Zentrum für Energietechnik

LEHRSTUHL FÜR TECHNISCHE THERMODYNAMIK UND TRANSPORTPROZESSE
PROF. DR.-ING. D. BRÜGGEMANN

International Seminar on ORC Power Systems, TU Delft, 2011

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Supercritical Organic Rankine Cycle for waste heat recovery at high temperatures

UNIVERSITÄT BAYREUTH

Waste Heat Utilization (WHU)
Potential

- Enova study (Norway): 7 TWh_{th} industrial waste heat with temperatures above 140 °C (mainly in cement/iron industry)
- Enova study applied on Germany gives a potential of 90 TWh_{th} > 140 °C
- Hamm et al.:
  - Germany: 42 TWh_{th}/a
  - Worldwide: 1530 TWh_{th}/a
- Companies are willing to use waste heat due to
  - increasing energy costs and
  - emission trading.

Waste Heat Utilization (WHU)
Supercritical vs. Subcritical Organic Rankine Cycle

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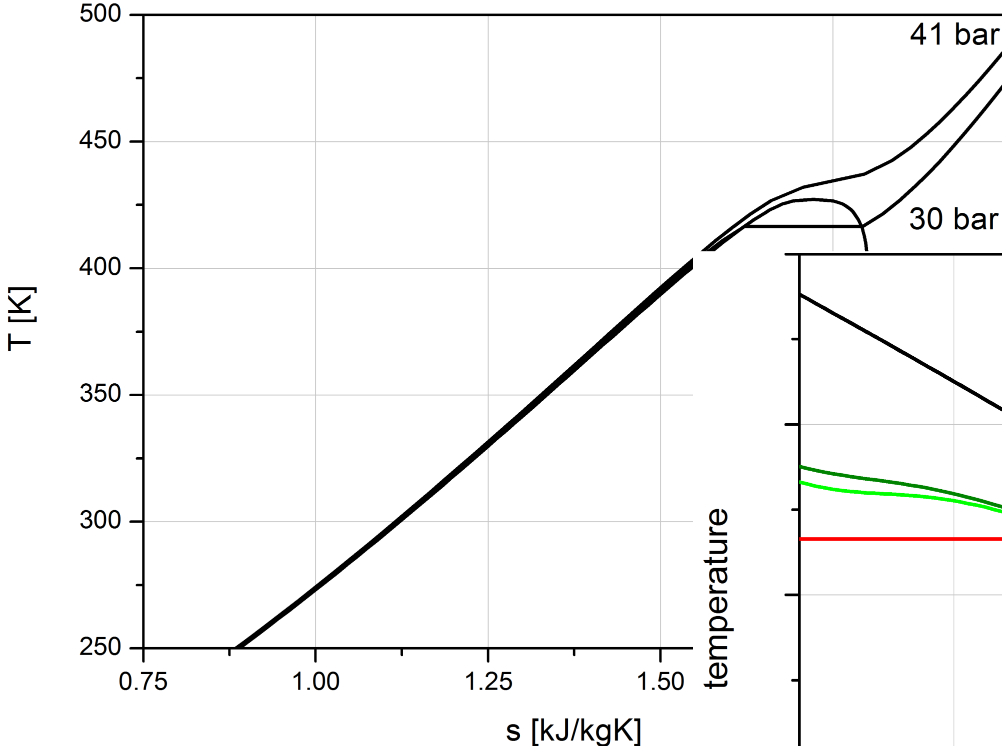
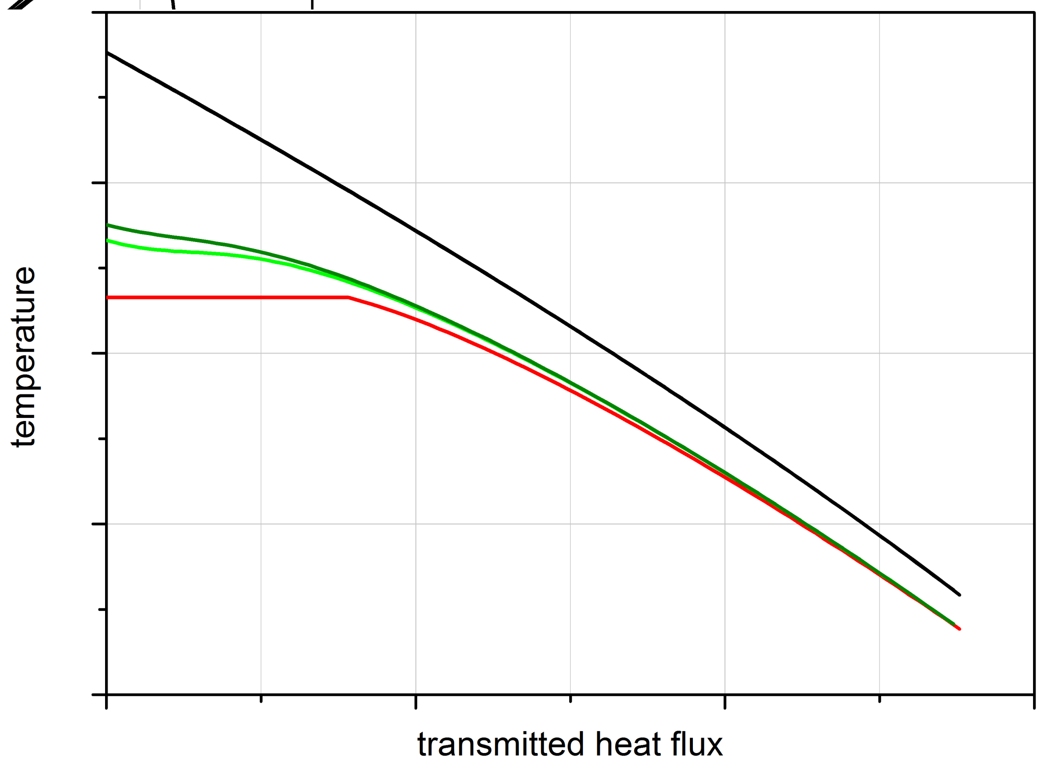


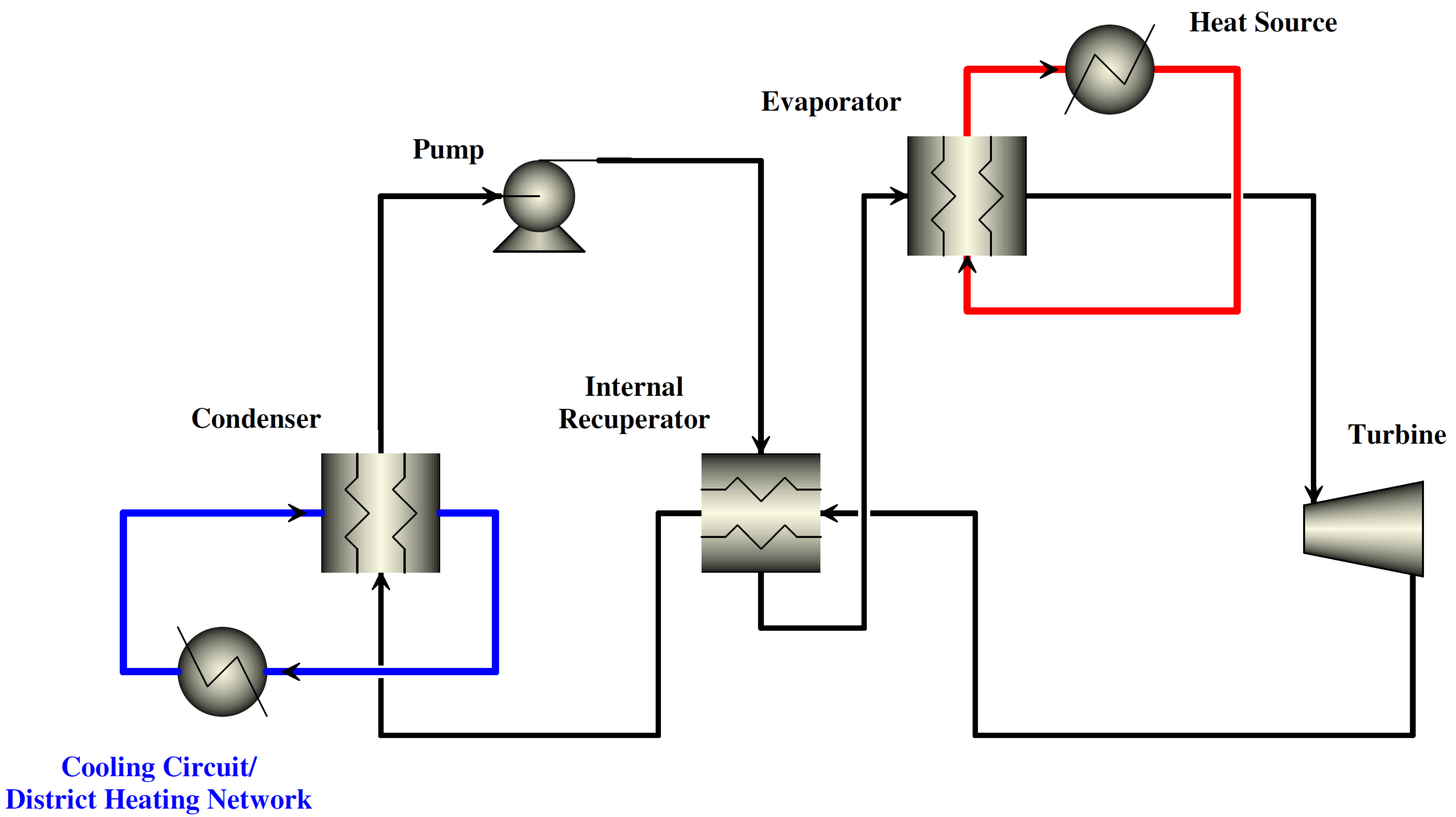
→ Non-isothermal heating



→ Lower exergy destruction

Methods

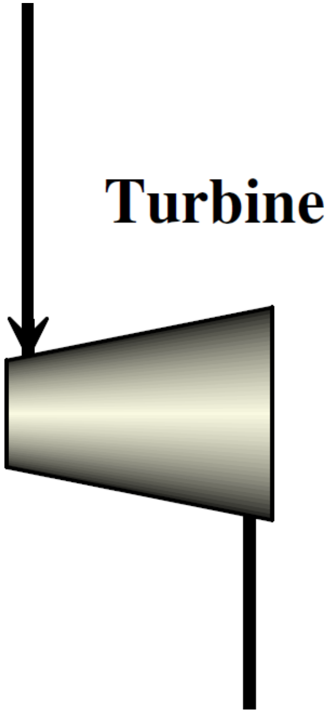
Simulation scheme within Aspen Plus V7.2

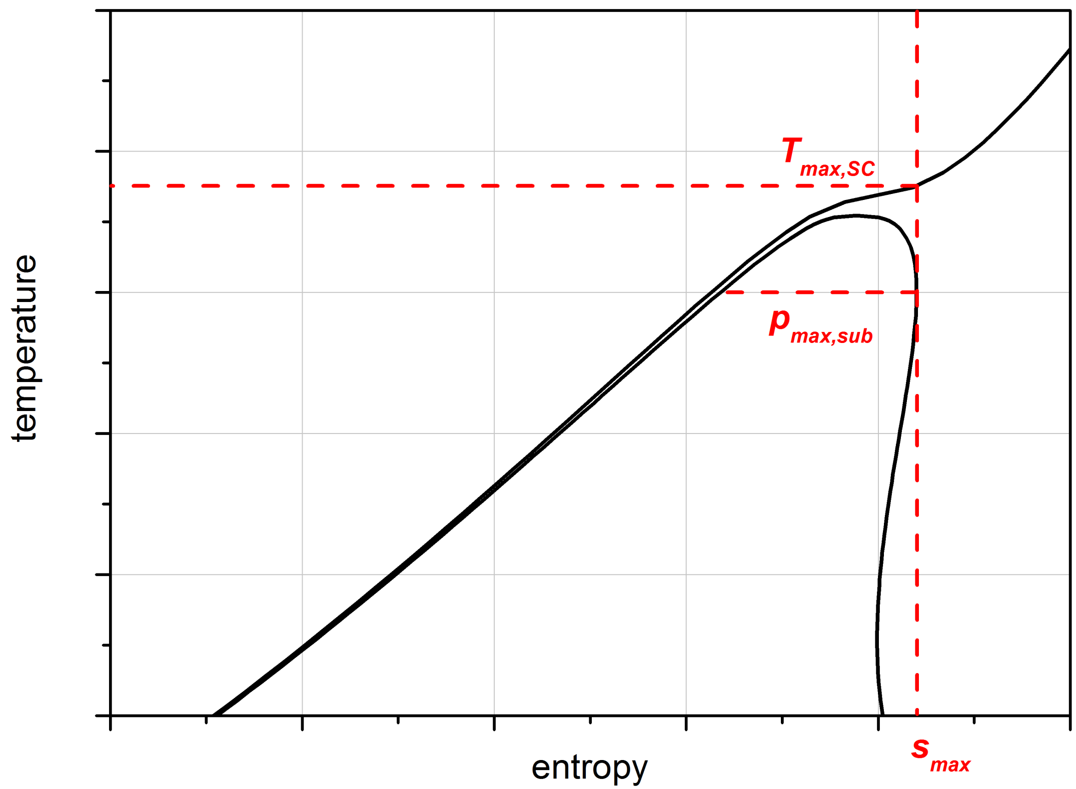


Methods
Boundary conditions

- Temperature range:
  - Heat source: 633.15 K ... 823.15 K
  - Heat sink: 353.15 K
  - ORC: maximum temperature according to s_{max}
- Minimum internal temperature approach
  - Heat source/ORC: 30 K
  - Internal recuperator, condenser: 10 K
- ORC working pressure range
  - Subcritical: 0.2 MPa ... $p(s_{max})$ (within 50 steps)
  - Supercritical: $1.01 \cdot p_{crit}$ ... $1.30 \cdot p_{crit}$ (within 30 steps)
- Efficiencies: 0.7 (pump), 0.8 (turbine/generator-unit)
- Pressure and radiation losses are neglected

Methods
Maximum pressure and temperature





Methods
Working fluids, equation of state and validation

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- Homologous series of 3 alkanes, 3 alkylbenzenes, 3 siloxanes and 2 cyclic siloxanes
- Peng-Robinson equation of state
  - Validation 1: PENG-ROB in comparison with BACKONE (Lai et al., 2011)

	$\dot{V}_{ORC\text{-}B\text{-}T}$ [l/s]	$\dot{V}_{ORC\text{-}A\text{-}R}$ [l/s]	η_{th} [%]	$\dot{Q}_V$ [MW]	$\dot{C}$ [kW/K]
Simulation with Peng-Robinson	51	1810	18.6	5.37	23.3
Simulation with BACKONE	51	1778	18.6	5.37	23.4
Relative deviation [%]	0.0	1.8	0.0	0.0	-0.4

  - Validation 2: PENG-ROB in comparison with further equation of states in Aspen Plus

Methods
Working fluids, equation of state and validation

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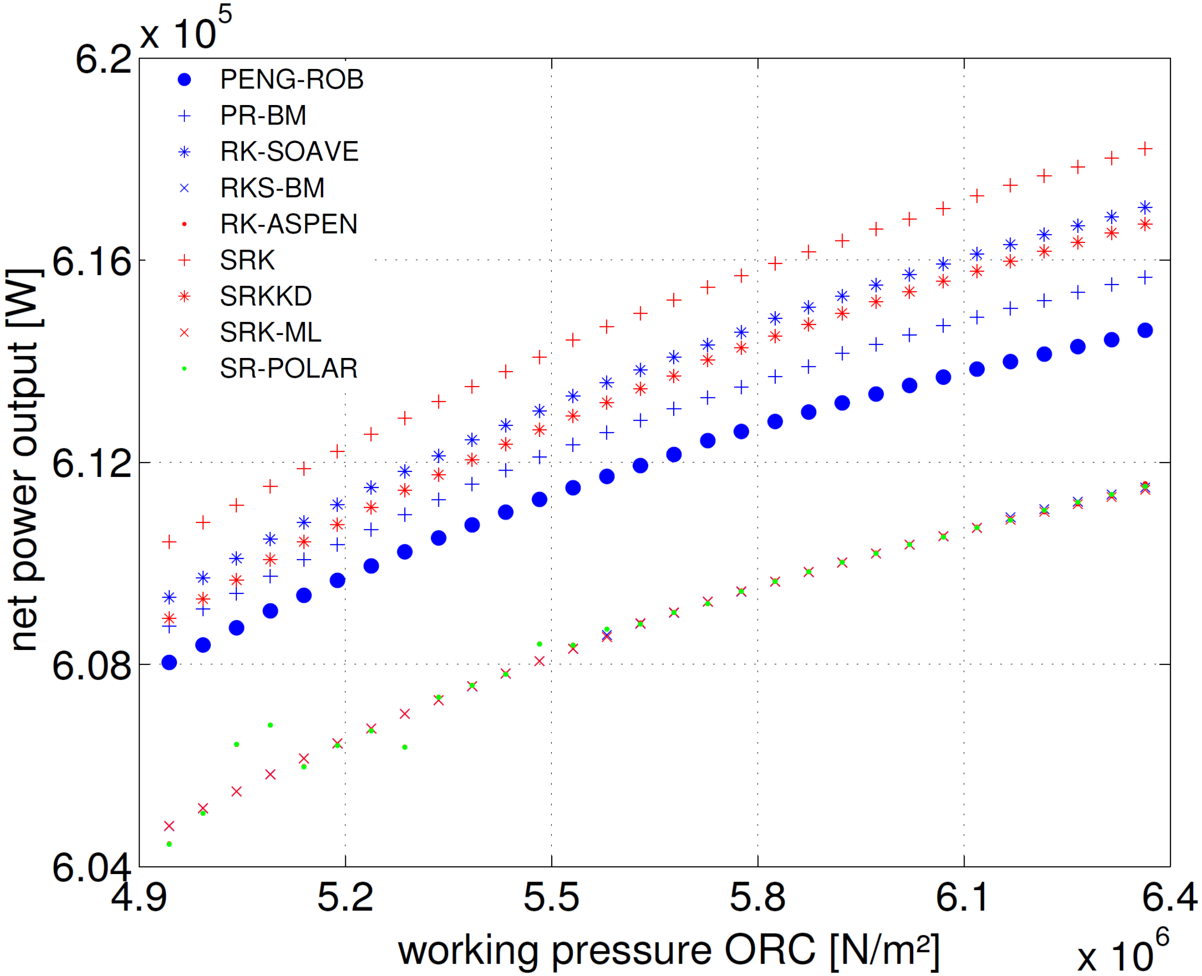

- → Relative deviation within 1%
- → Similar results can be found for the thermal efficiency (deviation < 2 %)
- → Similar results can be found for further working fluids

Thermodynamic results

Net power output vs. working pressure

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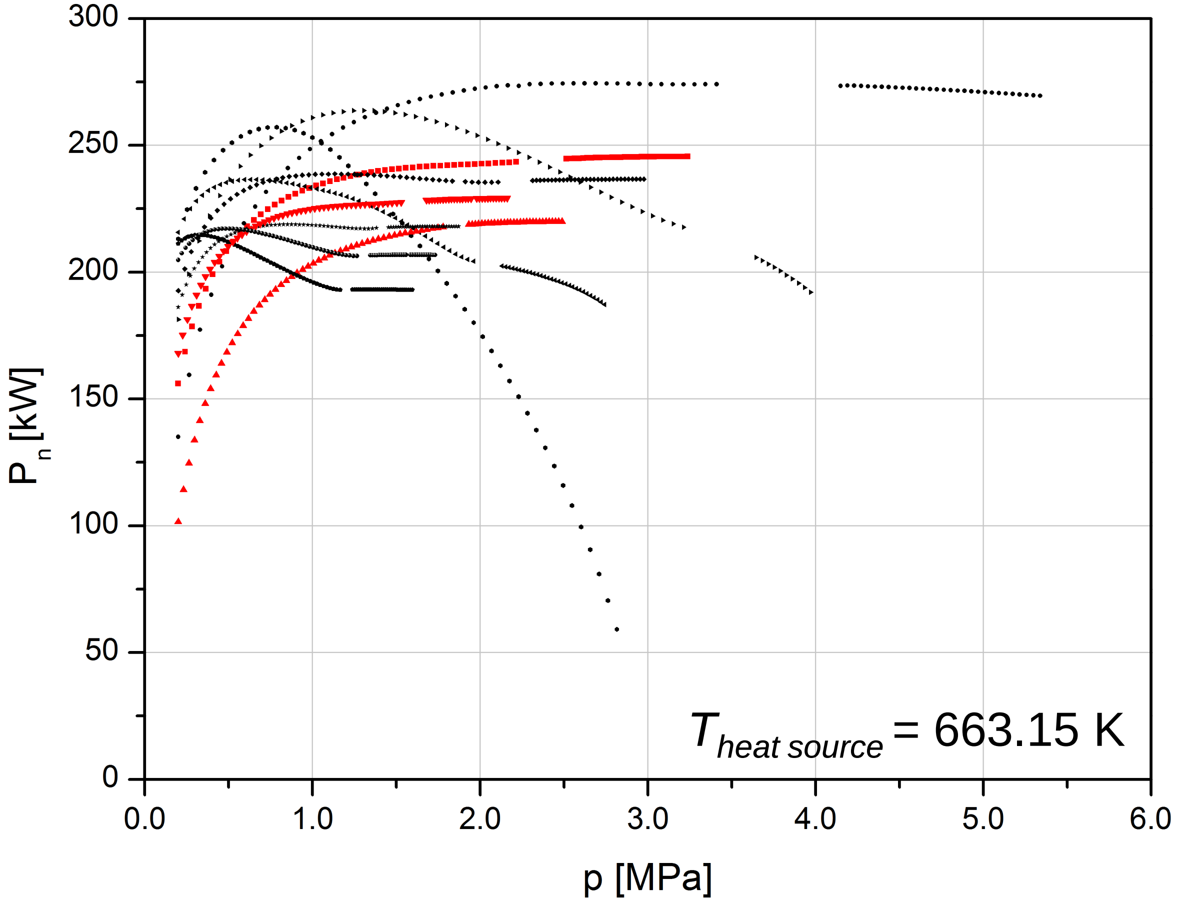
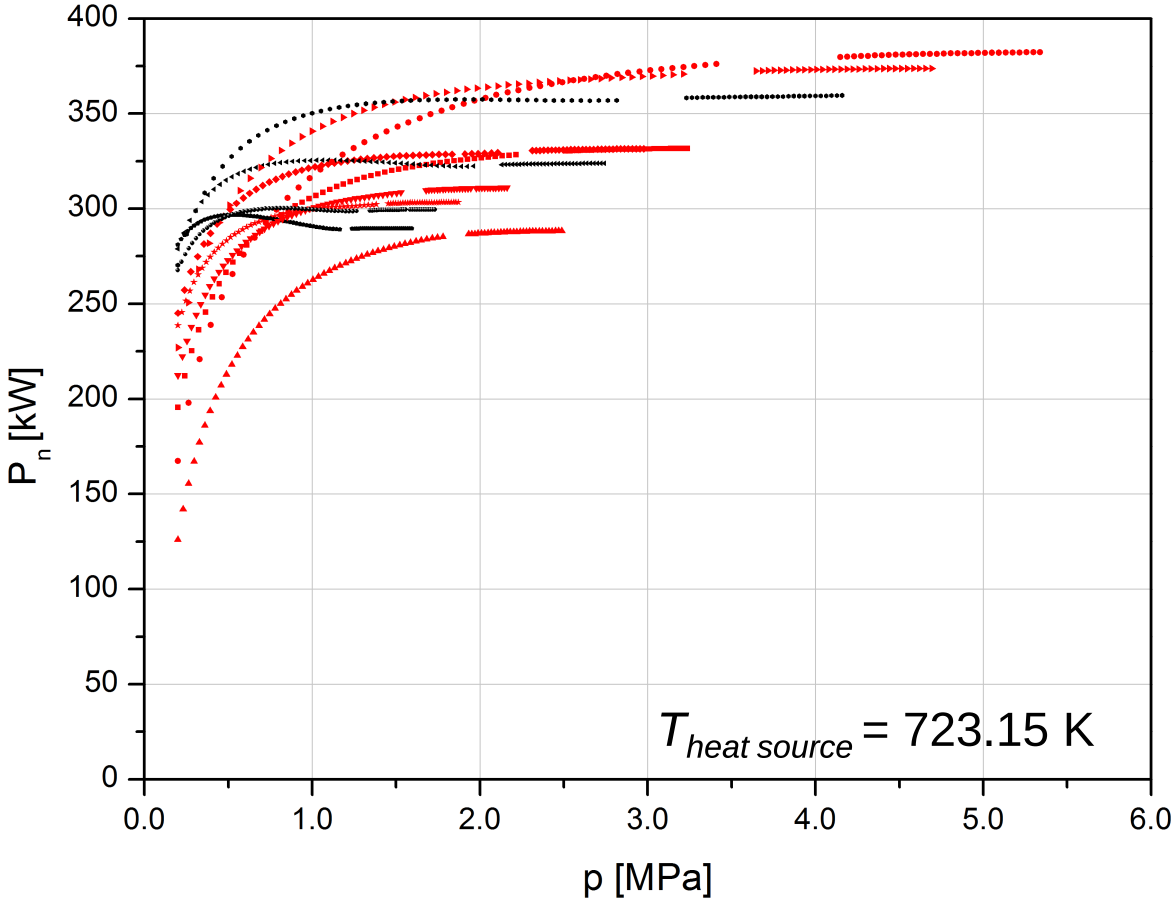


→ Efficiency increase/decrease depends on temperature of heat source

Thermodynamic results

Net power output vs. working pressure



- → Efficiency increase/decrease depends on temperature of heat source
- → The higher the temperature the more fluids show maximum net power output in supercritical mode

Thermodynamic results

Net power output vs. working pressure

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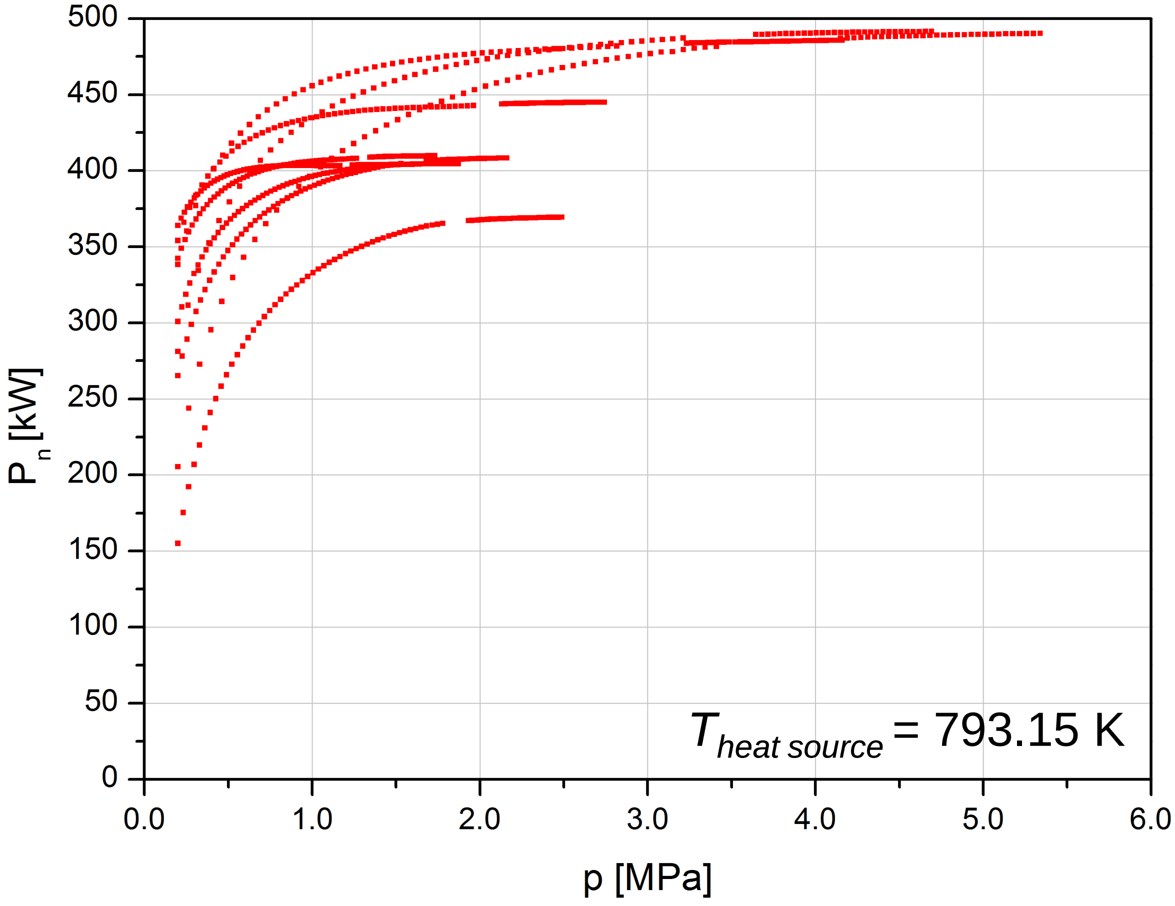

- → Efficiency increase/decrease depends on temperature of heat source
- → The higher the temperature the more fluids show maximum net power output in supercritical mode
- → At a certain temperature all fluids show best performance in supercritical mode

Thermodynamic results
Correlation of net power output and critical pressure

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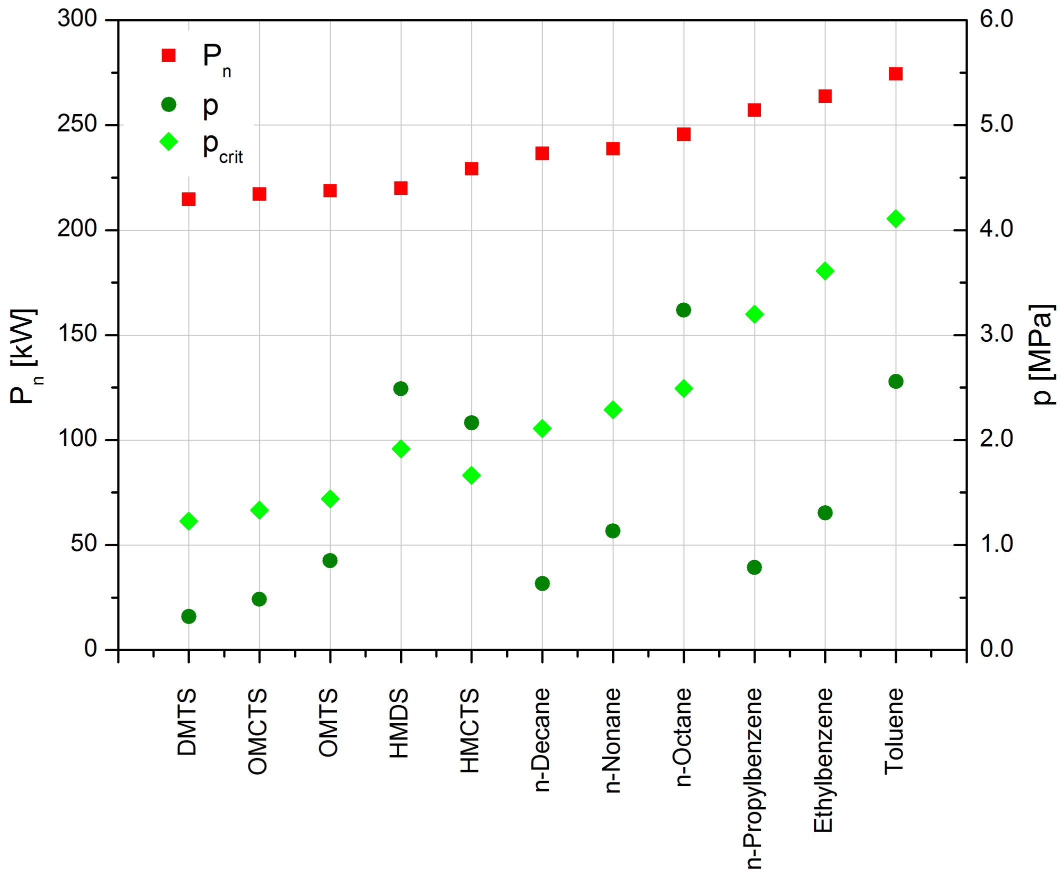
$T_{heat\ source} = 663.15$ K



→ Strong correlation of net power output from critical pressure at low heat source temperatures

Thermodynamic results
Correlation of net power output and critical pressure

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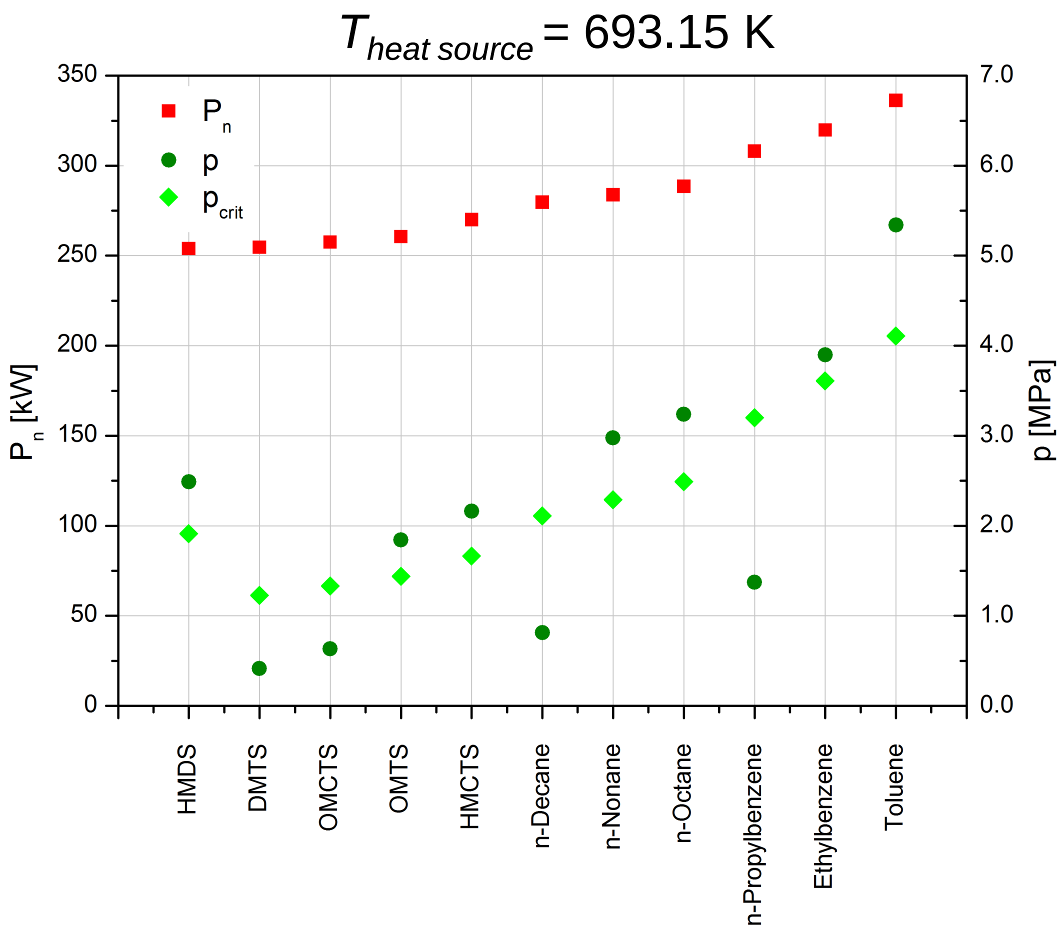

- → Strong correlation of net power output from critical pressure at low heat source temperatures
- → Correlation weakens for higher heat source temperatures

Thermodynamic results
Correlation of net power output and critical pressure

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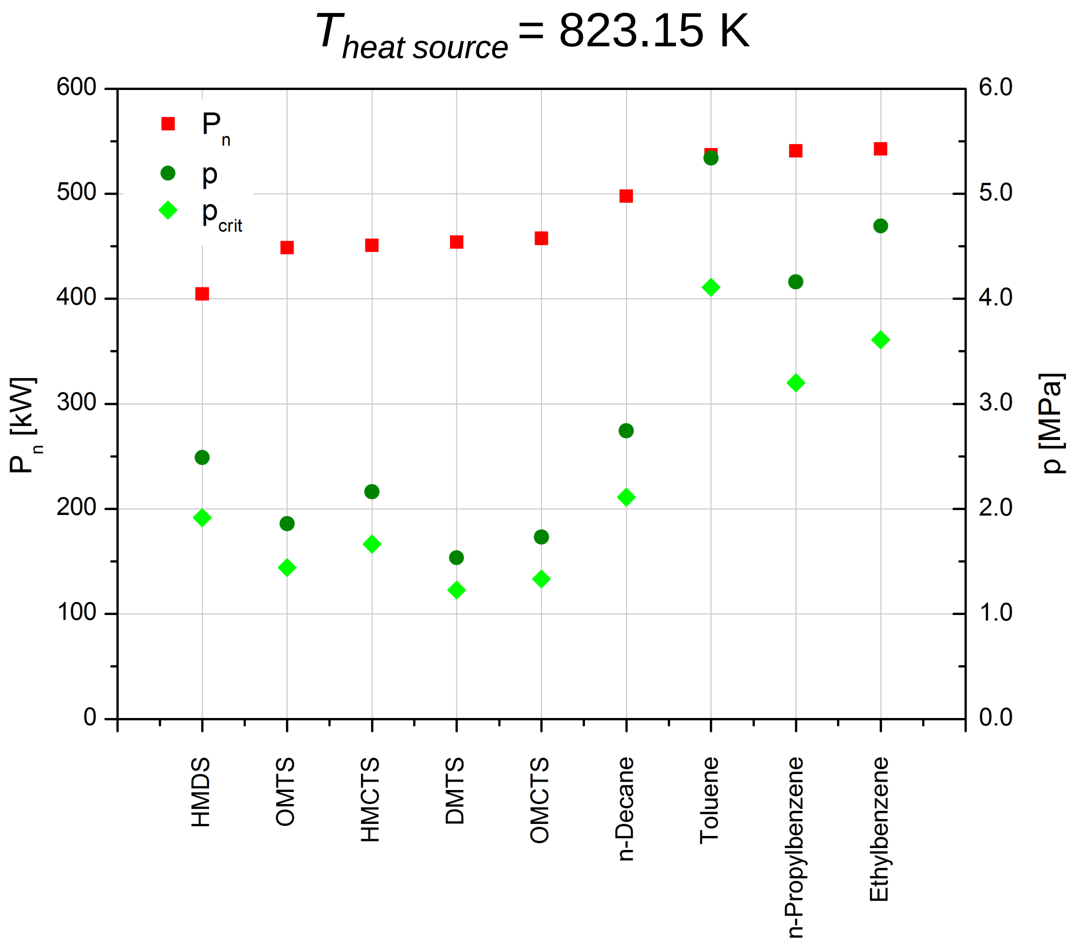

→ Strong correlation of net power output from critical pressure at low heat source temperatures

→ Correlation weakens for higher heat source temperatures

→ Correlation vanishes for even higher heat source temperatures

Thermodynamic results

Correlation of net power output and critical temperature

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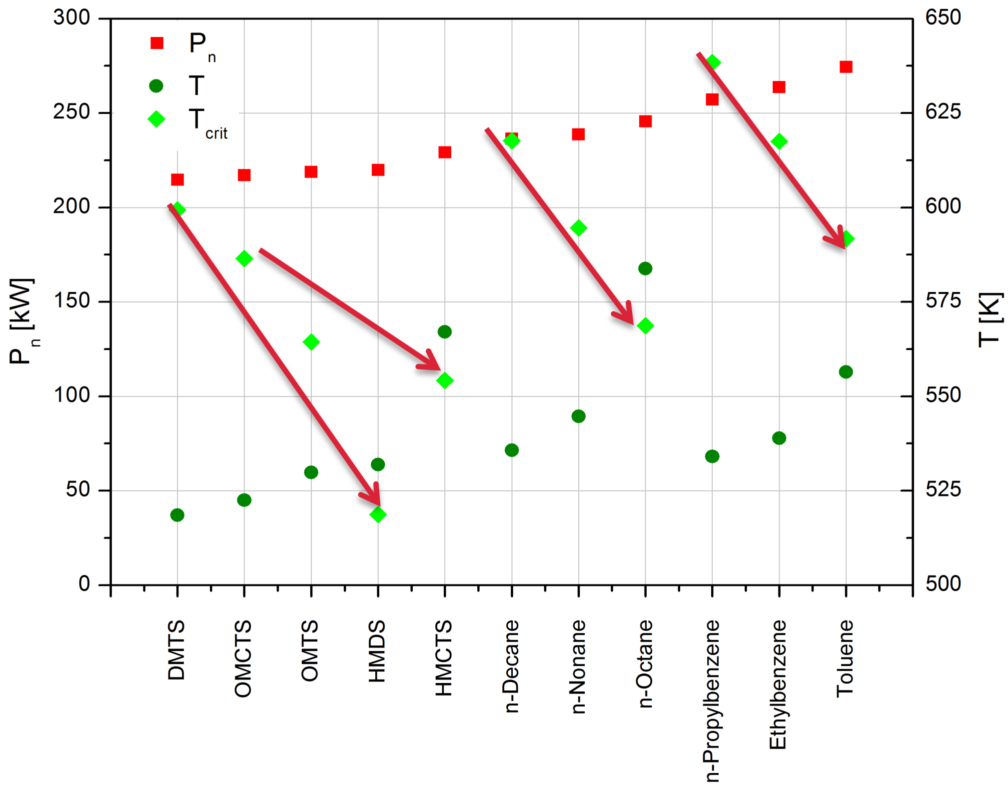
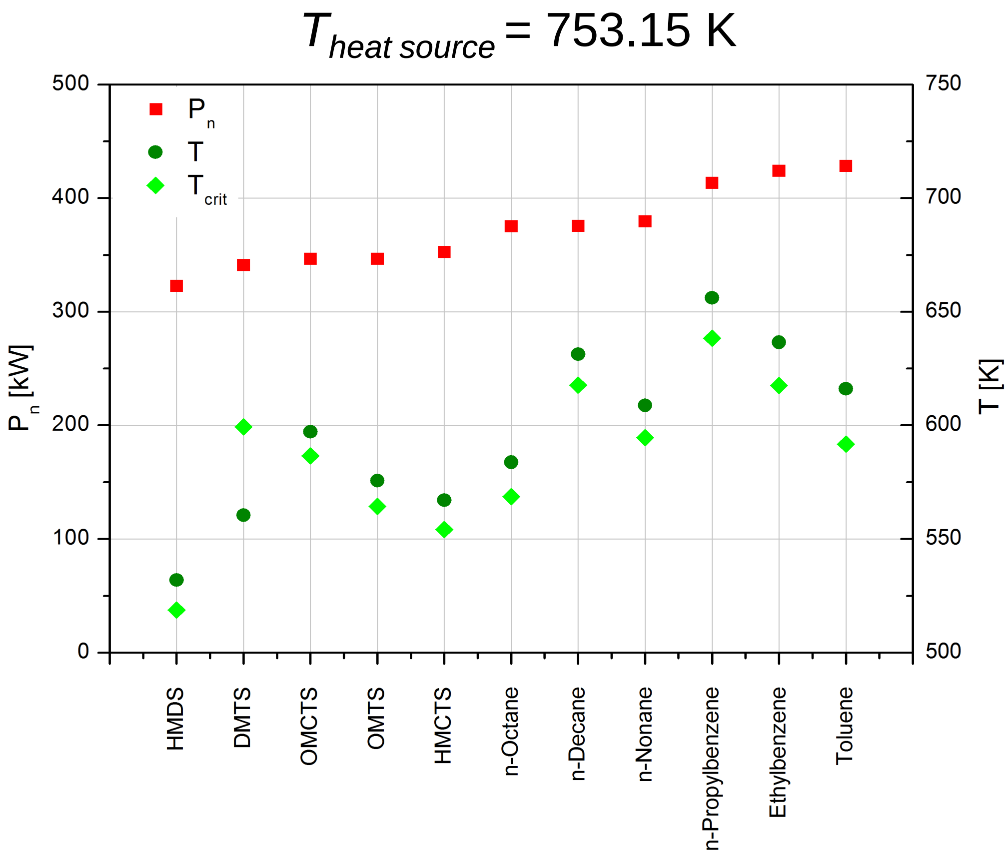


→ Correlation of net power output from critical temperature within a chemical class at low heat source temperatures

Thermodynamic results
Correlation of net power output and critical temperature



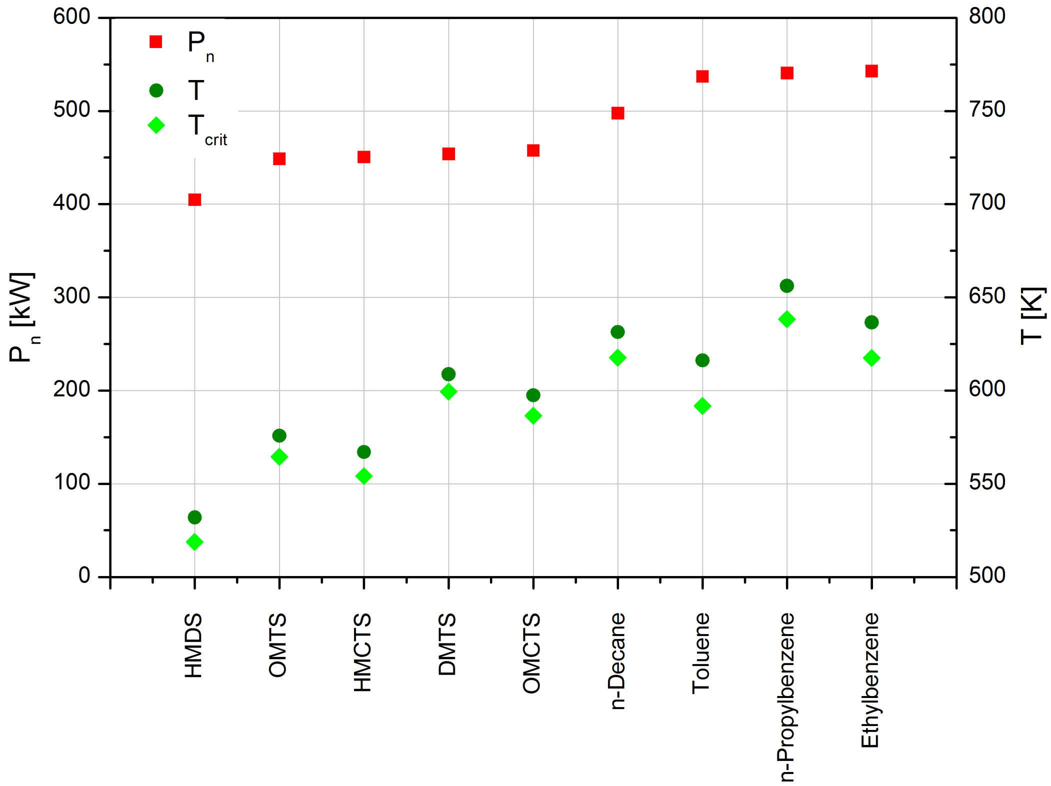
→ Correlation of net power output from critical temperature within a chemical class at low heat source temperatures

→ Correlation can just be seen for alkylbenzenes for higher heat source temperatures

Thermodynamic results

Correlation of net power output and critical temperature

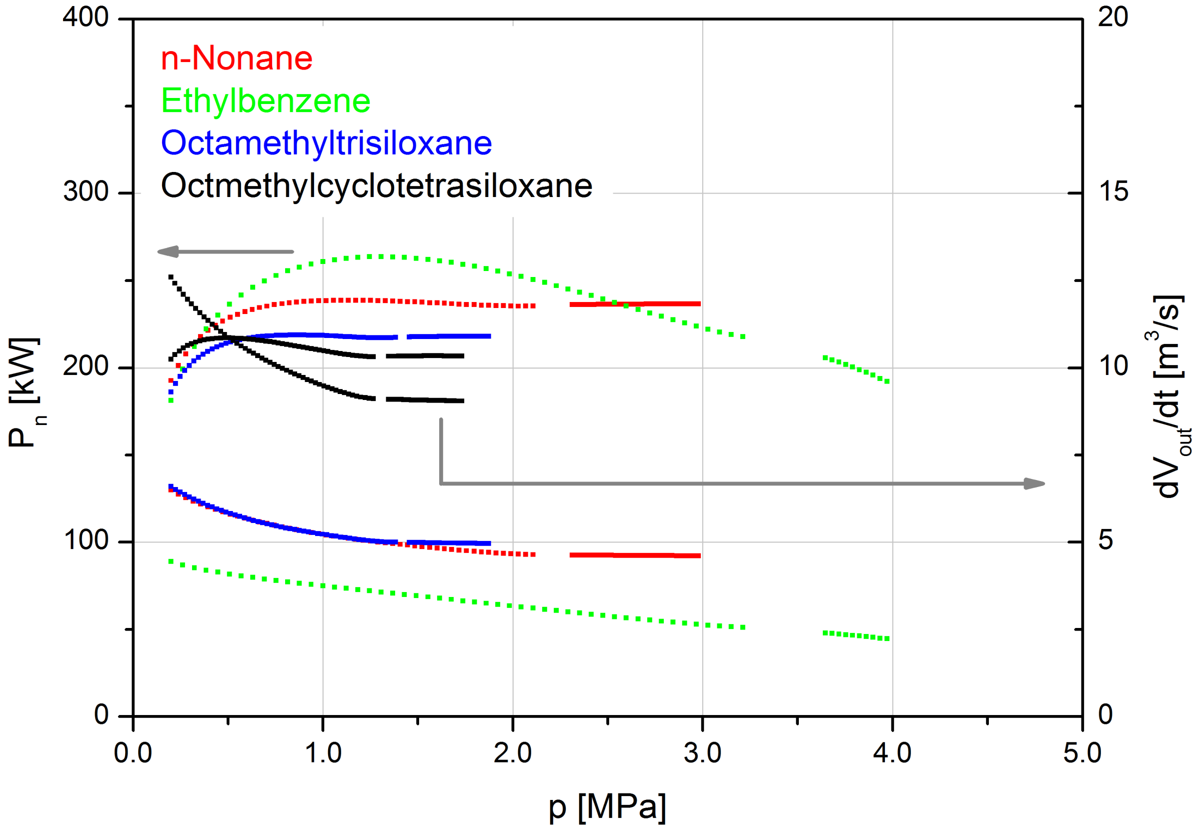
$T_{heat\ source} = 823.15$ K



- → Correlation of net power output from critical temperature within a chemical class at low heat source temperatures
- → Correlation can just be seen for alkylbenzenes for higher heat source temperatures
- → Correlation vanishes for even higher heat source temperatures

Constructional results
Comparison within chemical classes I

$T_{heat\ source} = 663.15$ K



- → OMCTS shows highest volume flow rates at turbine outlet
- → Volume flow rates of OMTS and n-nonane are similar
- → Ethylbenzene has lowest volume flow rates

Constructional results
Comparison within chemical classes I

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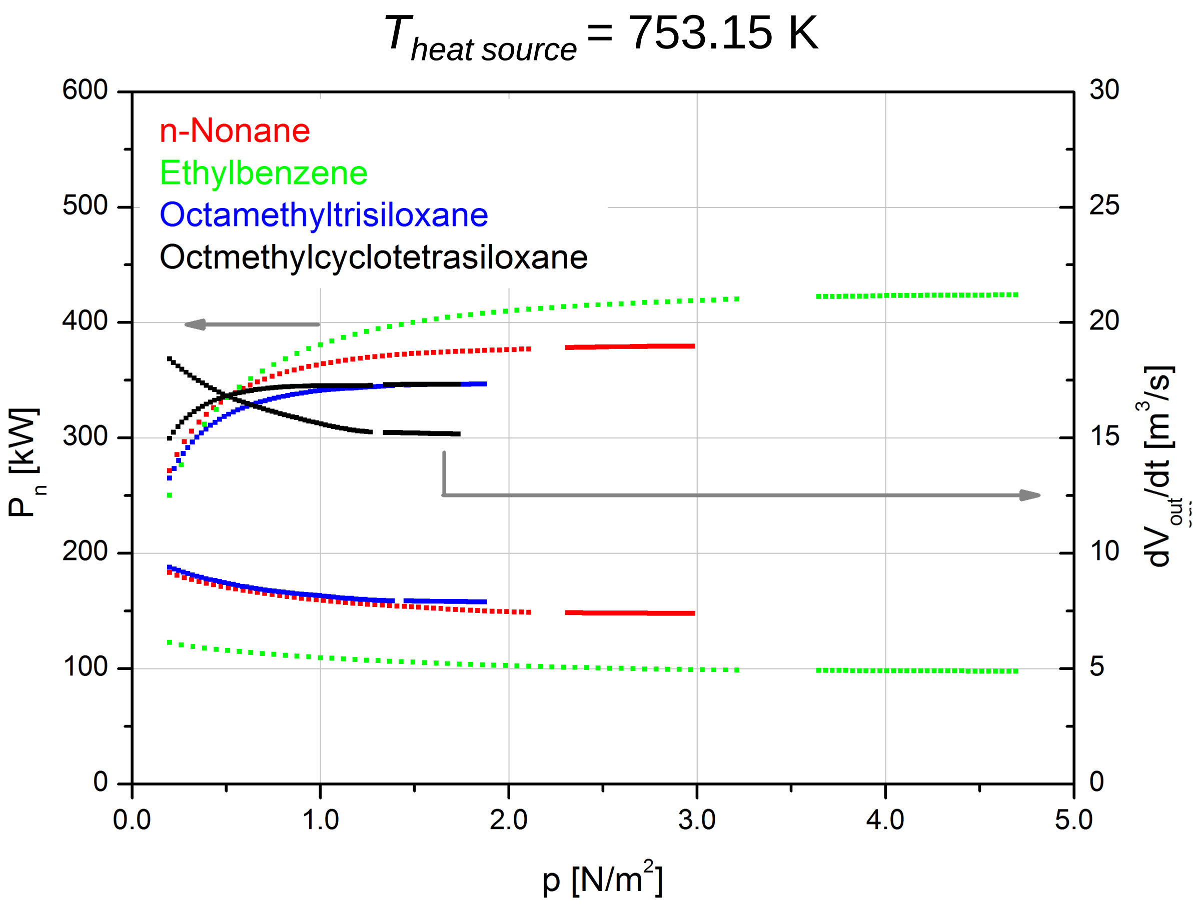

- → OMCTS shows highest volume flow rates at turbine outlet
- → Volume flow rates of OMTS and n-nonane are similar
- → Ethylbenzene has lowest volume flow rates
- → Same trends can be seen at higher heat source temperature

Constructional results

Comparison within chemical classes II

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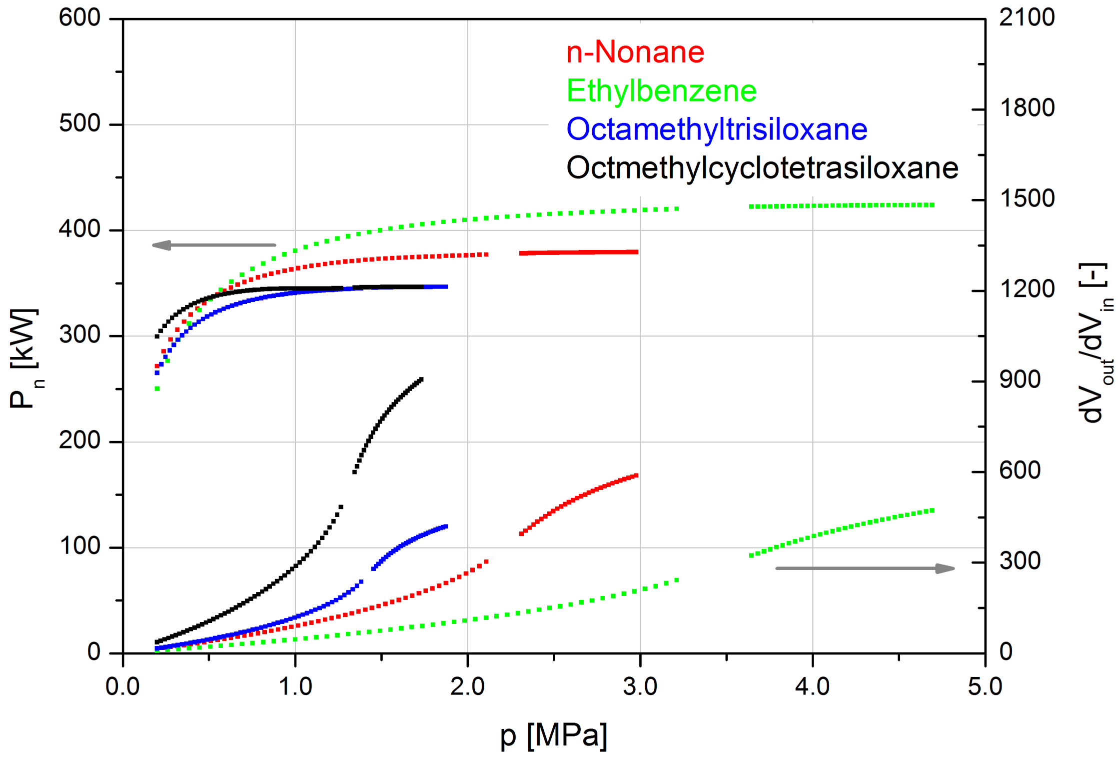
$T_{heat\ source}$ = 753.15 K



- → At fixed working pressure siloxanes show highest volume flow rate ratios within the turbine
- → OMCTS has steepest slope, volume flow rate ratio of ethylbenzene increases slightly
- → An inflexion point can be observed between sub- and supercritical mode of operation for all fluids

Comparison of chemical classes
Heat exchanger size

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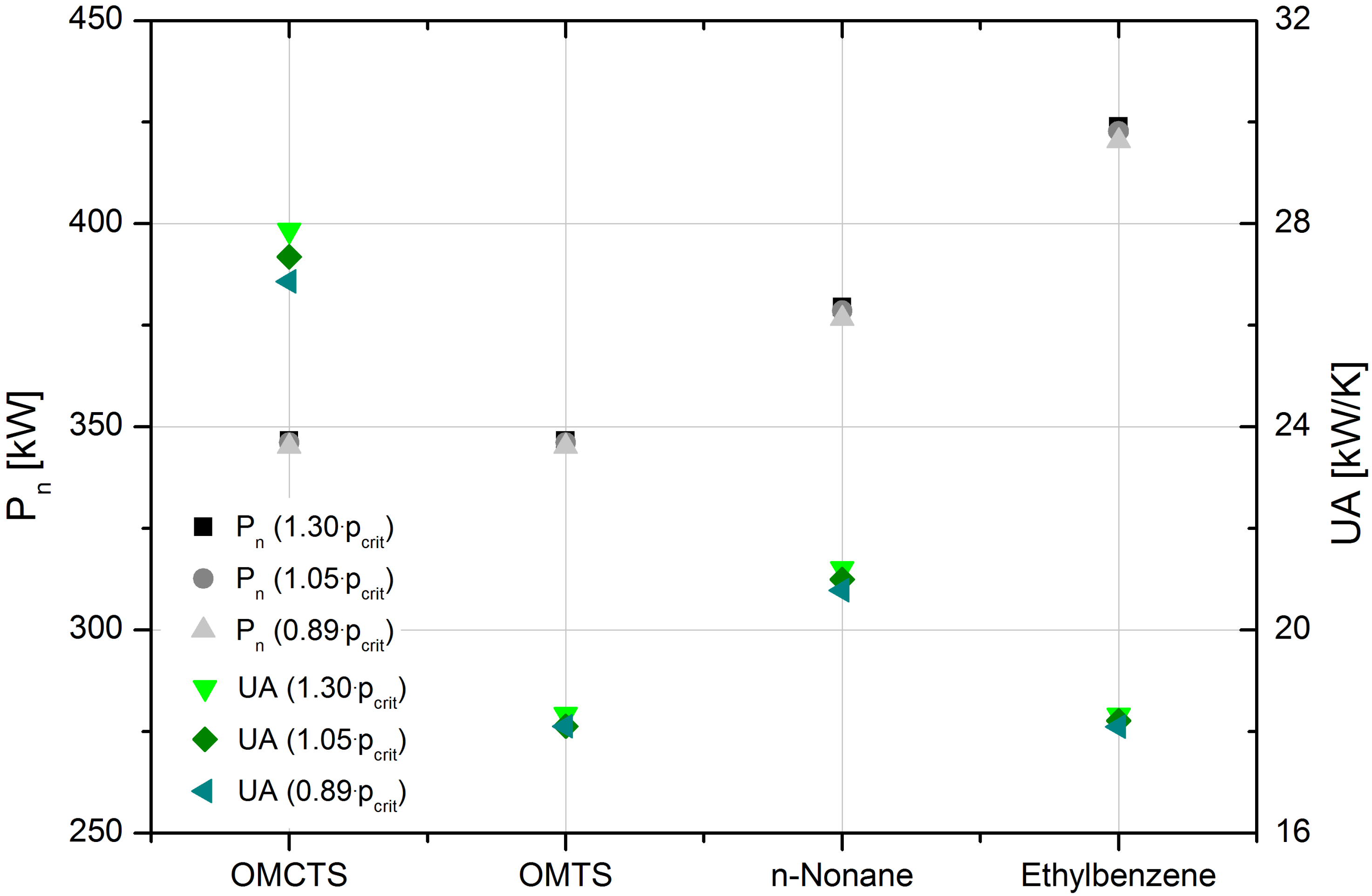

Heat transfer results
Nusselt number

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Miropol'skiy-Shitsman $Nu_b = 0.023\,\mathrm{Re}_b^{0.8}\,\mathrm{Pr}_{\min}^{0.8}$

Yamagata $Nu_b = 0.0135\,\mathrm{Re}_b^{0.85}\,\mathrm{Pr}_b^{0.8}\,\mathrm{F}_c$

$$F_c = 1.0 \text{ for } E > 1$$

$$E = \left(\frac{T_{pc} - T_b}{T_w - T_b}\right)$$

$$F_c = 0.67\,\mathrm{Pr}_{pc}^{-0.05}\left(\frac{\bar{c}_p}{c_{pb}}\right)^{n_1} \text{ for } 0 \le E \le 1$$

$$n_1 = -0.77\left(1 + \frac{1}{\mathrm{Pr}_{pc}}\right) + 1.49$$

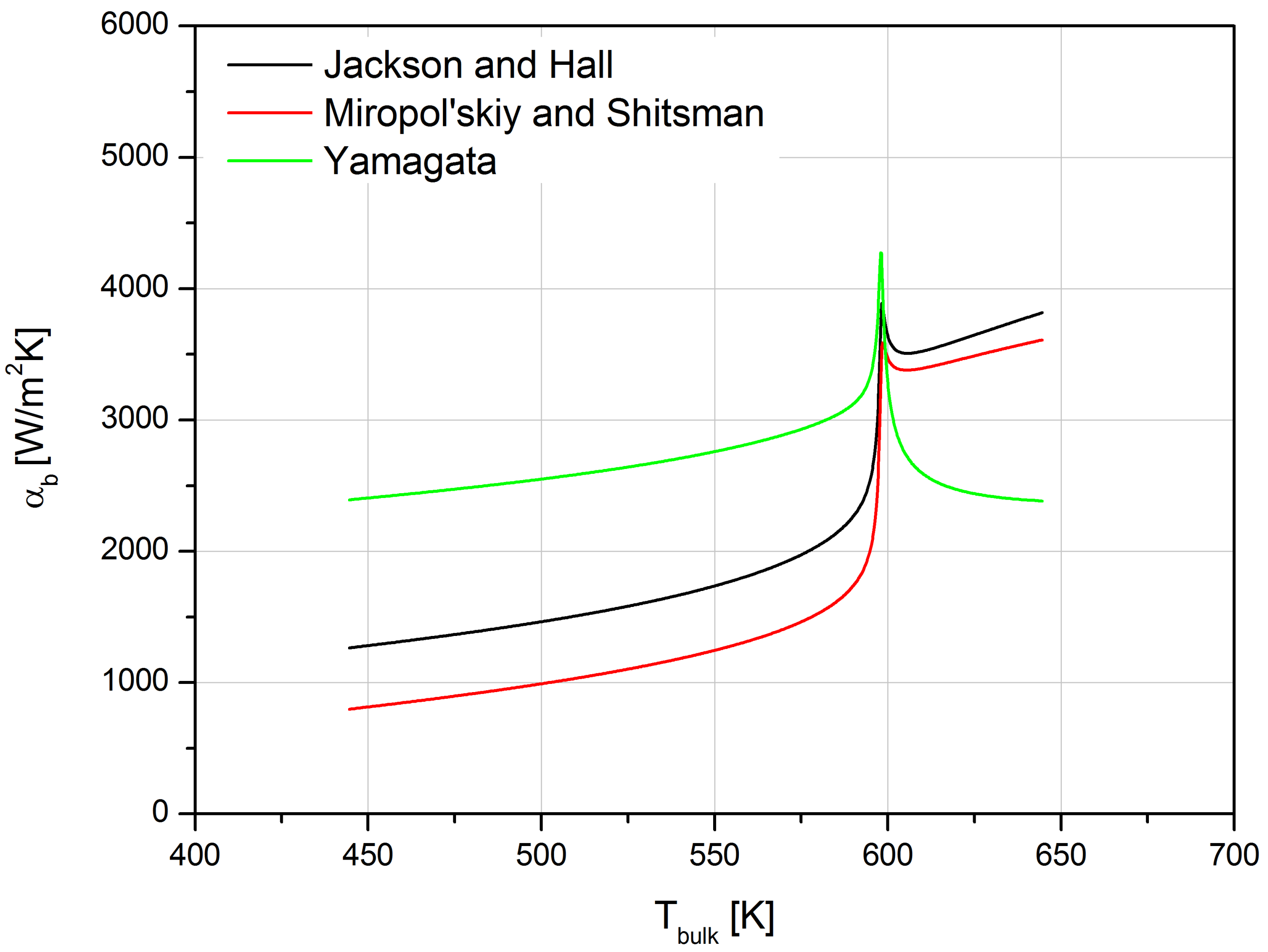
$$F_c = \left(\frac{\bar{c}_p}{c_{pb}}\right)^{n_2} \text{ for } E < 0$$

$$n_2 = -1.44\left(1 + \frac{1}{\mathrm{Pr}_{pc}}\right) - 0.53$$

Jackson and Hall

$$Nu = 0.0183\,\mathrm{Re}_b^{0.82}\,\mathrm{Pr}_b^{0.5}\left(\frac{\rho_w}{\rho_b}\right)^{0.3}\left(\frac{\bar{c}_p}{c_{pb}}\right)^{n} \text{ with } n = f(T_w, T_b, T_{pc}) \approx 0.4$$

Heat transfer results
Case 1: T_{wall}=const.



Heat transfer results

Case 1: T_{wall}=const.

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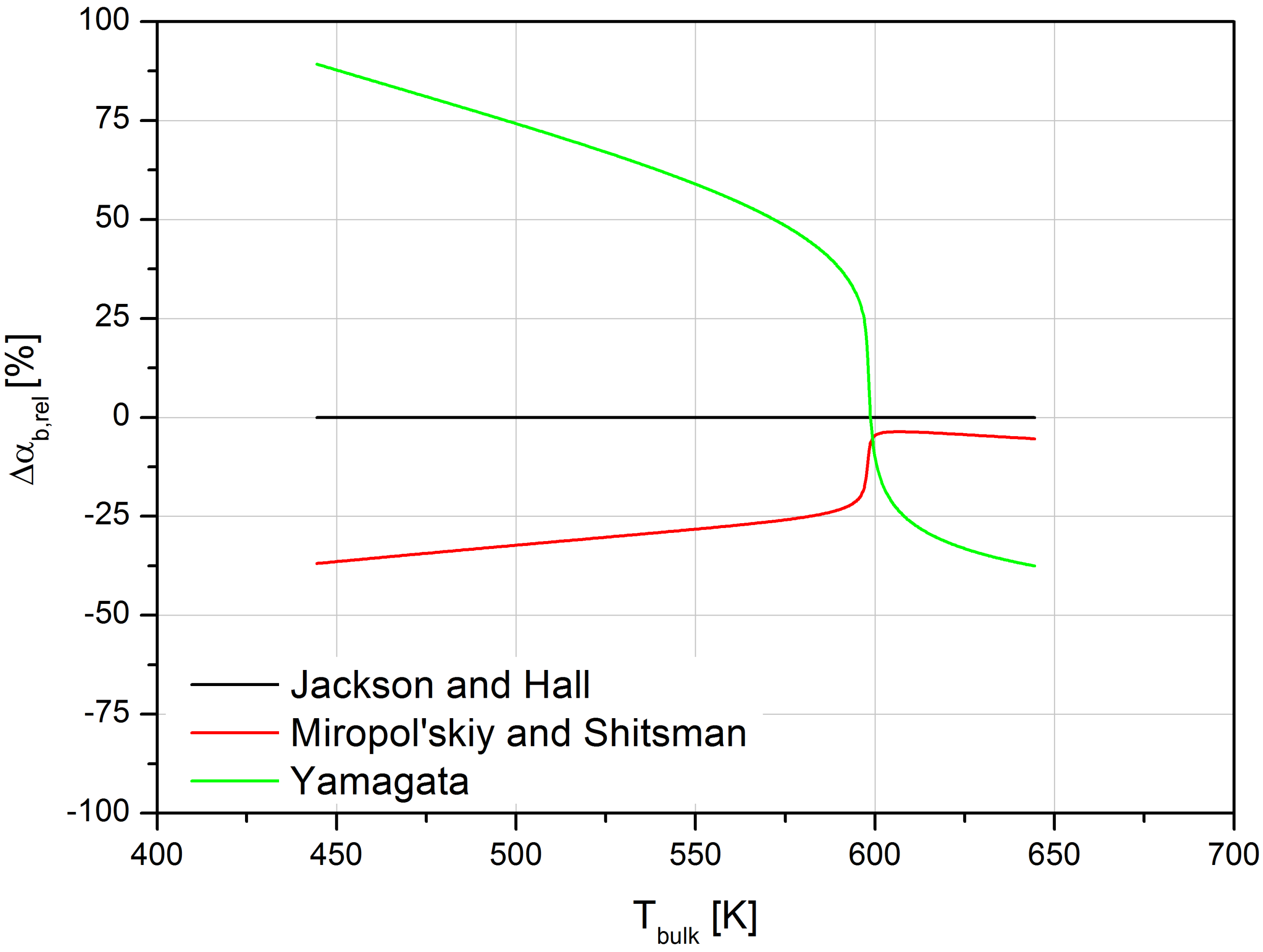
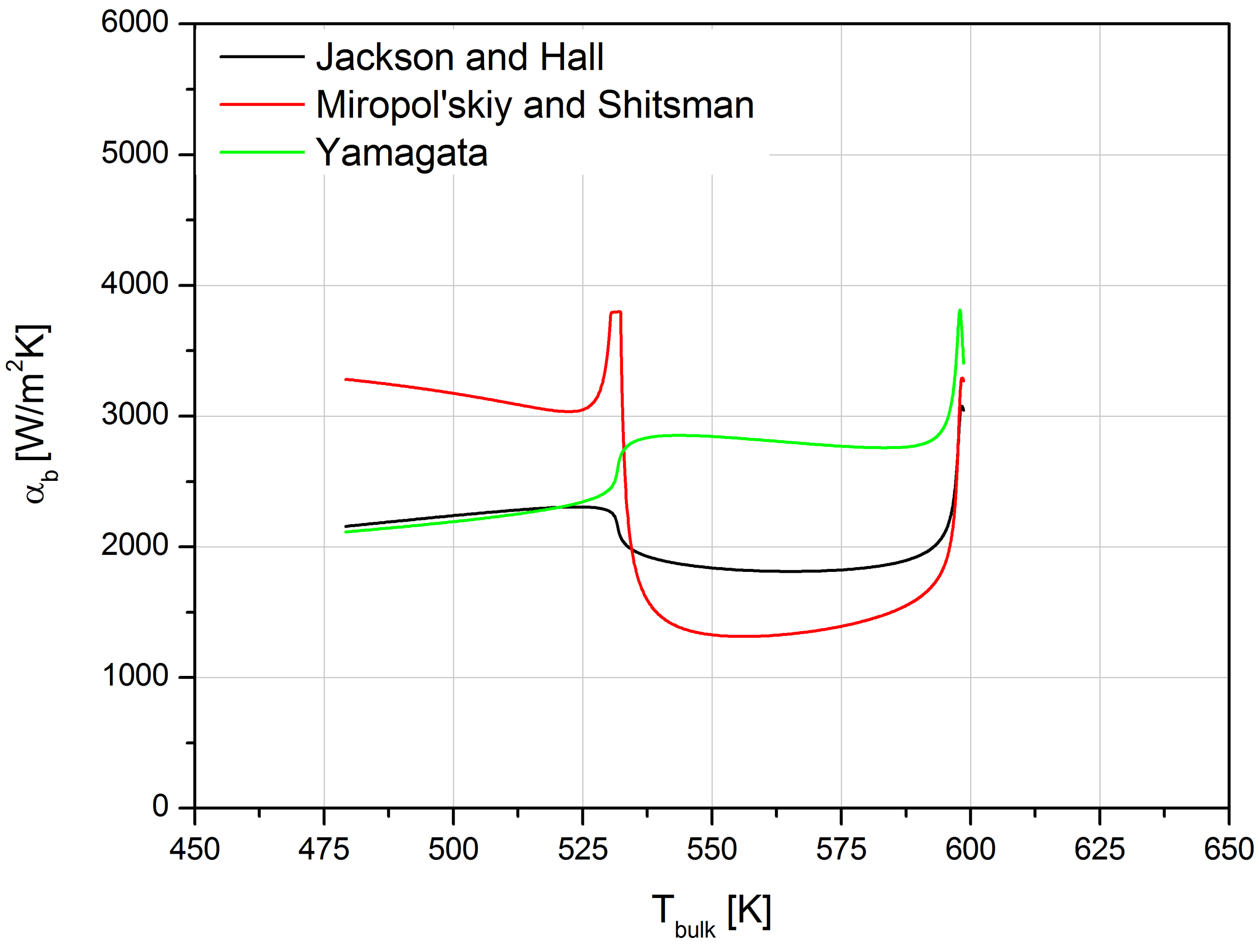


Heat transfer results

Case 2: $T_{wall}=T_{heat\ source}$



Heat transfer results

Case 2: $T_{wall}=T_{heat\ source}$

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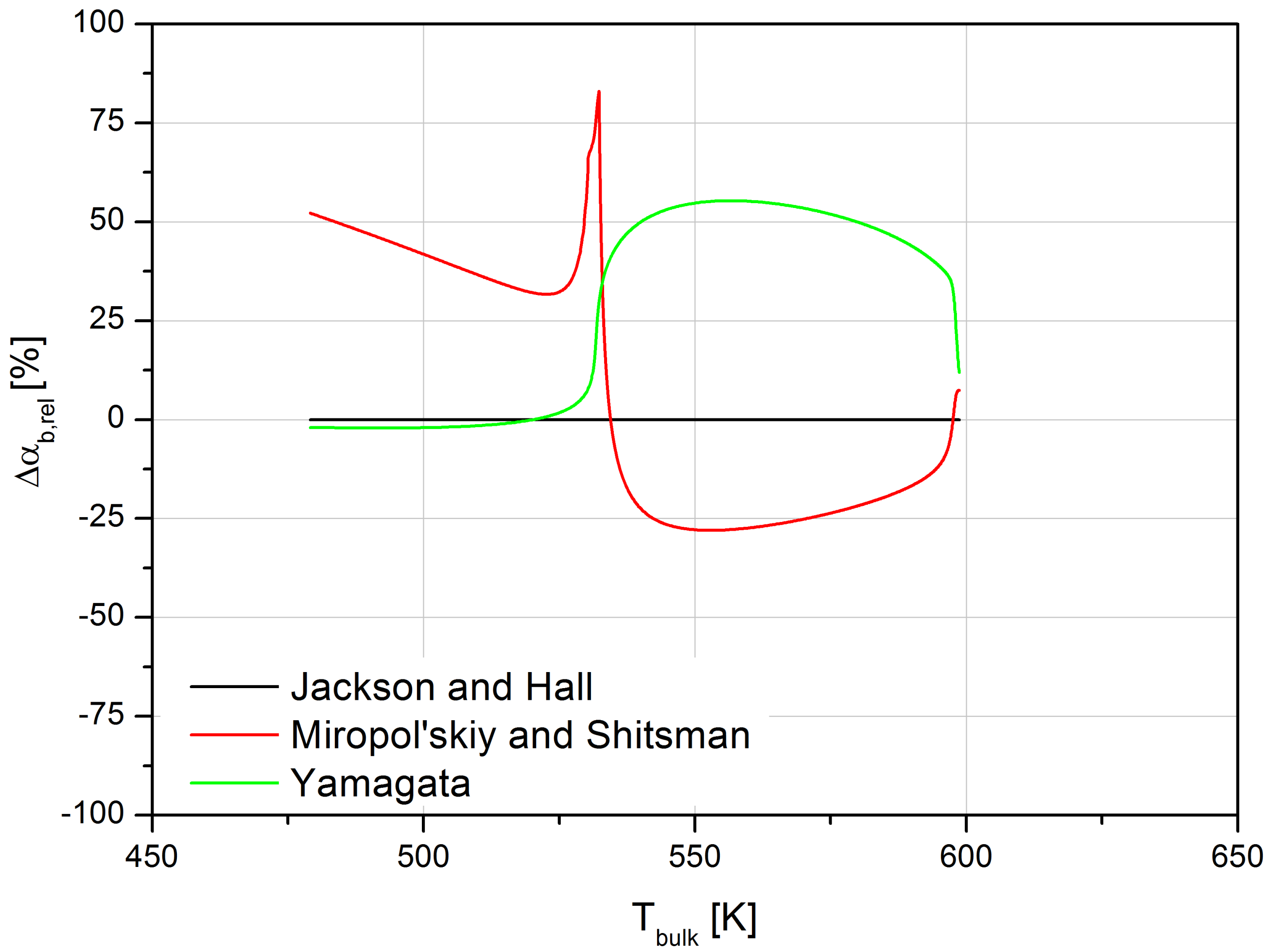

Summary

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- Study on supercritical Organic Rankine Cycle for waste heat utilization
- 11 fluids out of 4 chemical classes (alkanes, alkylbenzenes, linear siloxanes, cyclic siloxanes) were investigated.
- Net power output increase strongly depends on heat source temperature.
- Correlation between net power output and physico-chemical properties depends on heat source temperature and chemical class.
- Alkylbenzenes show highest net power output, lowest volume flow rate but highest working pressure.
- Linear siloxanes show smaller volume flow rates and heat transfer capacities UA than cyclic siloxanes for similar net power output.
- Prediction of heat transfer coefficients is quite complicated.

Future work

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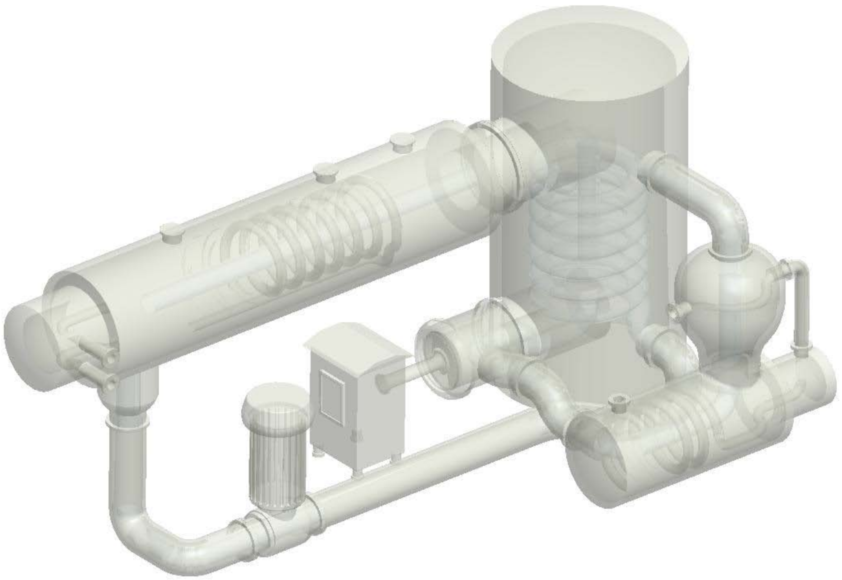
- Integration of pressure and radiation losses
- More detailed evaluation of heat transfer mechanism
- Fluid-to-Fluid modelling for heat transfer correlations
- Measurement of heat transfer coefficients in laboratory
- Economic evaluation of supercritical Organic Rankine Cycle



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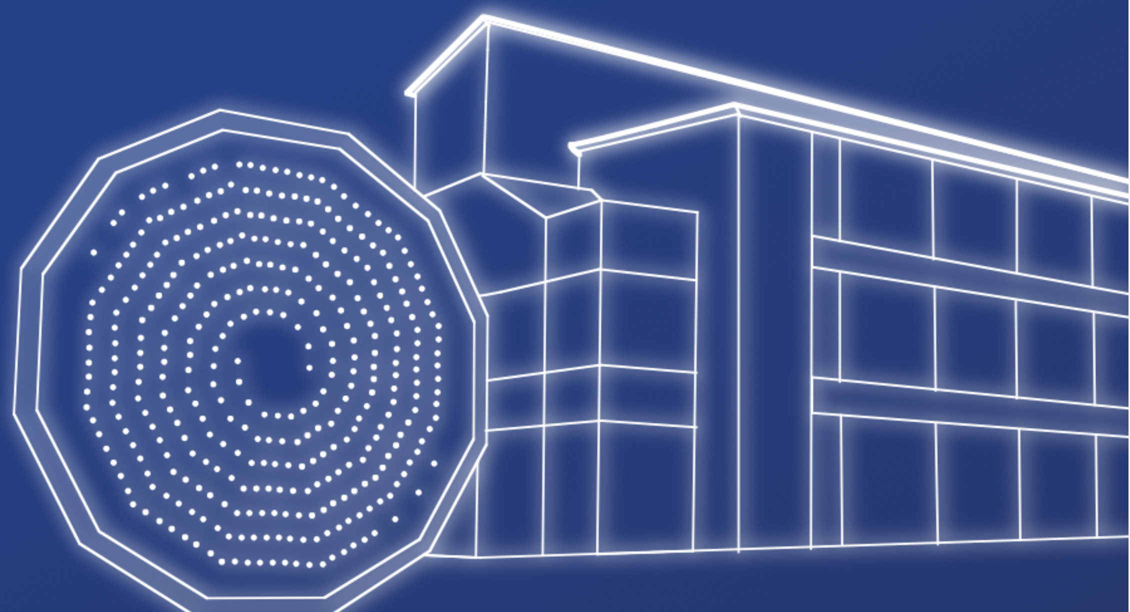

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