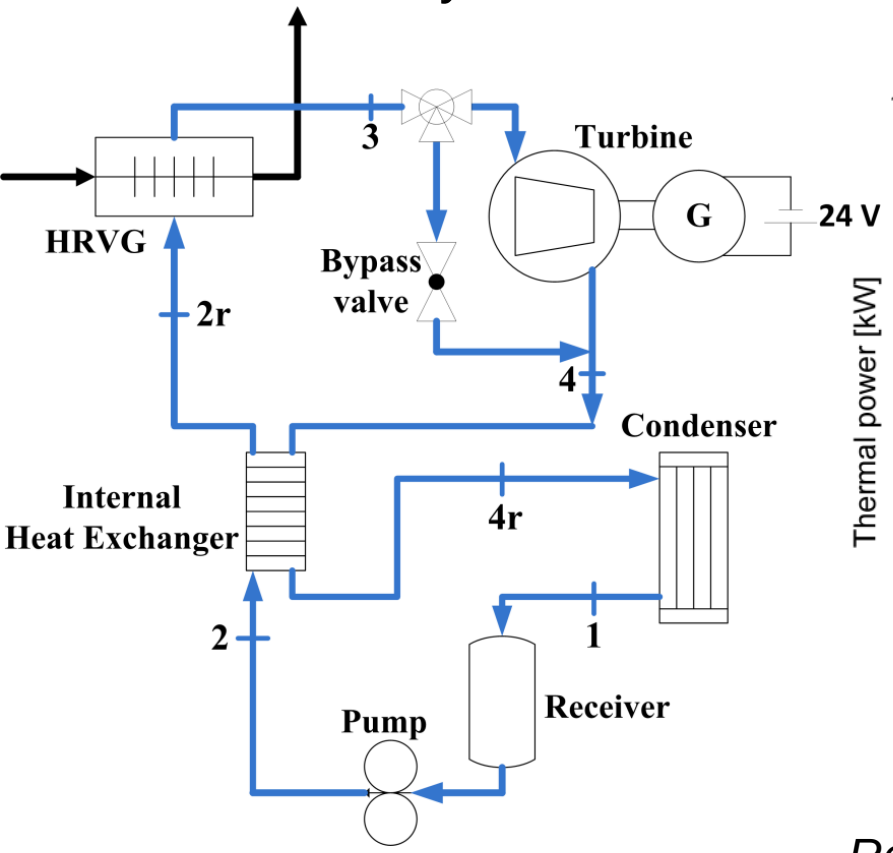
- **ORC based plant for Waste Heat Recovery from Internal Combustion Engine**
  - R245fa as actual fluid choice → road to R1233zd
  - Heat recovery vapor generator → finned coil heat exchanger
  - Axial turbine (smaller and lightweight, high efficiency)
  - Internal gear pump
- **Overall plant performances**
  - Compactness
  - Maximum heat recovered about 55 kW
  - Up to 10 % thermodynamic efficiency (maximum ICE load)
  - 3 % of global efficiency (24 V electrical power)

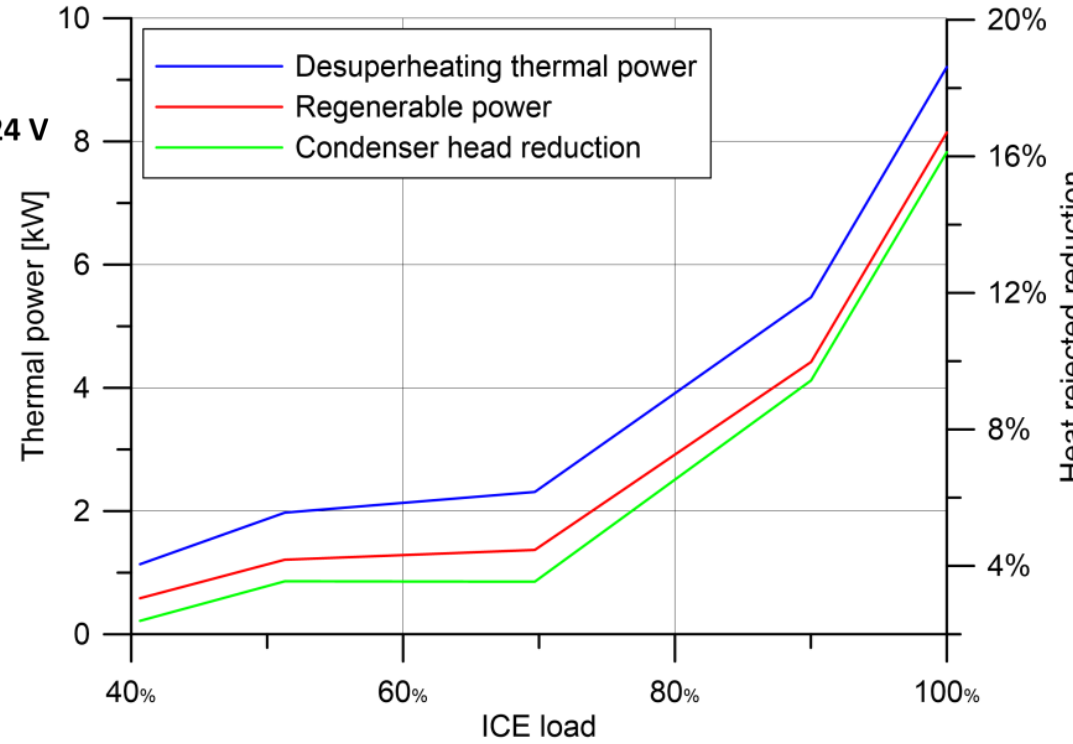
Conclusions

- **Axial turbine conversion efficiency**
  - 80% of isentropic efficiency → 6 kW thermodynamical power
  - 2,5 kW as maximum rated electrical power
  - Very low 24 V DC electrical conversion efficiency (40-50%)
  - Lubrication oil management
  - Turbine start-up difficulties due to the fluid thermal regimation (need of a turbine bypass branch)

Regeneration stage study

- Up to 16-18 % of thermodynamic efficiency improvement
- Heat recovery reduction of the same amplitude





Reduction of condenser heat rejected
→ Smaller condenser

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