RAY W. HERRICK LABORATORIES

Employing a Single-Screw Expander in an Organic Rankine Cycle with Liquid Flooded Expansion and Internal Regeneration

D. Ziviani[a,b], *S. Gusev[a], S. Schuessler[c], A. Achaichia[c], J.E. Braun[b], E.A. Groll[b]*

M. De Paepe[b], M. van den Broek[b]

[a] Department of Flow, Heat and Combustion Mechanics, Ghent University, Belgium

[b] Purdue University, School of Mechanical Engineering, Ray W. Herrick Laboratories, West Lafayette, IN, USA

[c] Honeywell Deutschland GmbH, Offenback, Germany

4th International Seminar on ORC POWER SYSTEMS

ORC 2017
13 - 15 September
MILANO, Italy

Outline

- Introduction
- Isothermal Expansion
- ORCLFE System Description
- Cycle Modeling
- Results
- Conclusions

Introduction (1/2)

RAY W. HERRICK LABORATORIES

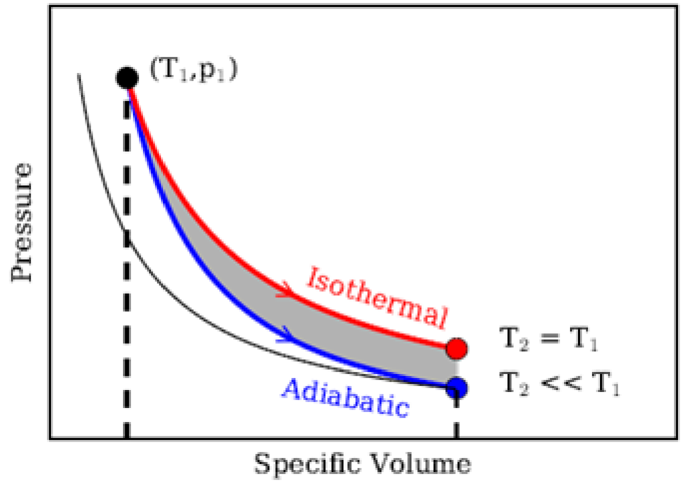
- ORC systems for waste heat recovery are widely investigated
- Research is heavily focused on optimization of such systems:
  - Working fluid
  - Components (e.g., HEX, expanders)
  - Cycle thermodynamics (e.g., PEORC)
- As volumetric expanders are often employed in the medium to low power range, the expansion process is far from being adiabatic:
  - ➢ Possibility to pursue an isothermal expansion
- Concept of ORC with flooded expansion and internal regeneration
  - ➢ What type of expander ?
  - ➢ Include the actual performance of an expander in the cycle evaluation

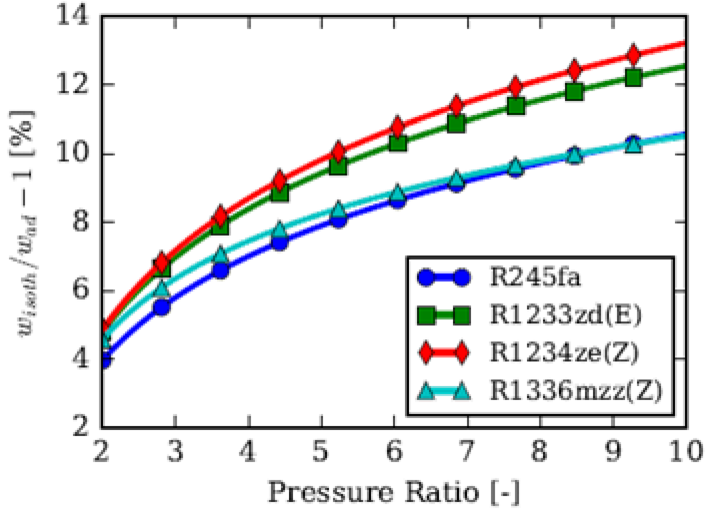
Introduction: Literature Overview (2/2)

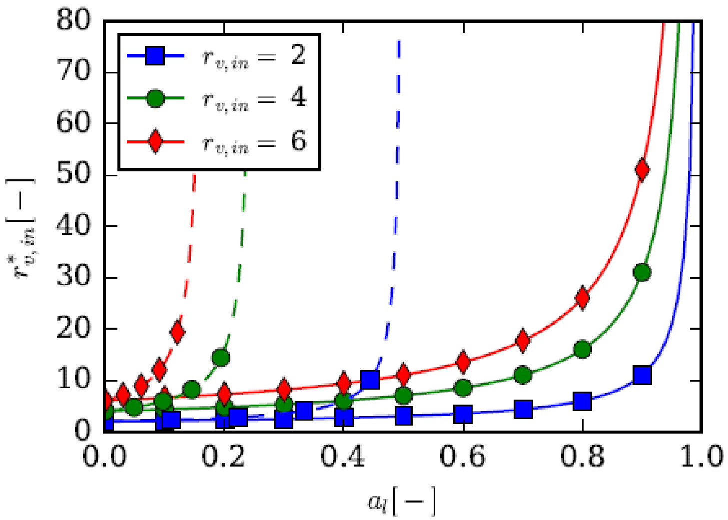
- Concept of flooded expansion has been firstly investigated by Hugenroth et al. (2007) in an Ericsson cycle cooler
- Woodland et al. (2013) analyzed the benefits of flooded expansion and internal regeneration in an ORC along with practical challenges
- Open-drive scroll expanders were used due to availability, efficiency and displacement required for the baseline cycles
- E. Georges (2012) characterized the performance of a scroll expander. It was concluded that higher volume ratios would be desired to benefit from flooding

J.J. Hugenroth, J.E. Braun, E.A. Groll, G.B. King, "Thermodynamic analysis of a liquid-flooded Ericsson cycle cooler", I.J.R.,30 (2007), 1176-1186.
B.J. Woodland, A. Krishna, E.A. Groll, J.E. Braun, W.T. Horton, "Thermodynamic comparison of organic Rankine cycles employing liquid-flooded expansion or solution circuit", A.T.E., 61 (2013), 859-865.
E. Georges, "Investigation of a Flooded Expansion Organic Rankine Cycle System", Master's Thesis, University Of Liege (2012).

Isothermal Expansion





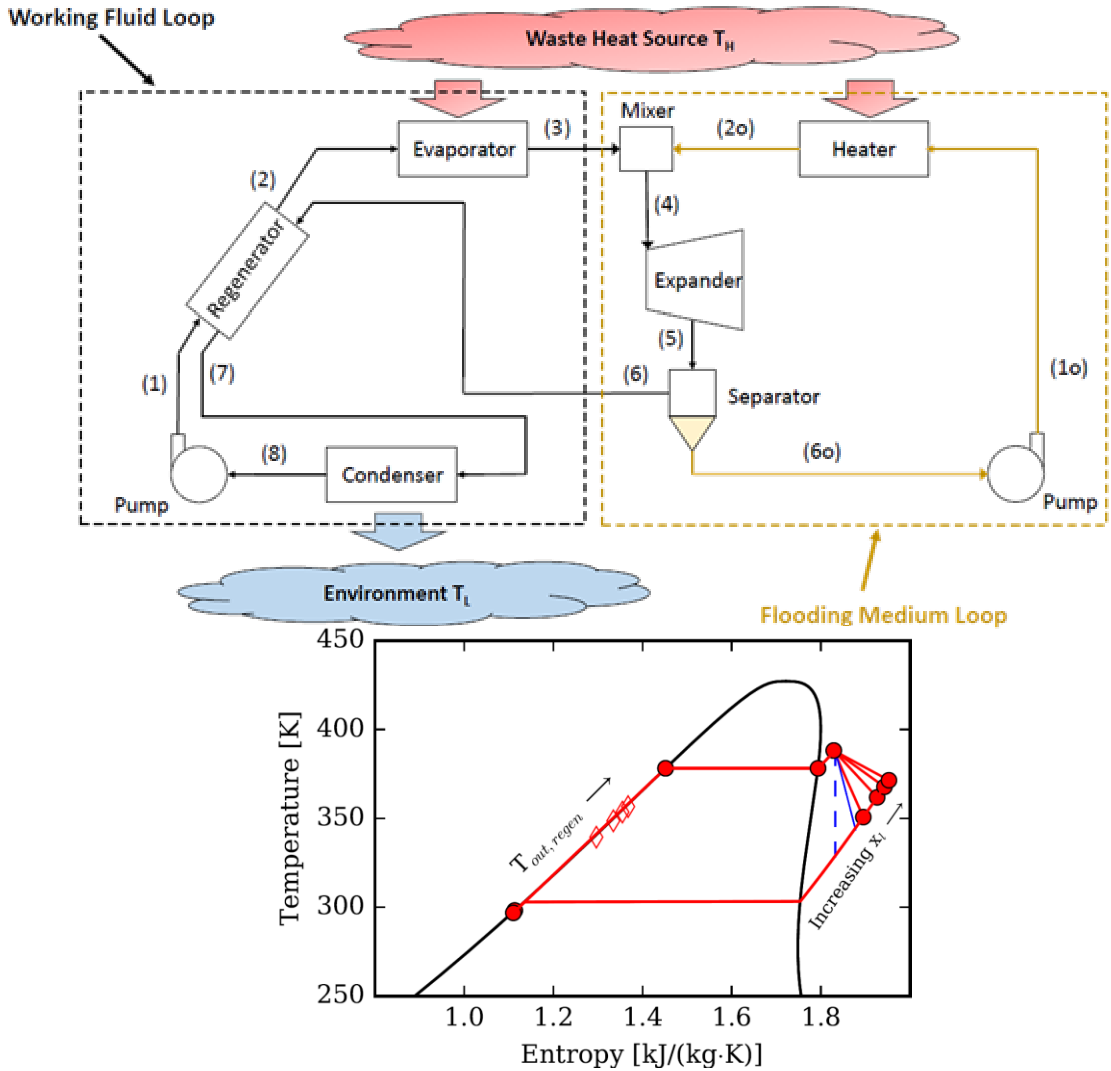


$$r_{v,built-in} = \frac{V_{ex,exp}}{V_{su,exp}}$$

$$r^*_{v,built-in} = \frac{r_{v,built-in} - a_l}{1 - a_l}$$

$$a_l = \frac{V_{l,in}}{V_{su,exp}}$$

ORCLFE System description



Cycle Modeling: Assumptions (1/2)

RAY W. HERRICK LABORATORIES

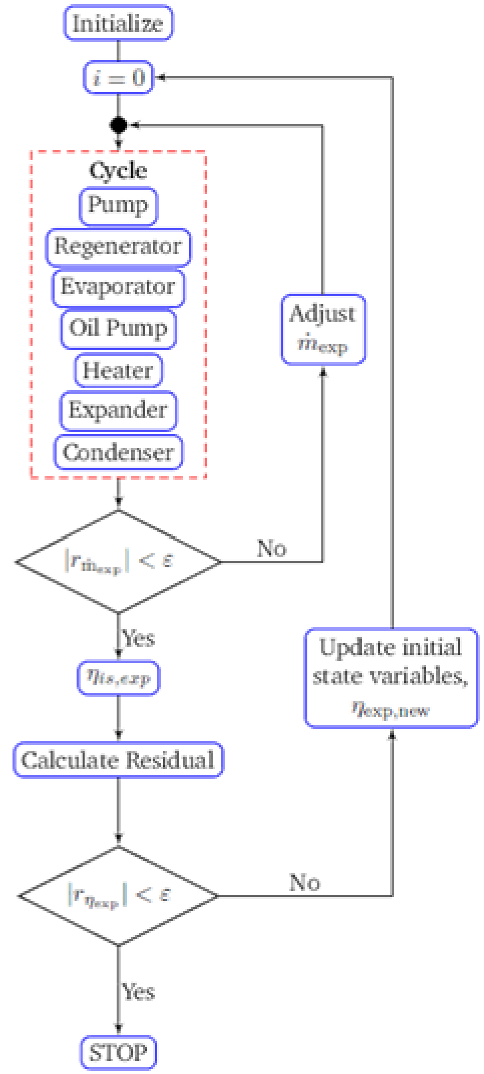
- Real gas model for the working fluid
- The flooding medium is considered incompressible and volatile
- The ideal mixture model is used
- Pressure drops in the heat exchangers in line sets are neglected
- The liquid and the gas flows are assumed to be in thermal and mechanical equilibrium
- Perfect mixing
- Perfect separation process in the oil separator except where specified
- Fixed volumetric displacement rate for the expander with a filling factor equal to unity

Cycle Modeling (2/2)

Ray W. Herrick Laboratories

Fluid	MM (kg kmol^{-1})	T_{crit} (°C)	p_{crit} (kPa)	OEL (ppm)	Safety Group	AL (yr.)	ODP (-)	$GWP_{100yr.}$ (-)
R245fa	134.05	153.9	3651.0	300	B1	7.6	0.0	1020
R1234ze(Z)	114.04	153.7	3533.0	800	AL2	0.027-0.049	0.0	>3
R1233zd(E)	130.49	166.5	3623.6	800	A1	0.071	0.0	1
R1336mzz(Z)	164.06	171.3	2900.0	500	A1	0.060	0.0	2

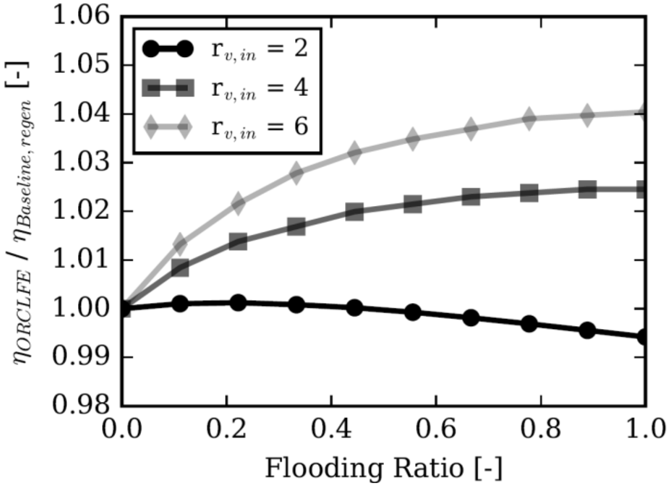
Description	Value
Condenser outlet subcooling	5 °C
Temperature difference between heat sink and condenser outlet	5 °C
Cold sink temperature	20 °C
Evaporator pinch point temperature difference	5 °C
Heat source temperature	100-150 °C
Heat source mass flow rate	1 kg/s
Flooding ratio	0-1
Regenerator effectiveness (if not specified)	0.9
Pump isentropic efficiency	0.5
Pump electric motor efficiency	0.9
Expander isentropic efficiency	Calculated
Expander mechanical effciency (if not specified)	0.8
Expander ambient heat transfer (UA_{amb})	0.01 kW/(m^2 K)
Negligible pressure drop in linesets, separator, mixer and heat exchangers	-
Negligible heat loss in linesets, separator, mixer, pumps	-

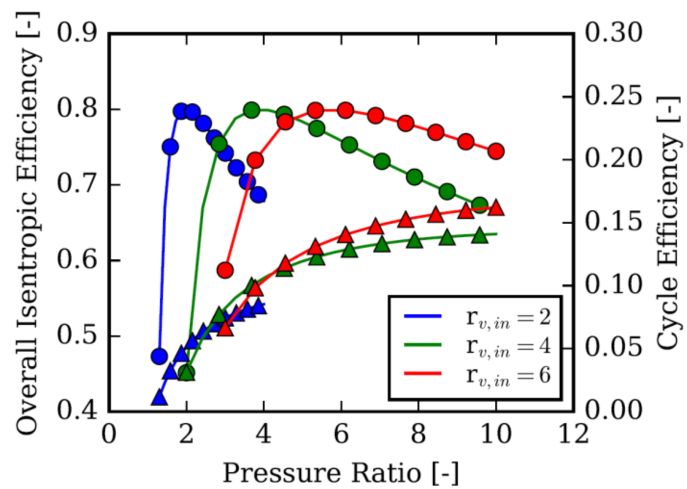


Results: ORC vs ORCLFE

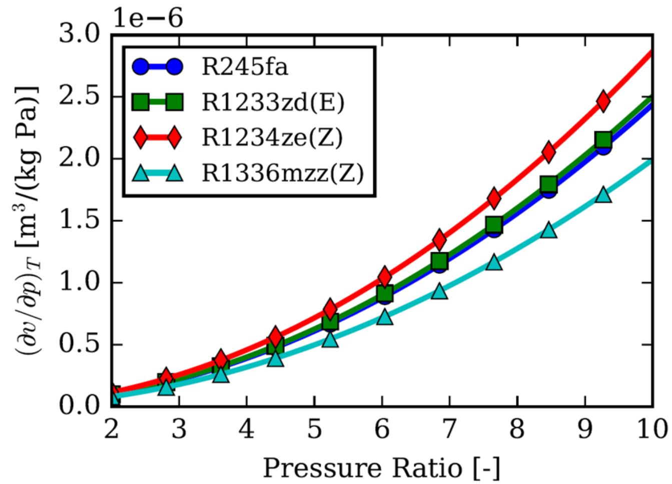
RAY W. HERRICK
LABORATORIES

- Fixed heat source 120 ºC, R245fa

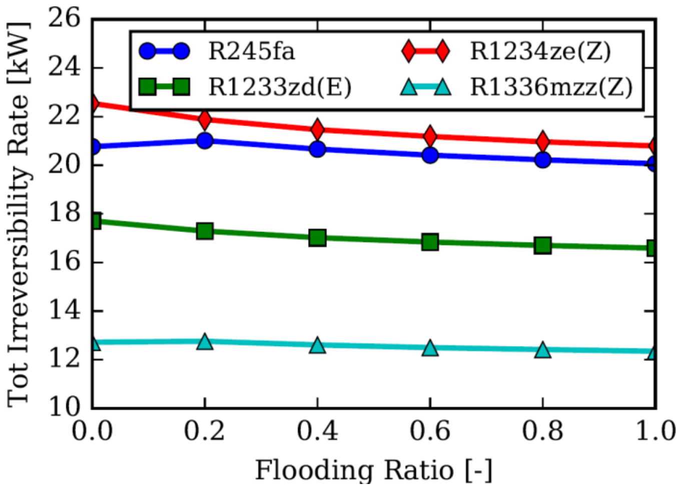


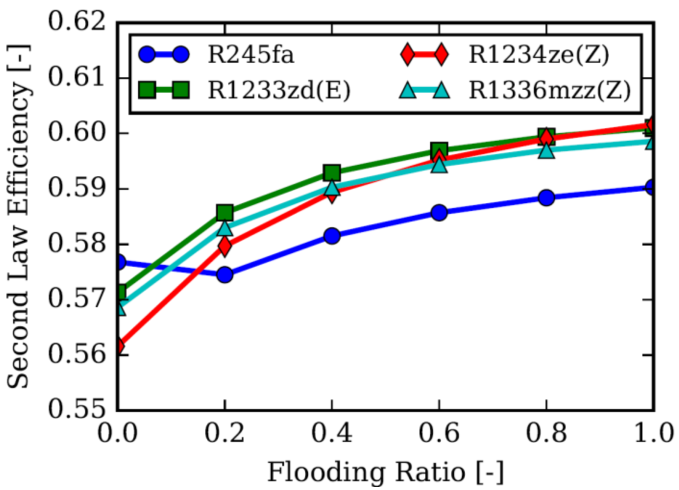


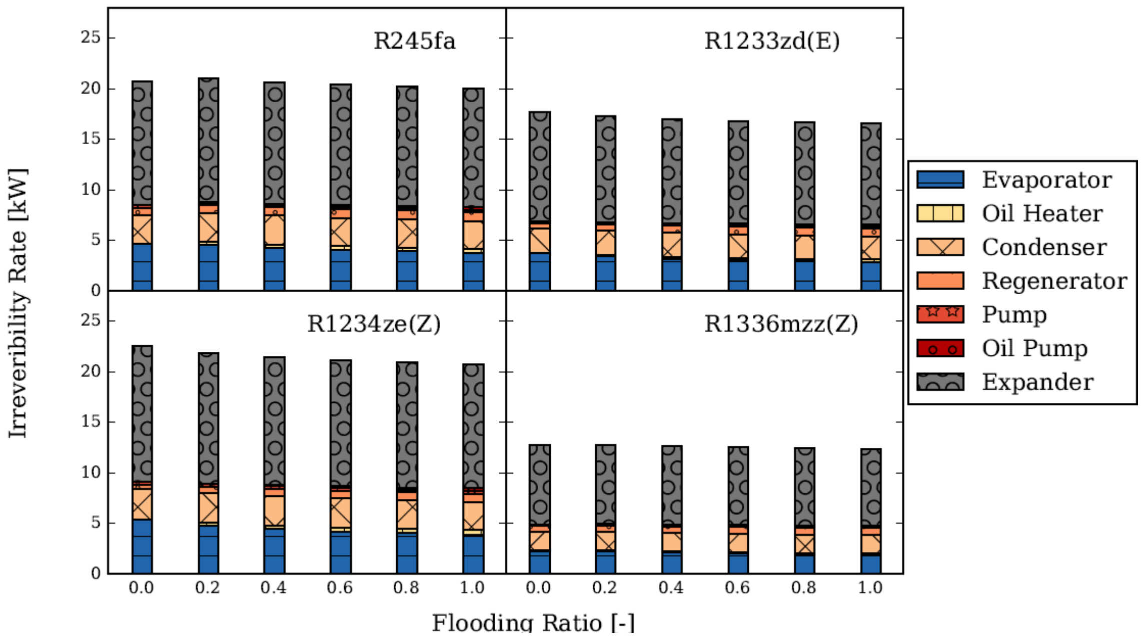
- Efficiency of the expansion process is related to properties of the fluids and increase of specific volume with respect to decrease of pressure



Results: Irreversibility





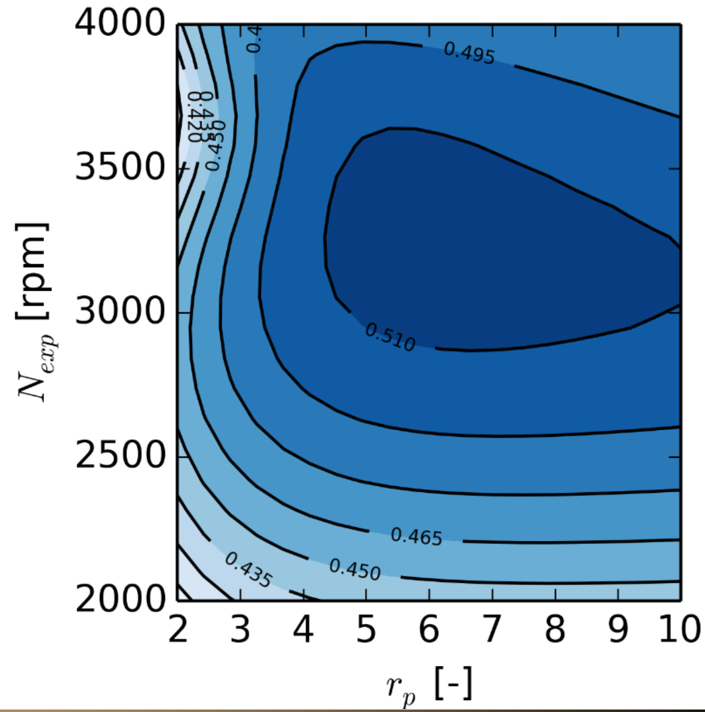


$$\eta_{II,ORCLFE} = \frac{\eta_{I,ORCLFE}}{\eta_{Carnot}}$$

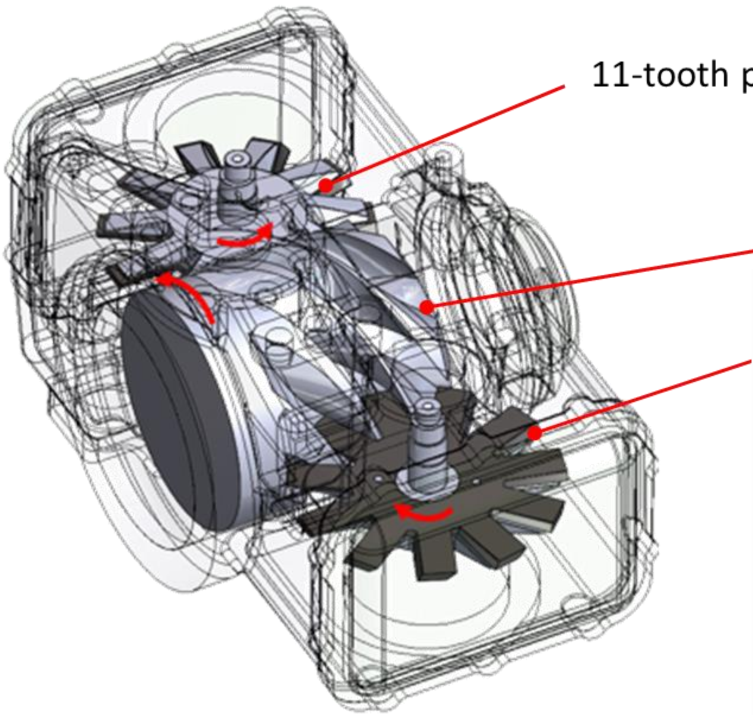
Results: Optimization (1/3)

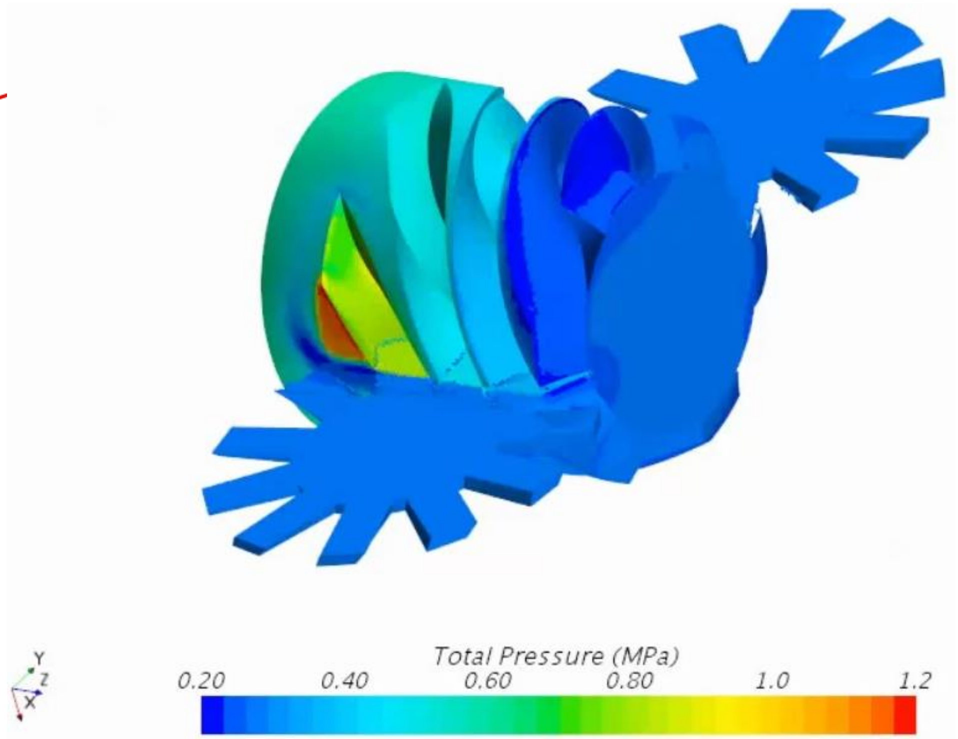
- Screw expanders are usually oil-flooded machines which are favorable to implemented the ORCLFE concept
- Utilize a single-screw expander to evaluate the benefits of flooded expansion. Experimental characterization of such machine has been performed
- The volume flow of the cycle is imposed by the displacement of the machine
- Mechanical losses have been obtained by calibrating a semi-empirical model

Engaging ratio	[-]	11/6
D_{sr}	[mm]	122
D_{sw}	[mm]	132
$V_{g,max}$	[cm^3]	57.39
$r_{v,built-in}$	[-]	5.3
L_{rotor}	[m]	121



Results: Optimization (2/3)

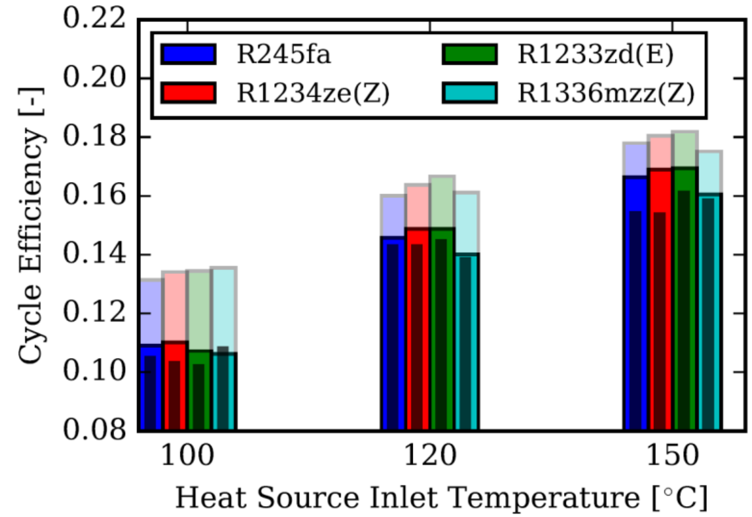


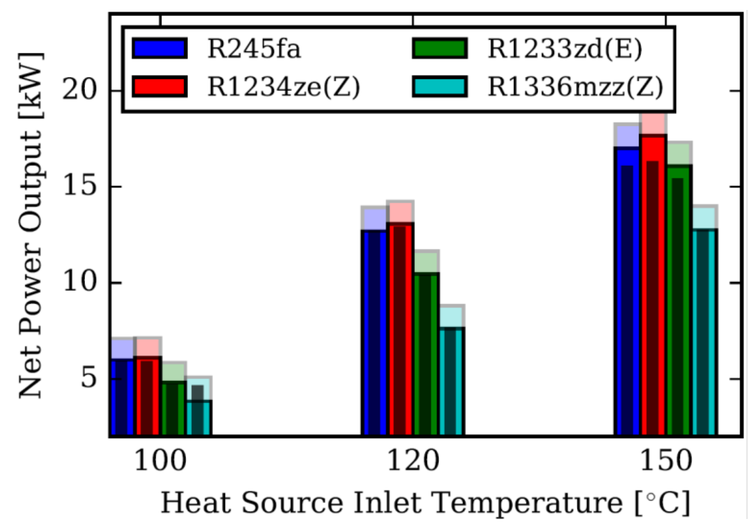


Results: Optimization (3/3)

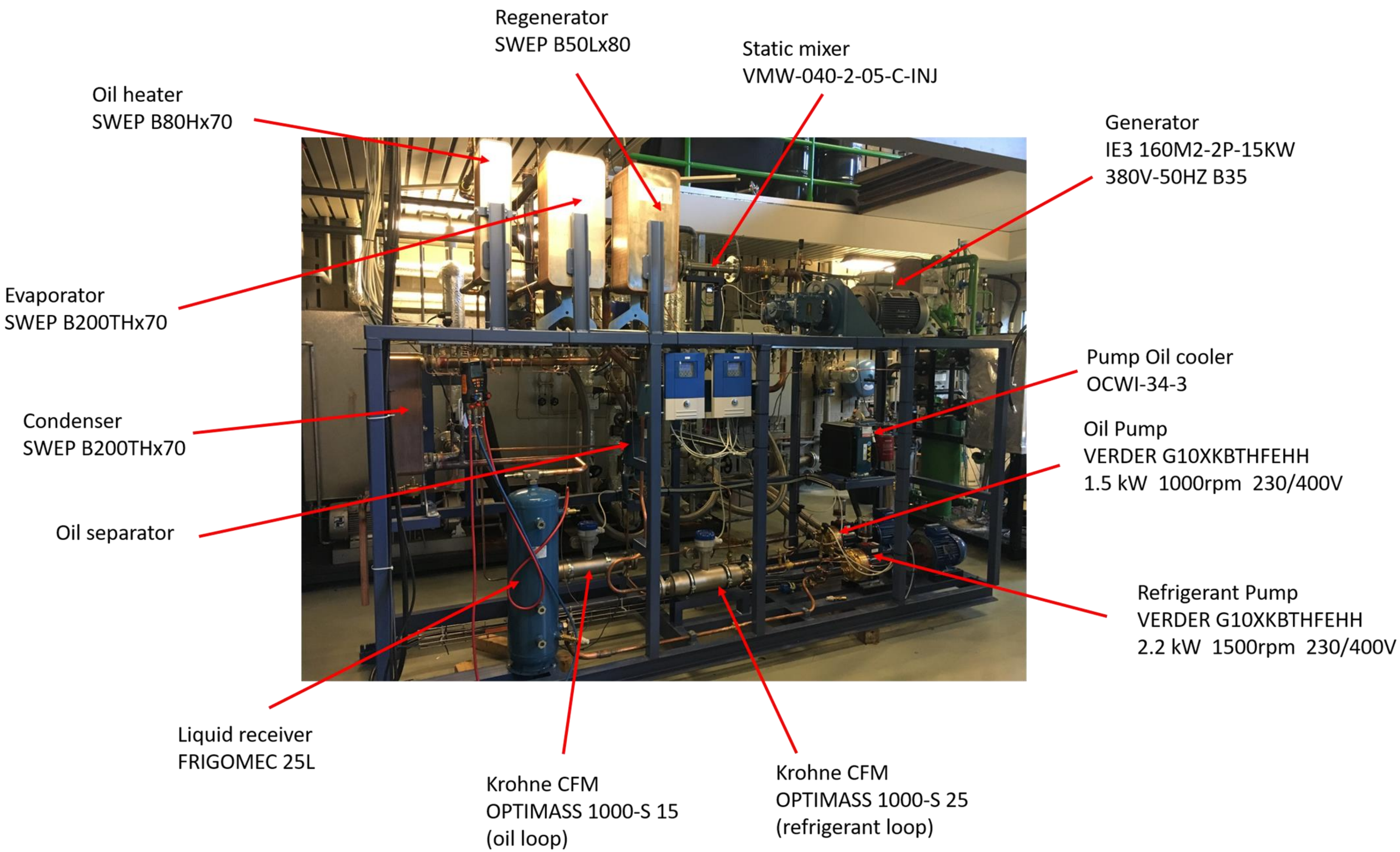
RAY W. HERRICK LABORATORIES

Fluid	T_H (°C)	y_l (-)	p_{cd} (kPa)	r_p (-)	$\dot{W}_{net}$ (kW)	η_{ORCLFE} (-)
R245fa	100	0.3293	177.8	4.873	5.977 (2.05%)	0.1091 (+3.81%)
	120	0.1761	177.8	7.131	12.69 (+0.47%)	0.1458 (+2.03%)
	150	1.00	177.8	9.839	17.01 (+6.25%)	0.1663 (+7.77%)
R1234ze(Z)	100	0.4409	210.2	4.437	6.103 (+4.66%)	0.1101 (+6.58%)
	120	0.2939	210.2	6.392	13.07 (+1.79%)	0.1488 (+4.13%)
	150	1.00	210.2	8.778	17.66 (+8.61%)	0.169 (+9.88%)
R1233zd(E)	100	0.3885	154.6	4.839	4.799 (+3.31%)	0.1072 (+4.89%)
	120	0.244	154.6	7.088	10.46 (+1.26%)	0.1488 (+2.90%)
	150	0.4711	154.6	9.265	16.07 (+4.69%)	0.1694 (+5.02%)
R1336mzz(Z)	100	1.00	89.01	5.494	3.839 (-16.03%)	0.1062 (-1.85%)
	120	0.167	89.01	8.912	7.598 (-0.39%)	0.1405 (+1.01%)
	150	0.130	89.01	12.31	12.76 (-0.‘55%)	0.1605 (+1.26%)





Results: Experimental Test Rig



Conclusions

RAY W. HERRICK LABORATORIES

- Flooded expansion with PD expanders and internal regeneration have been investigated to improve the performance of ORC systems
- High built-in volume ratio expanders such as screw-type are desirable to benefit from the presence of large amounts of oil in the working chamber
- By employing a single-screw expander with $r_{v,built-in} = 5.3$, ORCLFE led to 9.88% cycle efficiency increase in the case of R1234ze(Z) a 150 ºC
- As the flooded medium mitigates the friction losses, the potential improvements on net power output and cycle efficiency are up to 20%
- Accounting for the working fluid and lubricant oil solubility yielded to in increase of oil pump specific work of to three times
- As a results of the study, a dedicated test rig has been designed and built