Impact of water and oil contents in ethanol applied to ORC for exhaust heat recovery in heavy duty trucks

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EXOES at a glance

References:

RENAULT TRUCKS

MAN

faurecia

Valeo

PEUGEOT

TENNECO

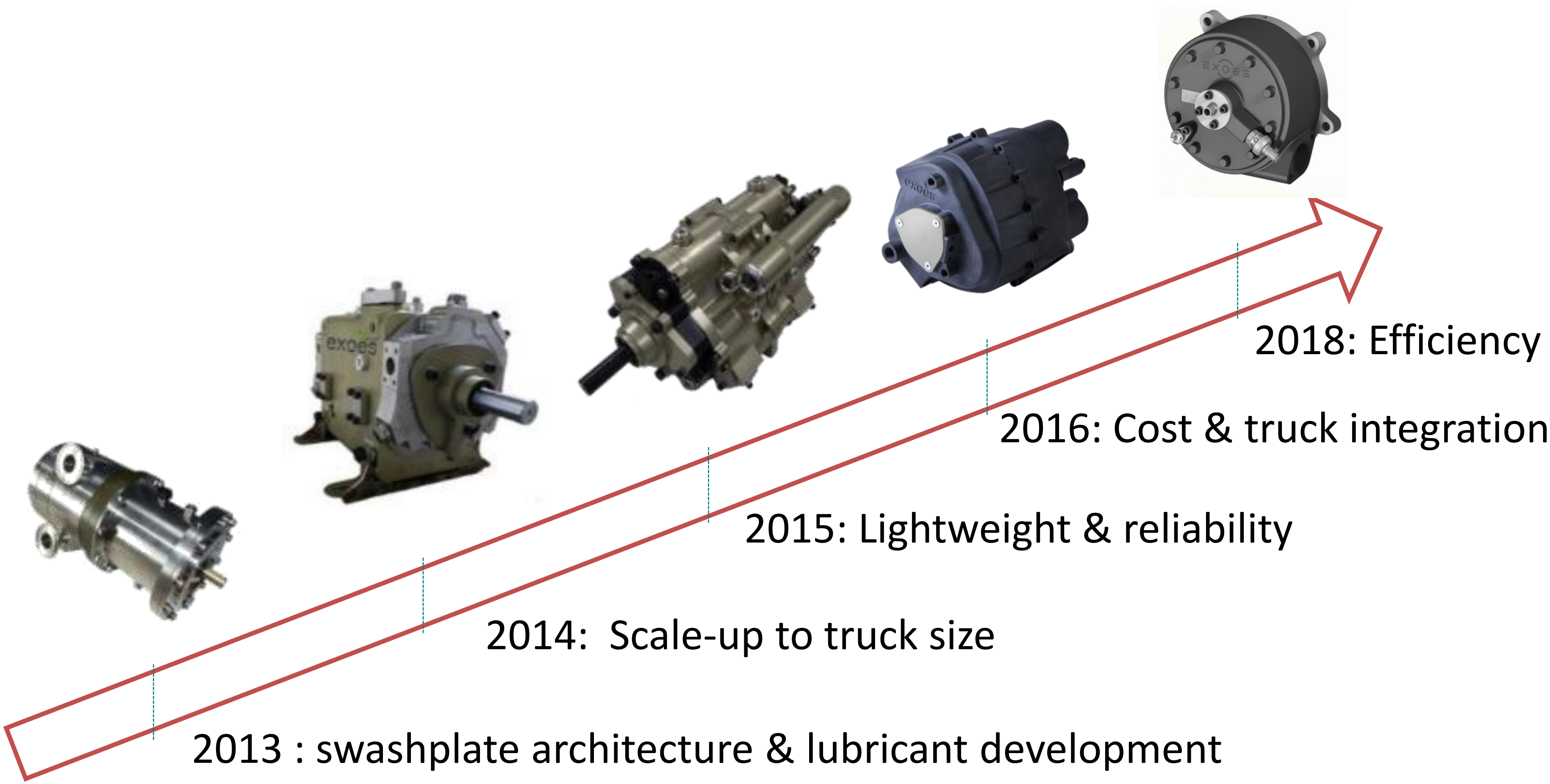
EXOES at a glance

Demo vehicle tested in 2017

thanks to a collaborative project with FCM and Volvo

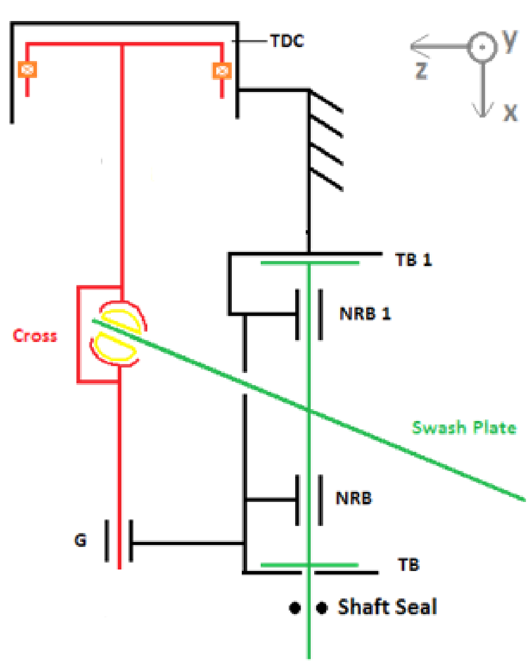
ORC experience

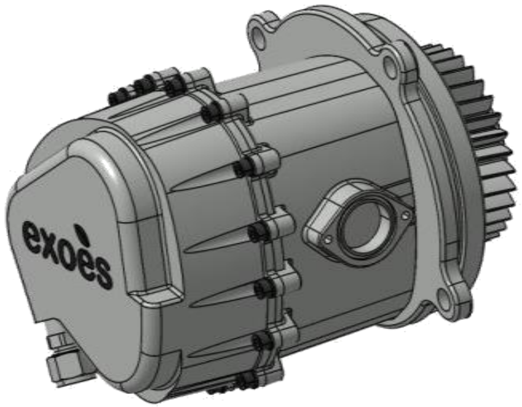
- Expanders development for Ethanol working fluid

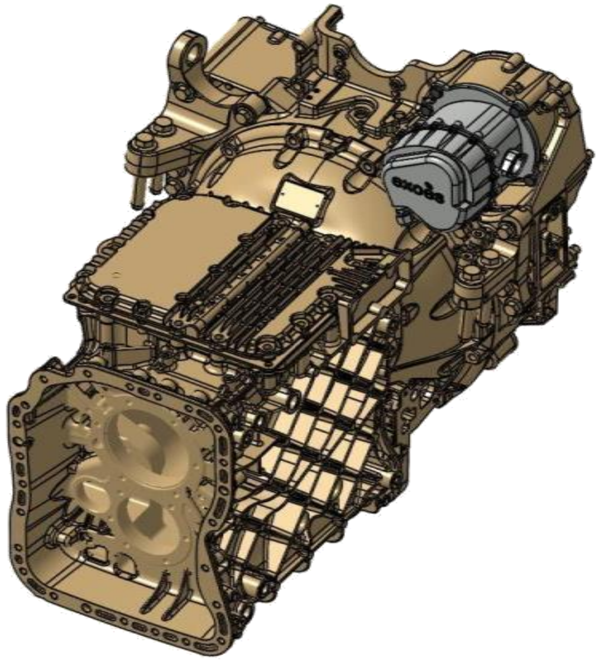


Piston expander technology

- EVE-T2: Single acting swashplate technology – 3 pistons
- Inlet poppet valves, and exhaust ports and valves

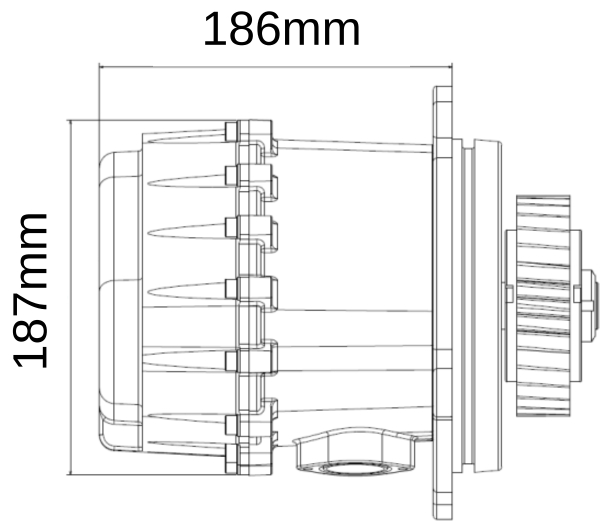






Expander Datasheet

	EVE-T2
Speed range	1,000 - 4,530 RPM
Shaft power range	<12 kW
Eff. Is. efficiency range	Typ. 55 - 65%
Size	< D200xL200mm
Weight without coupling	15kg
Oil circulation rate	Typ. 10%
Outlet pressures	1 - 4barA
Inlet pressures	<40 barA
Nominal pressure ratio	15 – 20 for ethanol
Nominal gear ratio	1.5 – 2.5 for trucks
Transmission	Freewheel
Bypass valve	Integrated

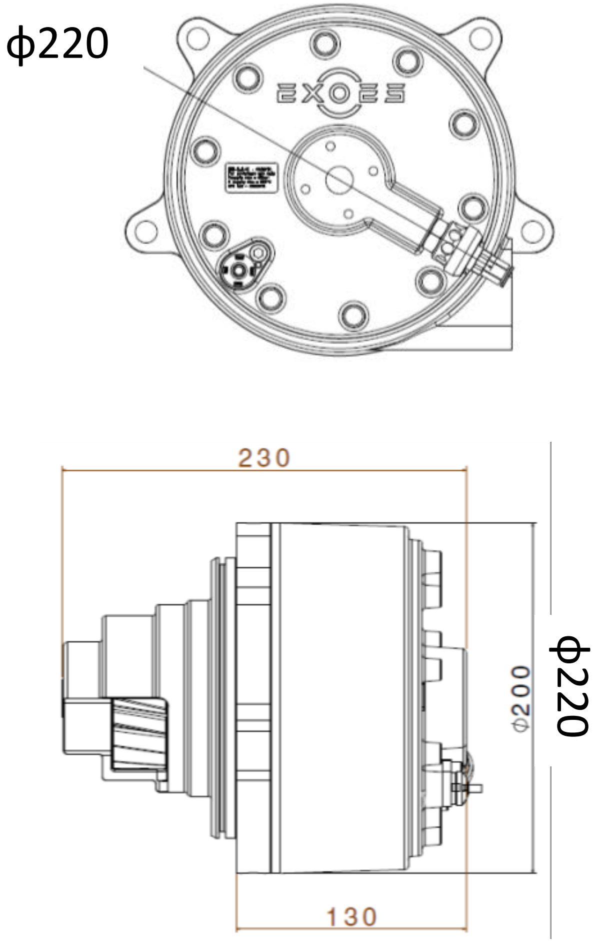


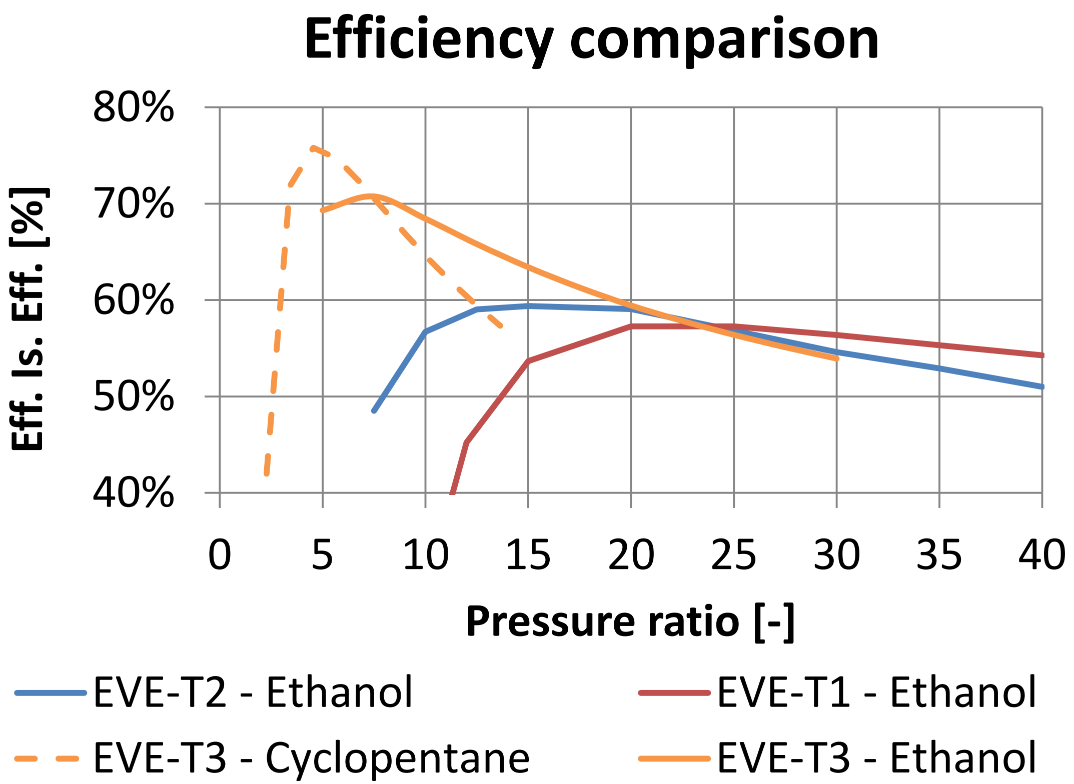
Future scroll expander

- Compliant Scroll – Volume ratio 4.3 – Capacity 135cm^3

	EVE-T2 - piston	EVE-T3 - scroll
Speed range (RPM)	1,000 - 4,530	1,000 – 6,000
Shaft power range	<12 kW	<15 kW
Eff. Is. efficiency range	Typ. 55 - 65%	Typ. 55 - 75%
Size	< D200xL200mm	< D220xL130mm
Weight w/o coupling	15kg	18kg
Oil circulation rate	Typ. 10%	Typ. 5%

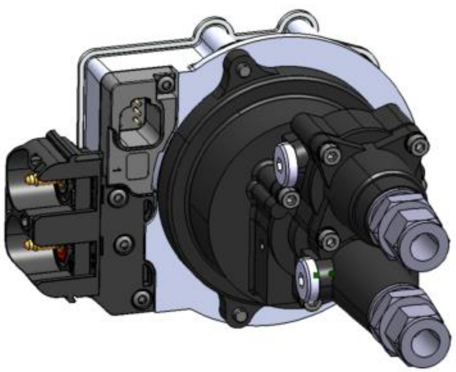
Efficiency forecast

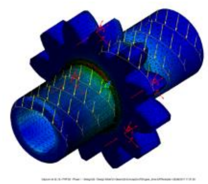


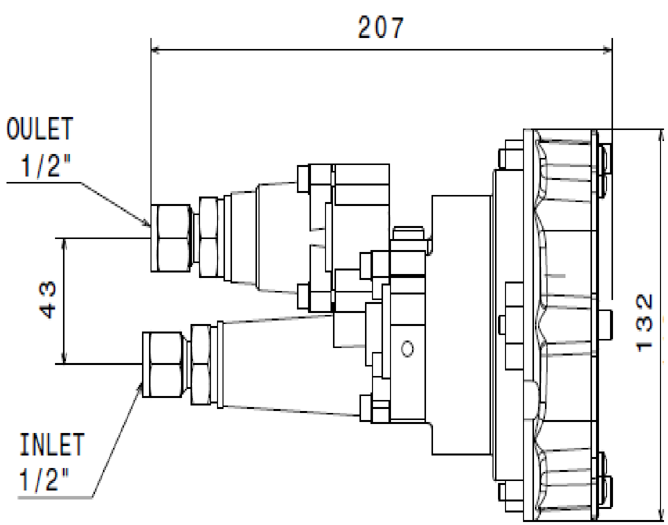


@ 2000rpm, 1bar outlet, 30°C superheat (EVE T1 and T2)
@ 3600rpm, 1bar outlet, 20°C superheat (Scroll - Ethanol)
@ 3600rpm, 2.2bar outlet, 20°C superheat (Scroll - Cyclopen)

Pump datasheet







	HPP – T1
Flow	45 – 600 L/h
Elec. power range	<1.2 kW
Eff. Is. efficiency range	<65%
Size	<D130xL210mm
Weight	<4kg
NPSHr	~300mbar
Inlet pressures	1 - 4barA
Outlet pressures	1 - 40 barA
Additional functions	100 µm inlet filter 10 µm outlet filter Relief valve 43 barG
Sensors	In & Out pressures Temperature
Motor	24 Vdc – CAN bus

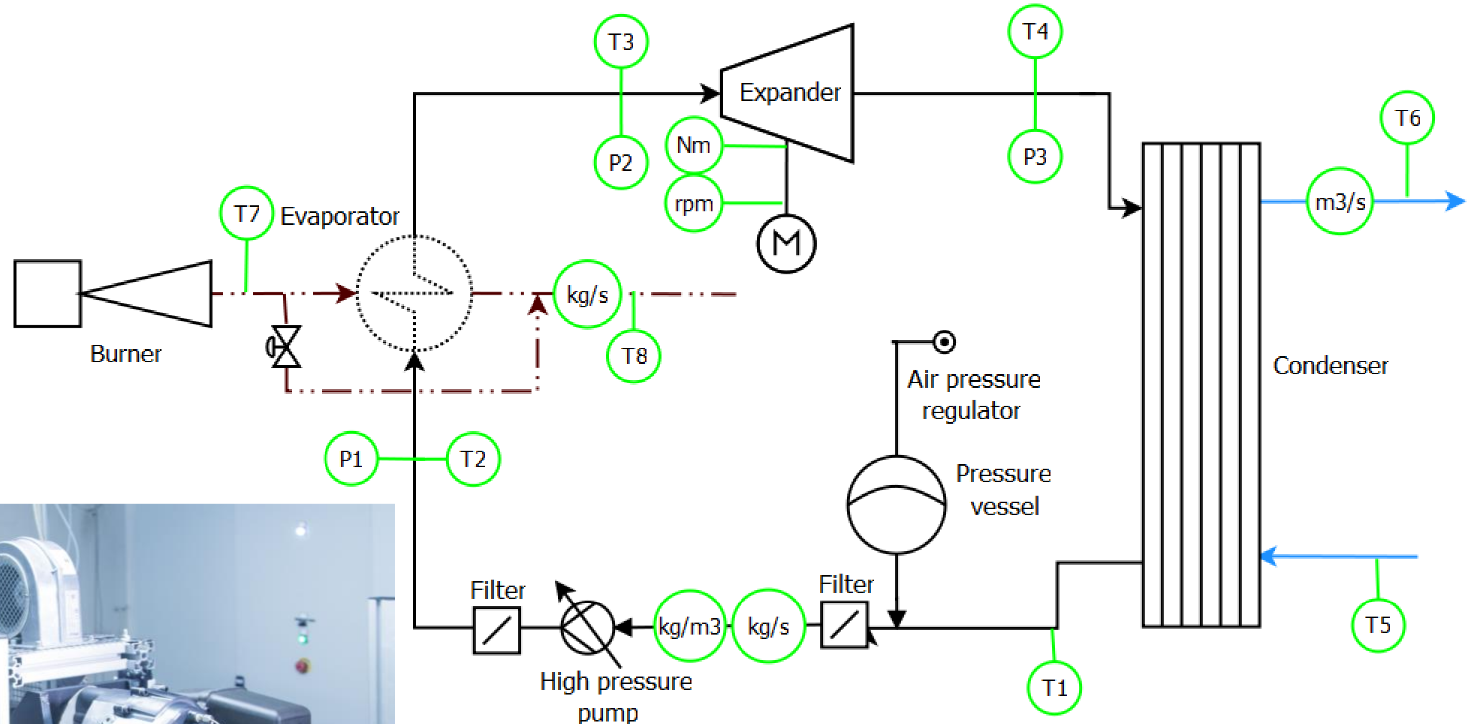
Working fluid impact

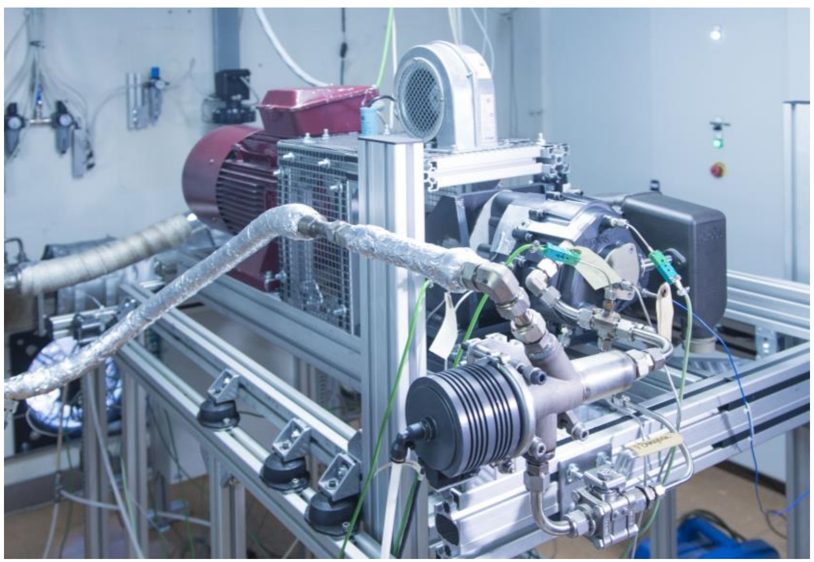
- OCR impacts:
  - Pump consumption
  - Heat transfer coefficient
  - Expander performance/wear

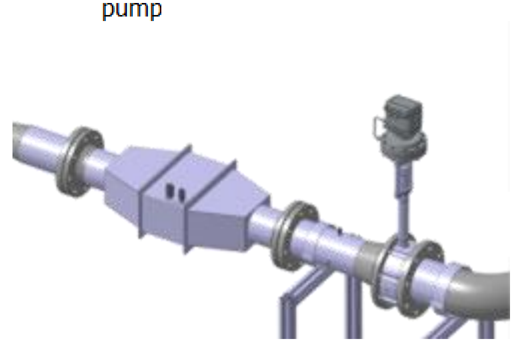
- Water content in ethanol impacts:
  - Pump consumption
  - Materials corrosion. Possibility to introduce aluminum parts…
  - … TCO. Aluminum exchanger instead of SS will largely reduce the cost of the system.

→ Our target: quantify the impacts

Test rig description







Source: Courtesy of MODINE

Test plan

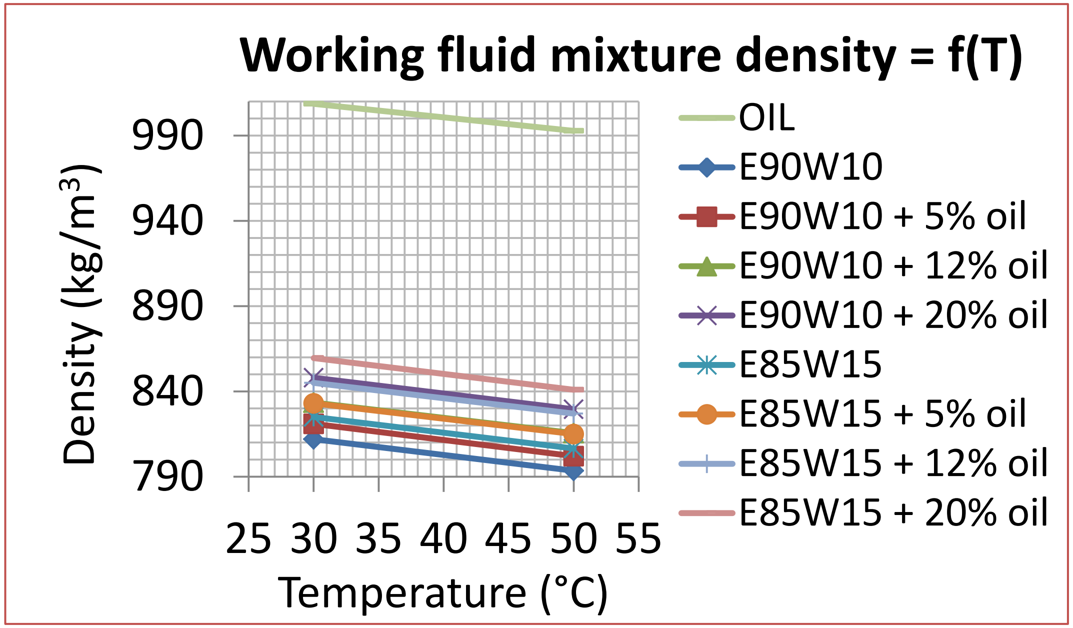
- Test plan: 108 measurement points

Fixed parameters	Value
Expander inlet superheat [°C]	30 (±2)
Expander outlet pressure [barA]	1.5 (±0.02)
Evaporator inlet temperature (working fluid side) [°C]	60 (±3)

Moving parameters	Value
Expander speed [RPM]	1,600 ; 2,400 ; 3,200 (±5)
Oil mass fraction [%]	7 ; 12 ; 17 (±2)
Water mass fraction in Ethanol [%]	4.5 ; 10 ; 15 (±2)
Evaporator inlet conditions (hot gas side)	
Point 1	142g/s ; 297°C
Point 2	182g/s ; 330°C
Point 3	226g/s ; 354°C
Point 4	293g/s ; 374°C

OCR real time measurement

- Measurements in lab preliminarily to test bench.
- PAG oil miscible with ethanol and water.
- Linear behavior with T prevalidated, impact of pressure neglected (Coriolis on LP side).



$$\frac{1}{\rho_{wf}} = \frac{x_{oil}}{\rho_{oil}} + \frac{(1 - x_{oil})}{\rho_{eth}}$$

- ρ_{wf} with Coriolis flowmeter
- ρ_{oil} and ρ_{eth} with lab tests

$\rightarrow x_{oil}$ during tests

OCR real time measurement

- Working fluid sampling during the tests

Fluid	xoil Real Time	xoil sampling	Error xoil
E95.5W4.5	19.1%	20%	0.9%
E95.5W4.5	8.5%	8.3%	-0.2%
E90W10	9.1%	7.4%	-1.7%
E90W10	11.7%	10.4%	-1.3%
E85W15	19%	16.6%	-2.4%
E85W15	16.9%	14.9%	-2.0%
E85W15	13.3%	11.7%	-1.6%
E85W15	8.2%	5.9%	-2.3%

Performance criteria

- $$Cycle\ efficiency = \frac{\dot{W}_{shaft} - \dot{W}_{pp}}{\dot{Q}_{hf\_su\_ev}} = \frac{Shaft\ power - Pump\ power}{Evaporator\ available\ power}$$
- $$Evaporator\ efficiency = \frac{\dot{Q}_{hf\_ev}}{\dot{Q}_{hf\_su\_ev}} = \frac{Hot\ gases\ recovered\ power}{Evaporator\ available\ power}$$

Where:

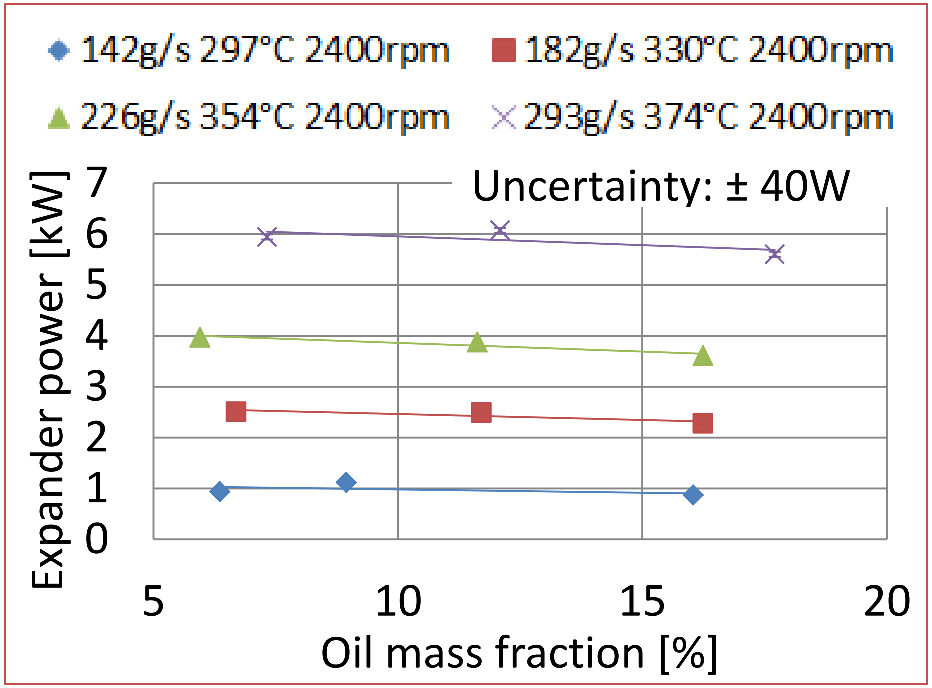
$$\dot{W}_{pp} = \frac{\dot{m}_{wf}}{\rho_{wf\_su\_pp}} \cdot \frac{(P_{wf\_ex\_pp} - P_{wf\_su\_pp})}{\eta_{pp}}$$

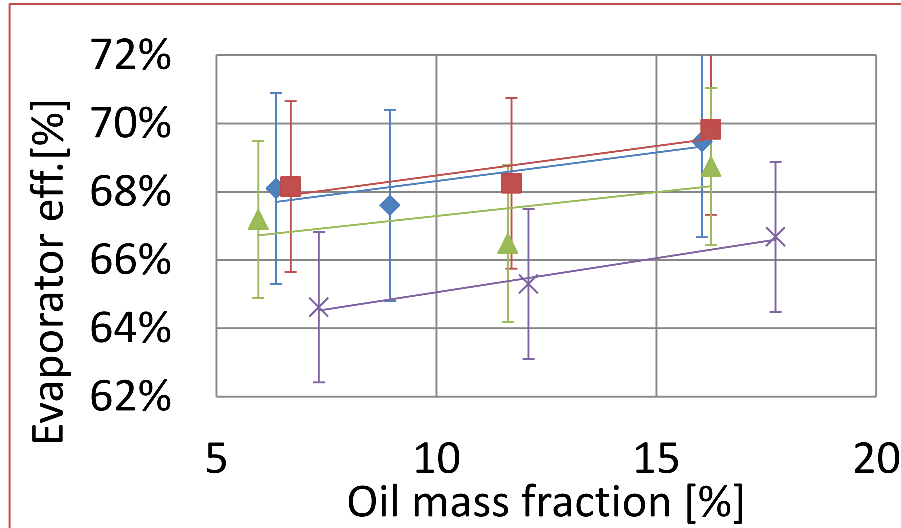
Assumption η_{is} 36%

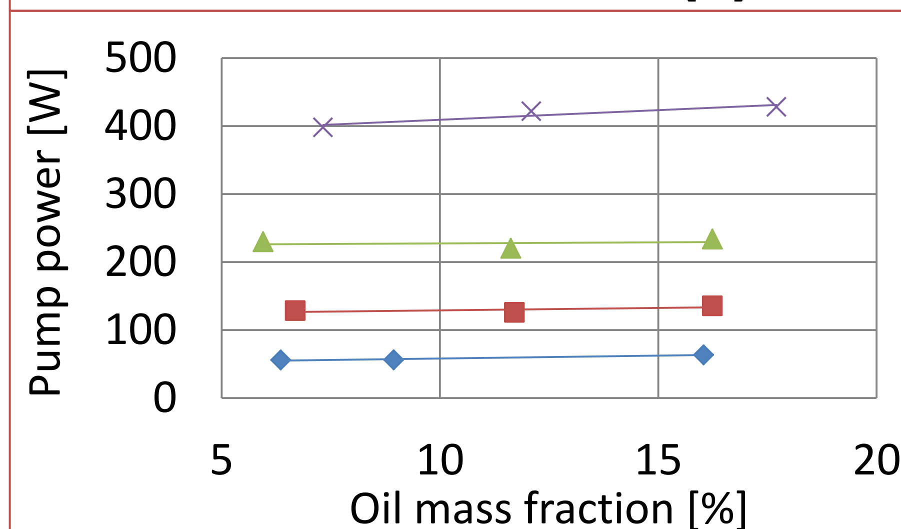
$$\dot{Q}_{hf\_su\_ev} = \dot{m}_{hf\_su\_ev} \cdot \left(Cp_{hf\_su\_ev} \cdot T_{hf\_su\_ev} - Cp_{hf\,(T_{wf\_su\_ev})} \cdot T_{wf\_su\_ev}\right)$$

$$\dot{Q}_{hf\_ev} = \dot{m}_{hf\_su\_ev} \cdot (Cp_{hf\_su\_ev} \cdot T_{hf\_su\_ev} - Cp_{hf\_ex\_ev} \cdot T_{hf\_ex\_ev})$$

OCR impact for E95.5W4.5

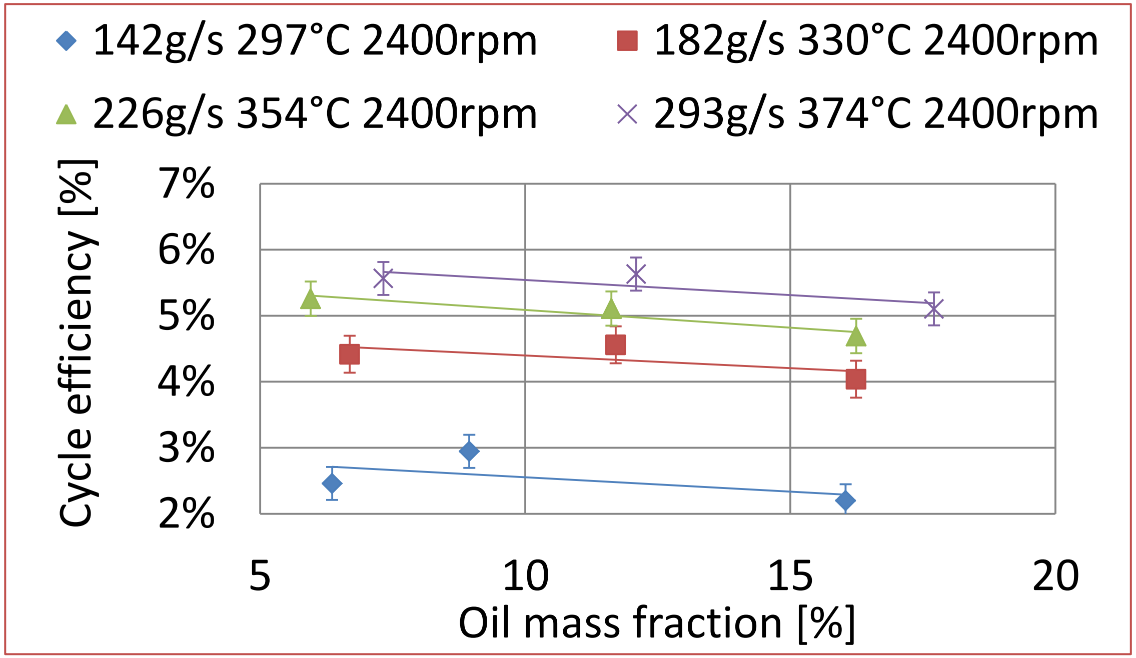






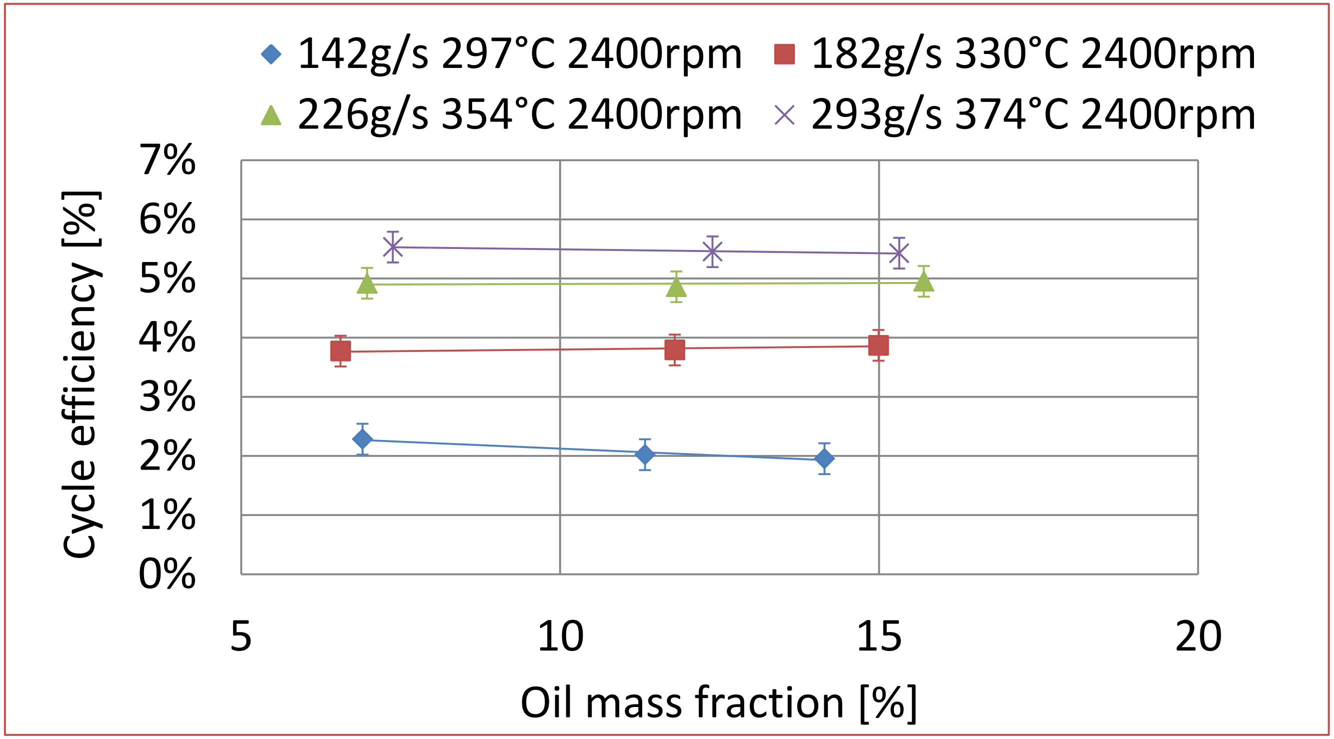
- Negative effect of OCR on:
  - Shaft power
  - Pump power
- No impact on evaporator

OCR impact for E95.5W4.5



- Cycle efficiency and fuel savings decreases with OCR.
- Shaft power loss and pump power increases are predominant.
- Same trend for E90W10.

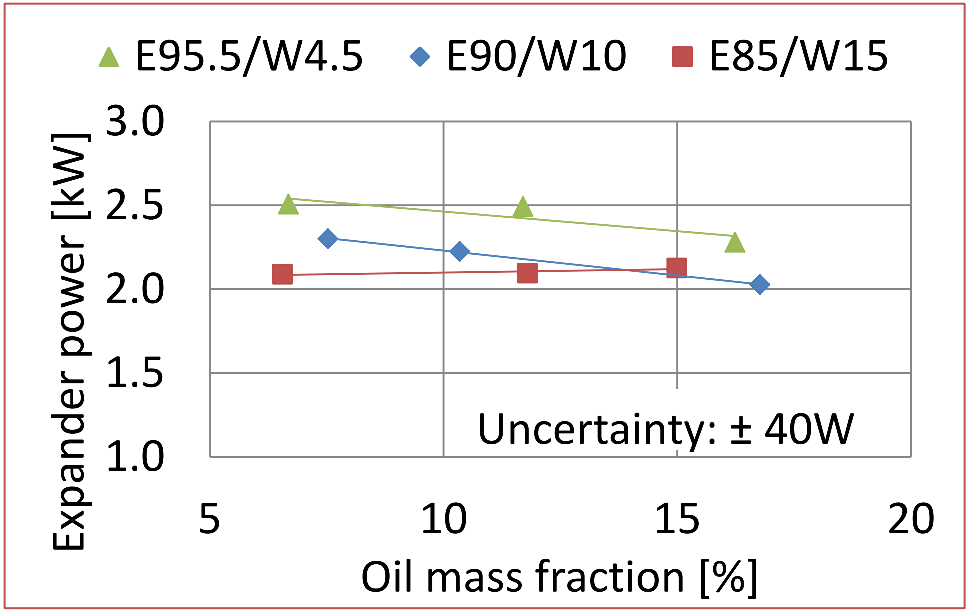
OCR impact for E85W15

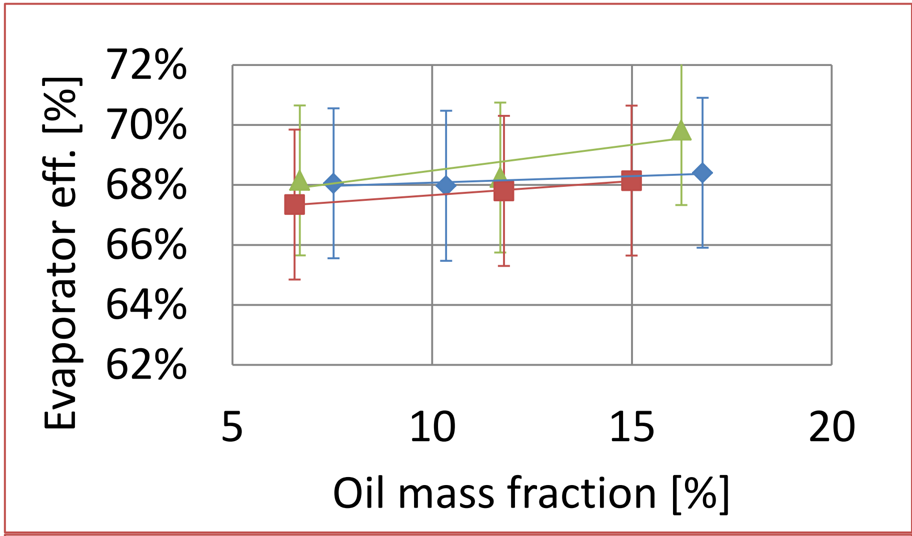


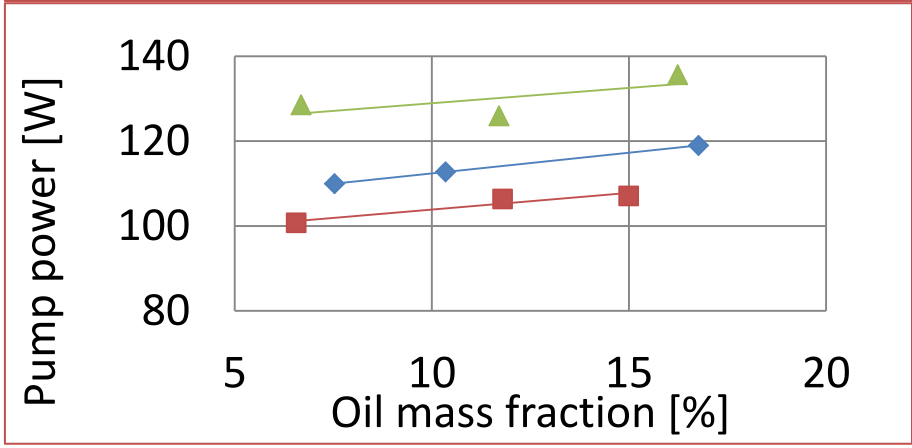
- Contrarily to E95.5W4.5 and E90W10, the cycle efficiency remains quite independant from OCR for E85W15.

Water content impact

- Performance at 2,400rpm 182g/s 330°C

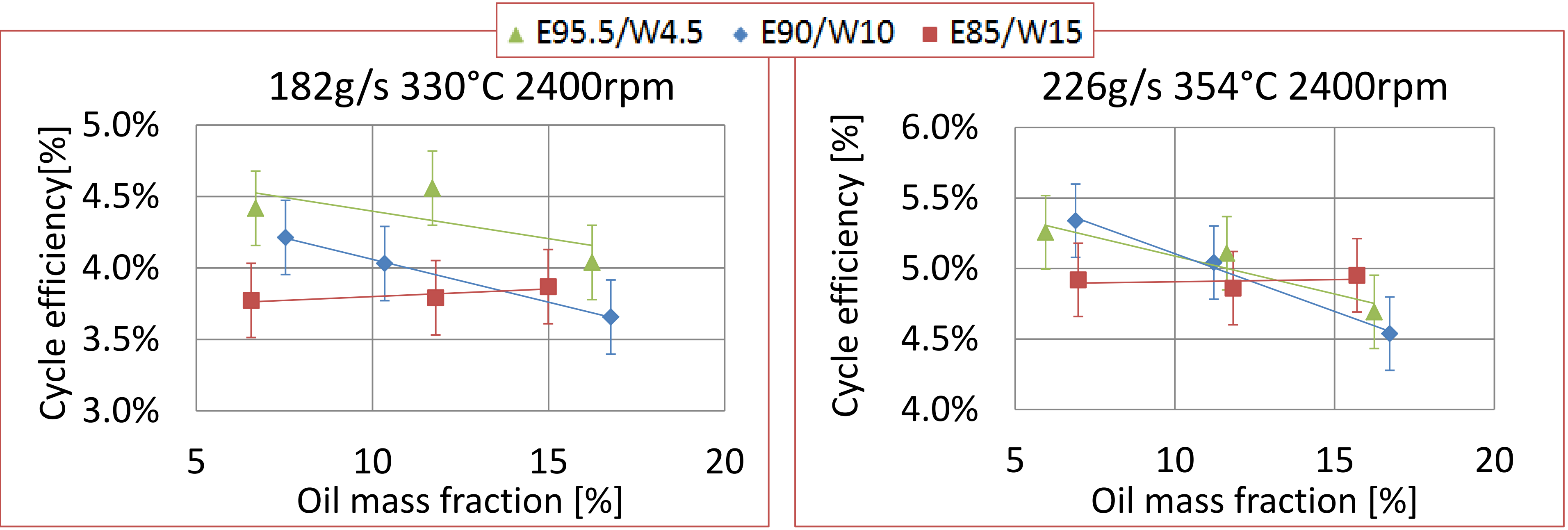






- The lower the water content:
  - the higher the shaft power
  - but the higher the pump power
- No impact on evaporator

Water content impact



- Cycle efficiency decreases with OCR for E95.5 and E90.
- For E85, efficiency is ≈independent from OCR and lower than for E95.5 and E90 except for high OCR.
- E95.5 and E90 show similar efficiencies and same trends.

Conclusion

- OCR impact (fixed water content):
  - The lower the OCR, the higher the fuel savings.
  - Except for E85W15 (no dependency).
- Water content impact:
  - For realistic OCR (≈ 10%), ethanol with low water content provides higher fuel savings…
  - … but high water content could allow the introduction of aluminum parts on the low pressure side (eg the condenser).
  - The balance between efficiency and cost must thus be checked to select the best water content.

Conclusion

Thank you for your attention

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