Reversible High Temperature Heat Pump – Organic Rankine Cycle System for Industrial Waste Heat Recovery (work package 3.4)

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Climate Neutral by 2050

- Global warming could exceed 2 °C in the 21st century (IPCC 2021)
- Limit temperature increase to 1.5°C (‘Paris Agreement on Climate Change’, 2015)
- Renewables target: 40% by 2030 (European Commission, 2021)
- Energy efficiency increase: 39%(primary energy consumption) 36% (final energy consumption) by 2030 (European Commission, 2021)
- Greenhouse gas emissions reduction target: 55% for 2030 (European Commission, 2021)

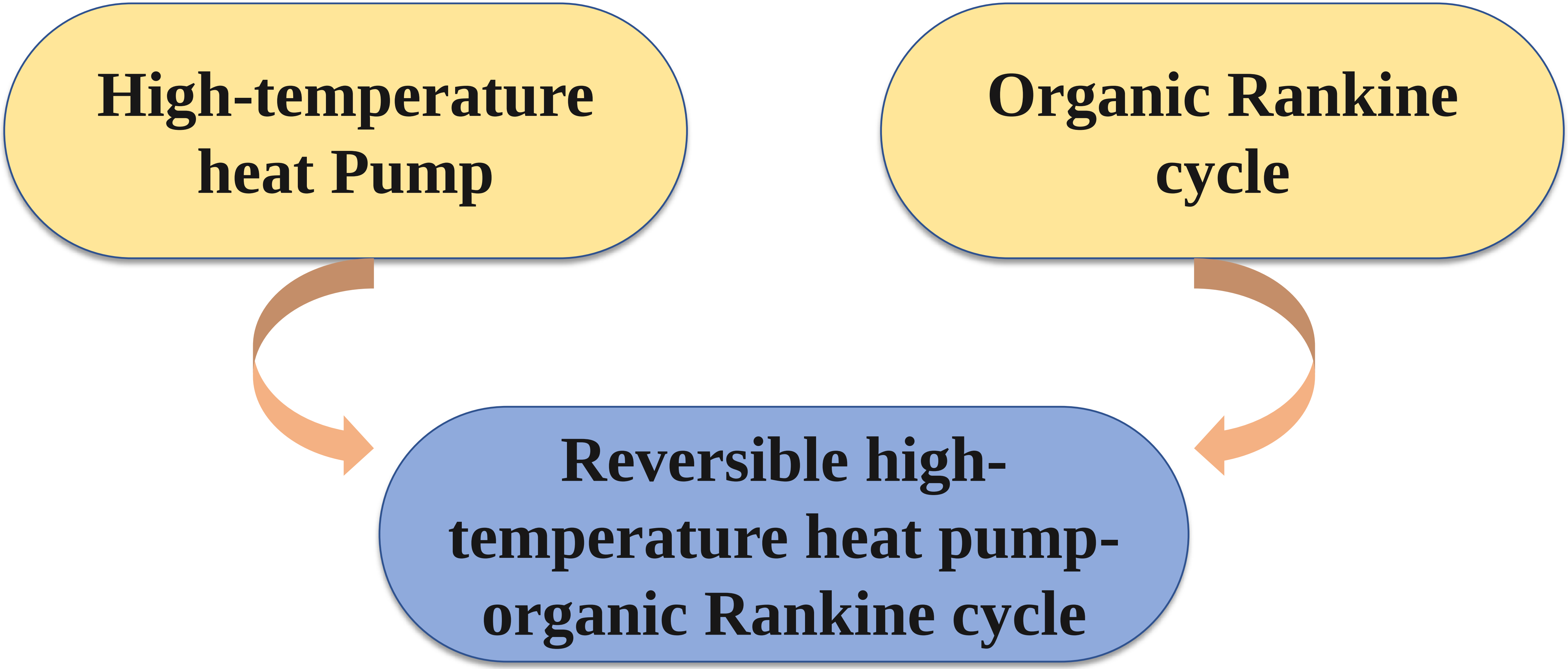
Industrial Waste heat potential

- 72% of global energy consumption is lost during conversion
- Total industrial waste heat potential
  31.9 PJ (Global)
  304.13 TWh/yr (European Union)
  24 TWh/year.(UK)
- 42% of industrial waste heat is below 100 °C
- 20% of industrial waste heat in 100 – 299 °C

Waste heat recovery technologies

- Absorption heat pump
- Compression heat pump
- Chemical heat pump
- Heat exchangers
- Kalina cycle
- Organic Rankine cycle
- Absorption refrigeration
- Adsorption refrigeration
- Thermal energy storage
- Combined heat and power systems

Waste heat recovery

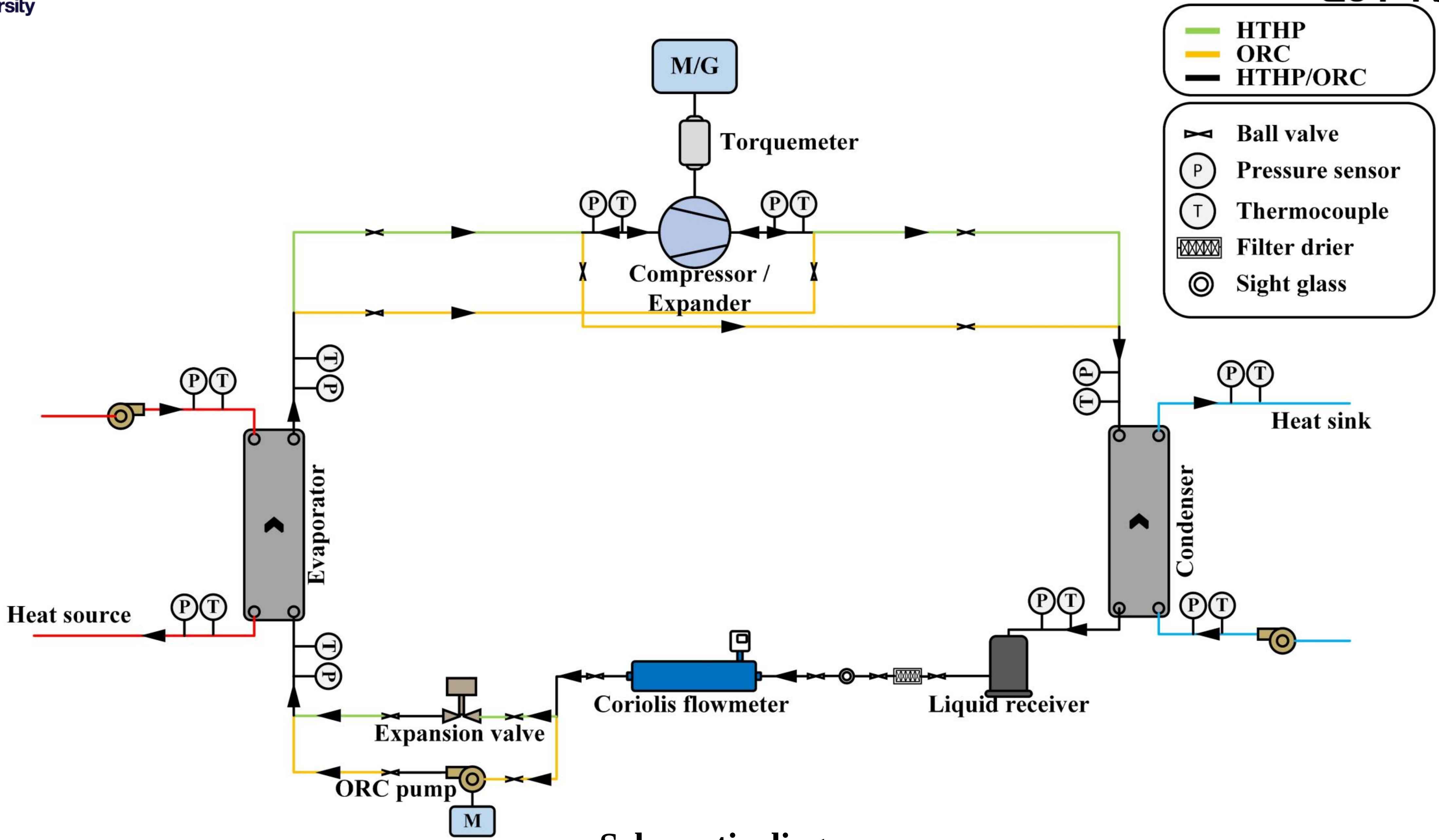


Potential applications

- **To provide process heat in industries operating in HTHP mode / to generate power (ORC mode) when there is no heating demand.**
- **The reversible system can also be implemented as part of a district heating network ,where the upgraded heat can be used for space heating in office and commercial buildings in winter season or for power generation (summer)**
- **Reversible system coupled to a thermal storage as a Carnot battery**

Objectives

- **To develop a lab-scale prototype of a compact reversible HTHP - ORC system (waste heat recovery temperature band < 100 °C)**
- **To operate a single volumetric machine as both compressor (HTHP) and expander (ORC)**
- **To operate the reversible system with a low GWP working fluid.**



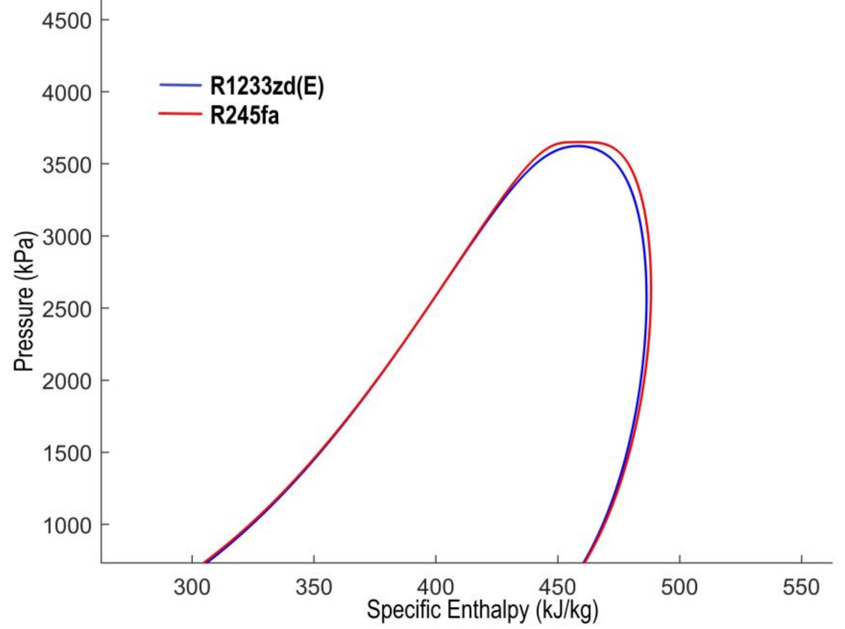
Schematic diagram

Refrigerant selection

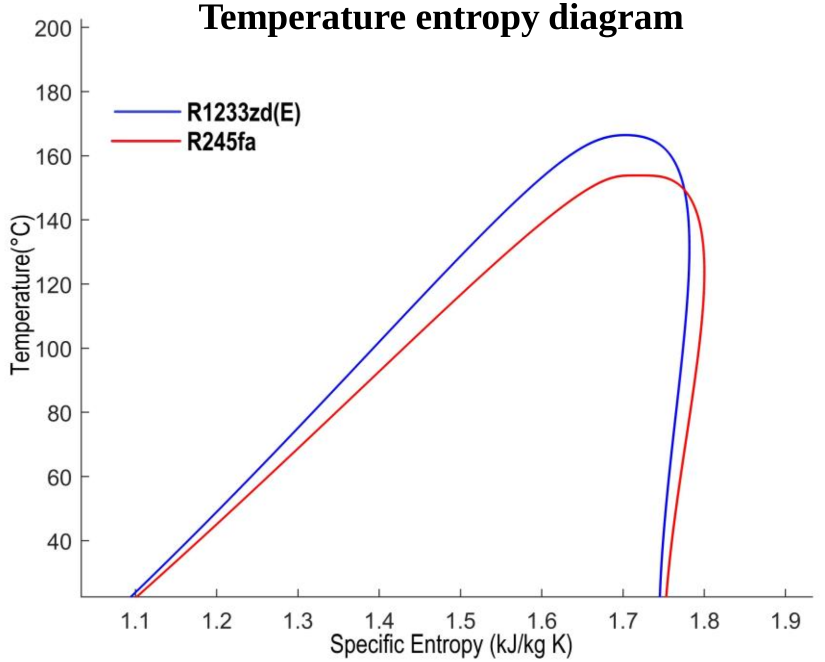
- **R1233zd(E)** shows improved/similar COP in high temperature heat pump applications compared to R245fa .
- Improved/similar cycle thermal efficiency in small scale ORC system in comparison with R245fa
- Can replace R245fa without changing compressor in HP system or expander in ORC systems
- Improved/similar isentropic efficiencies for compressor in HP and expander in ORC system in comparison with R245fa
- Similar/slightly lower power output in ORC systems compared to R245fa

Parameters	Ozone depletion potential (ODP)	Global warming potential (GWP)	Critical Temperature (°C)	Critical pressure (bar)
R245fa	0	1030	153.9	36.5
R1233zd(E)	0.00024	1	166.5	36.2

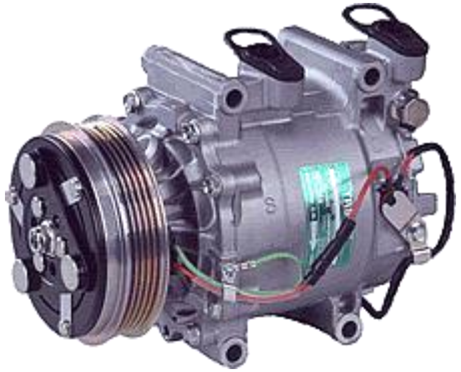
Pressure enthalpy diagram



Temperature entropy diagram



Compressor/Expander



Scroll compressor/expander

- Power range: 1-10 kW
- Low rotational speed
- Better wet expansion handling
- High compactness
- Low cost

Piston compressor/expander

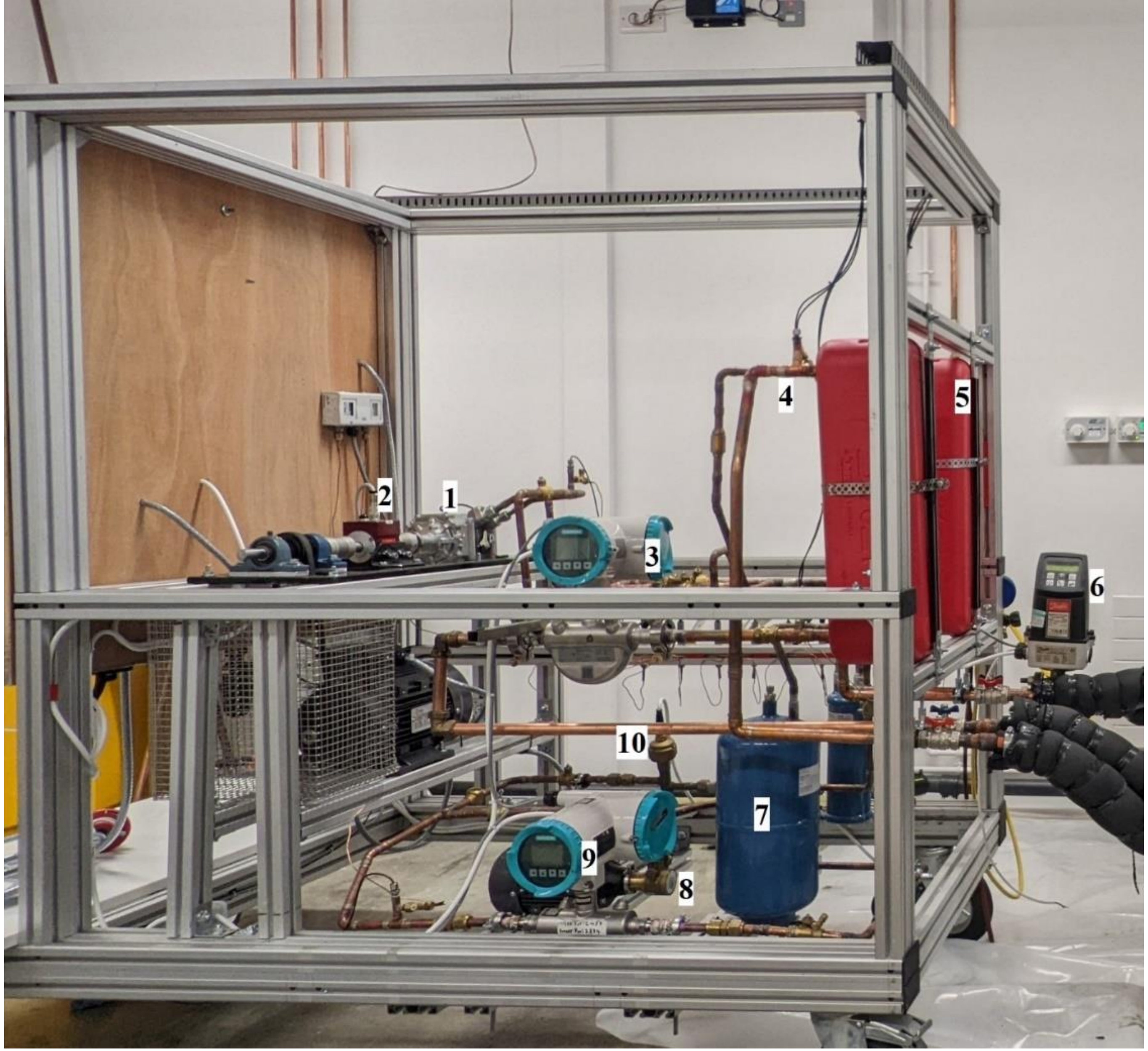
- Power range: 1-10 kW
- Medium rotational speed
- Poor Wet expansion handling
- Medium compactness
- Medium cost

Screw compressor/expander

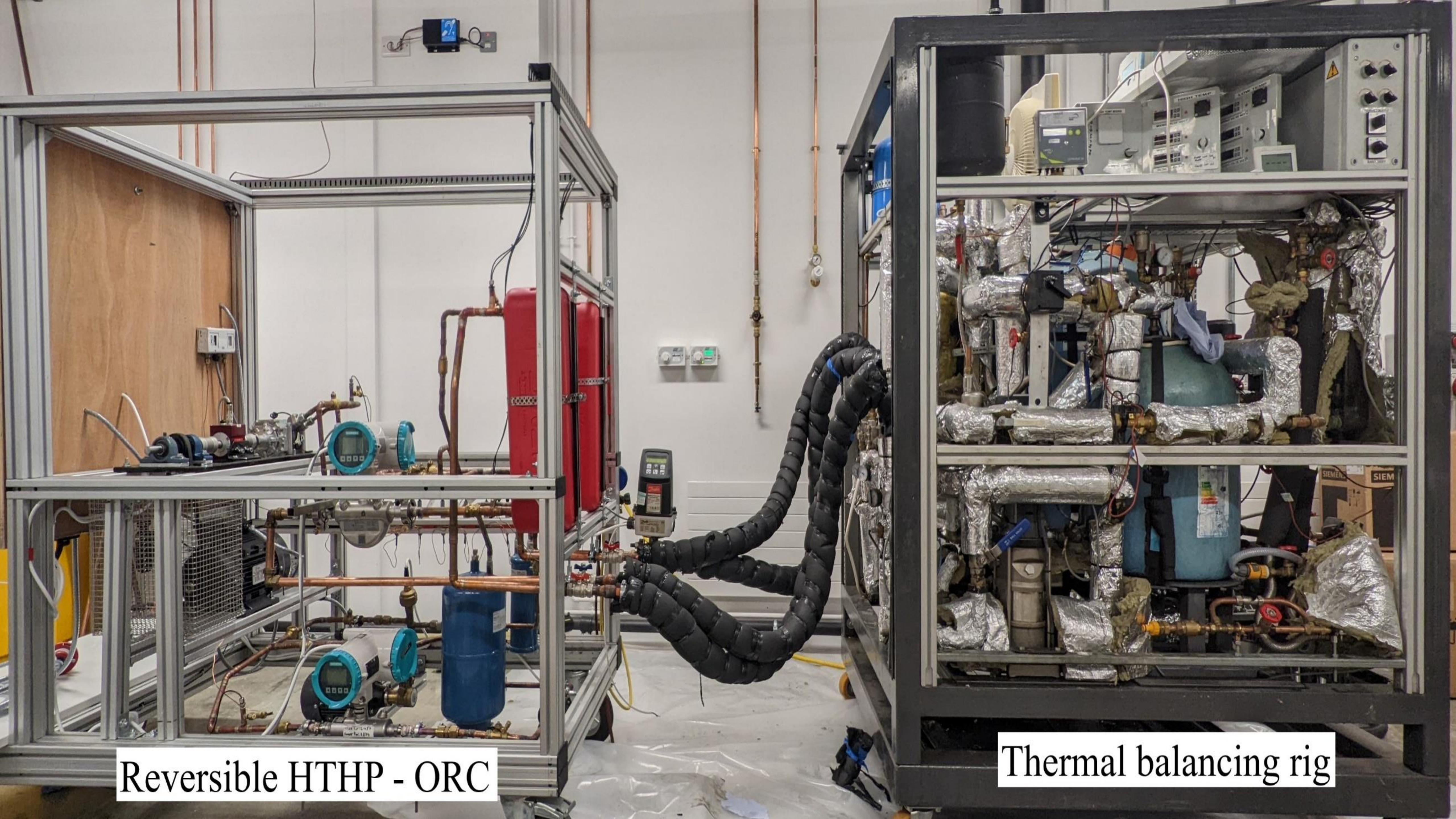
- Power range: 15 – 200 kW
- Low rotational speed
- Better wet expansion handling
- High compactness
- Medium cost

Vane compressor/expander

- Power range: 1-10 kW
- Low rotational speed
- Better wet expansion handling
- High compactness
- Low cost



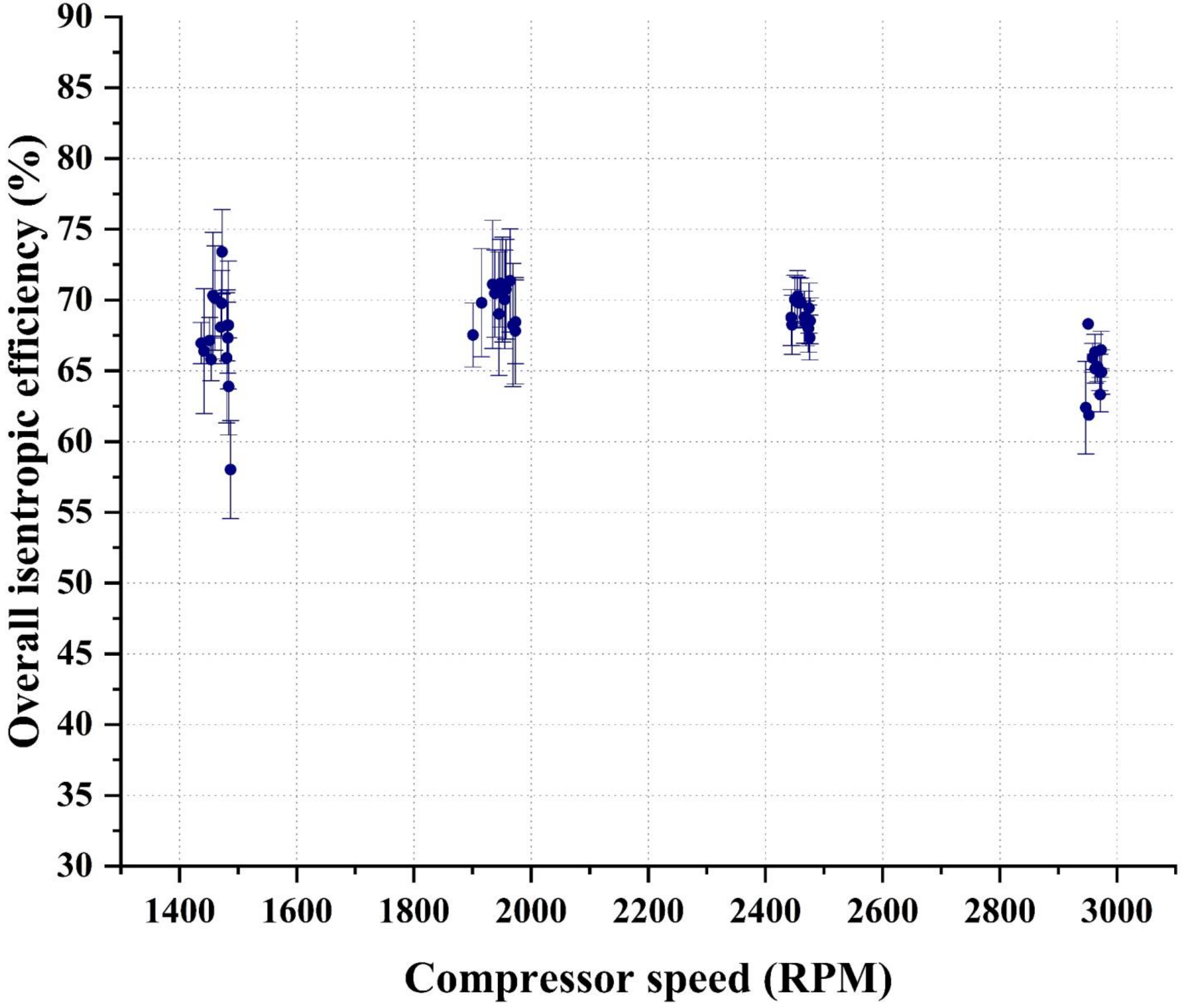
Experimental setup for reversible system (1. Scroll machine 2. Torque meter 3. Coriolis flow meter (sink side) 4. Condenser 5. Evaporator 6. Flow meter (source side) 7. Liquid receiver 8. ORC vane pump 9. Coriolis flow meter (refrigerant) 10. Expansion valve)


Reversible HTHP - ORC
Thermal balancing rig

Operating conditions

	HTHP	ORC
Source inlet temperature (°C)	40 - 85	65 - 90
Sink outlet temperature (°C)	55 - 105	10
Evaporator thermal load (kW)	2.7 – 8.53	5.78 – 17.5
Condenser thermal load (kW)	3 - 8.82	5.69 – 16.9
Mass flow rate (kg/s)	0.0186 – 0.056	0.024 – 0.069

Compressor performance (HTHP mode)



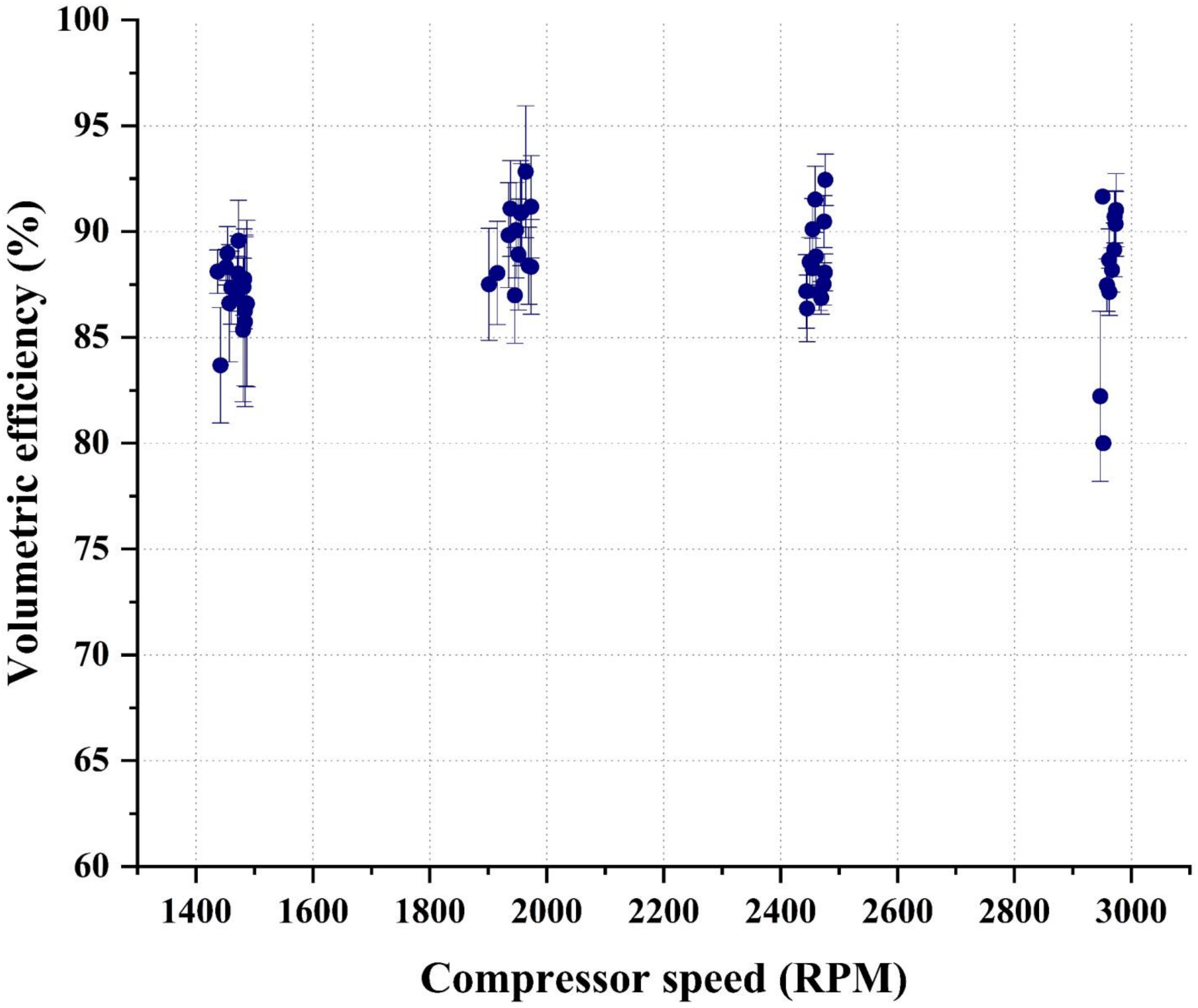
- **Overall isentropic efficiency** :

$$\eta_{is,overall} = \frac{\dot{m}_r\left(h_{dis,is} - h_{su}\right)}{\dot{W}_{mech}}$$

- **Highest isentropic efficiency : 73.4% at a pressure ratio of 2.2 (T_{source}: 60 °C, N_{cp}: 1473 RPM).**

- **Better efficiency values in 1500 – 2000 RPM range.**

Compressor performance (HTHP mode)



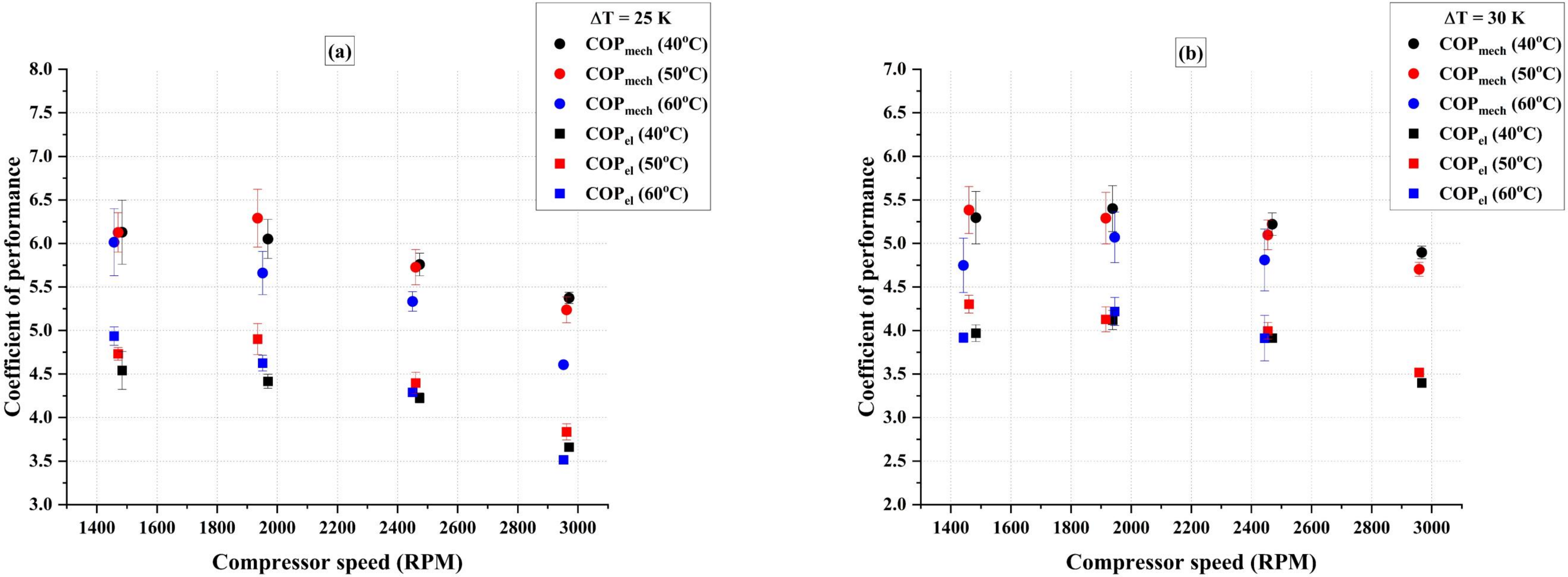
- **Volumetric efficiency**

$$\eta_{is,vol} = \frac{\dot{m}_r \nu_{su}}{(\dot{V}_s N_{cp}/60)}$$

- **Higher volumetric efficiencies were observed in the 2000 – 2500 RPM range**

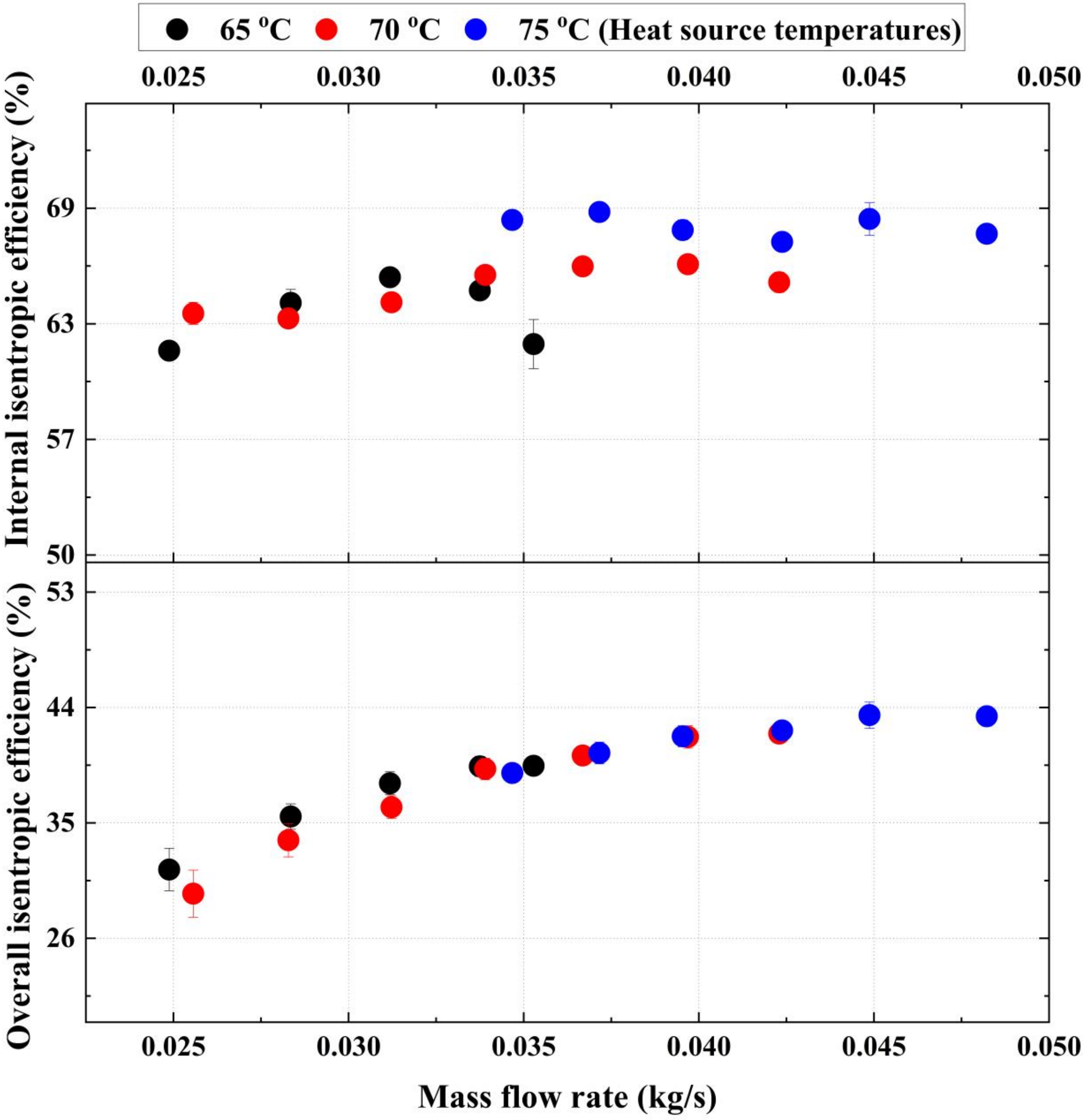
- **Highest volumetric efficiency (93%) reported at a pressure ratio of 2.17 and heat source temperature of 60 °C (N_{cp}: 1963 RPM).**

System performance (HTHP mode)



- At **40** and **50 °C** source temperatures and ΔT_{lift} of **35 K**, COP_{mech} were **4.67** (ΔT_{lift}: 34.4 K, N_{cp}: 1481 RPM) and **4.68** (ΔT_{lift}: 33.4 K, N_{cp}: 1901 RPM) respectively.
- At 60 °C (T_{source}), maximum achieved temperature lift was **32.2 K** (N_{cp}: 1442) with a COP_{mech} of **4.75**.
- Better COP values were obtained during the compressor speed range of **1500 – 2000 RPM**.

Expander performance (ORC mode)



- **Overall isentropic efficiency**

$$\eta_{exp,is,overall} = \frac{\dot{W}_{mech}}{\dot{m}_r\left(h_{su} - h_{dis,is}\right)}$$

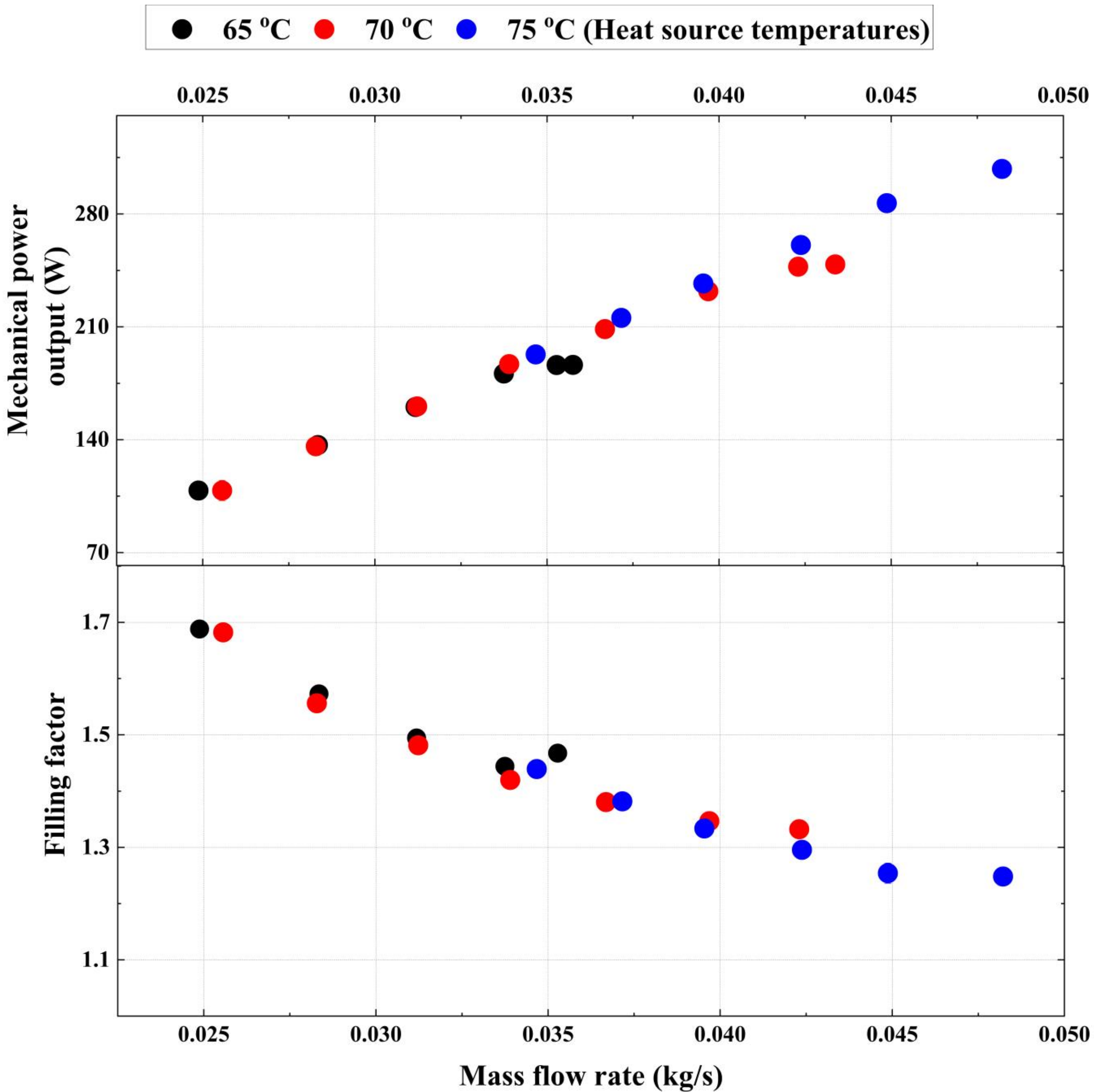
- **Internal isentropic efficiency**

$$\eta_{exp,is,int} = \frac{\left(h_{su} - h_{dis}\right)}{\left(h_{su} - h_{dis,is}\right)}$$

- Maximum overall isentropic efficiency of **43 %** was obtained at a source temperature of **75 °C**.

- The highest value for internal isentropic efficiency was found to be **69 %**.

Expander performance (ORC mode)



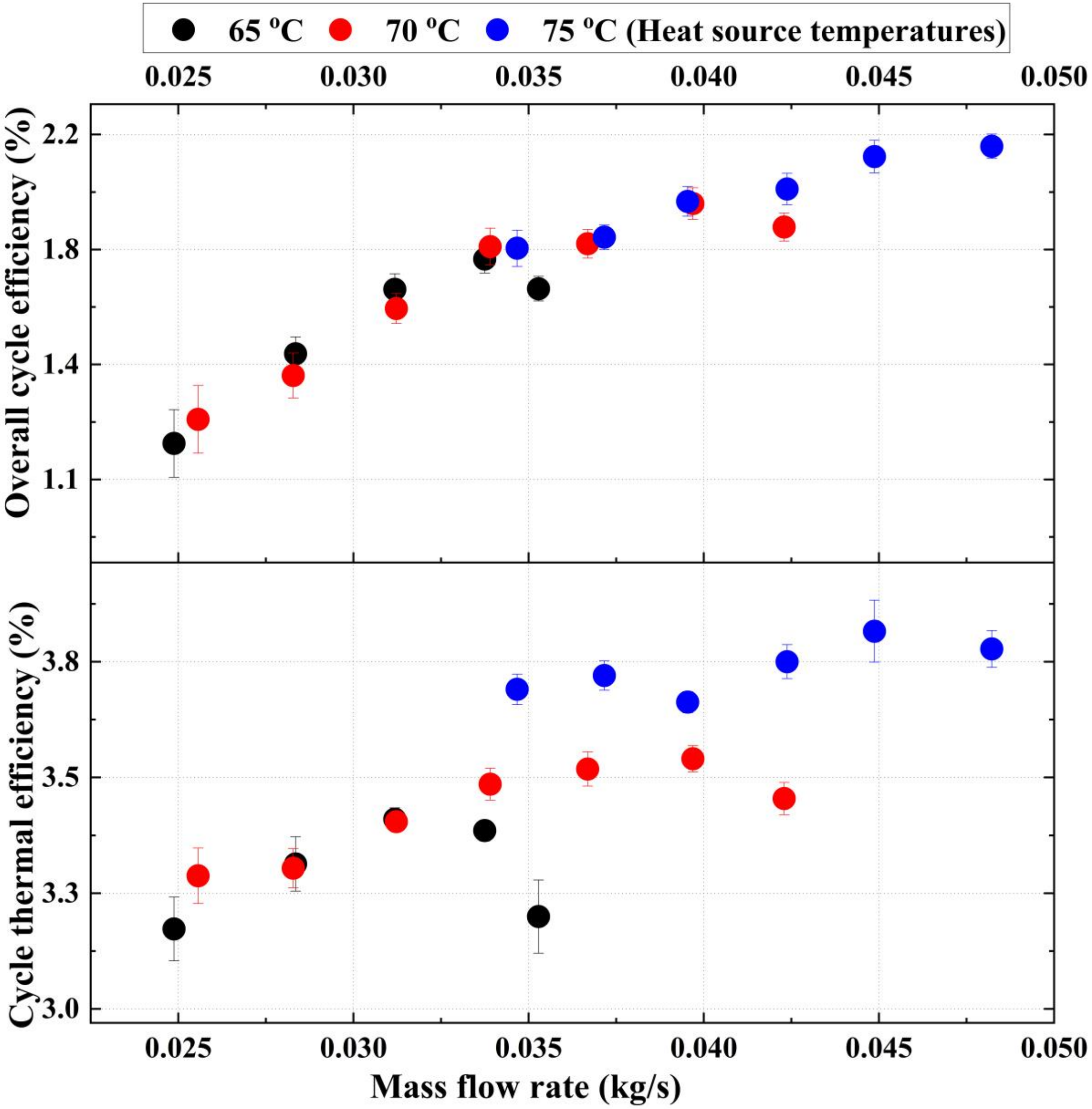
- **Filling factor**

$$\phi_{ff} = \frac{\dot{m}_r v_{su}}{(\dot{V}_s N_{cp}/(60 * r_v))}$$

- Higher filling factor values up to **1.69** at T_{source} = **65 °C** were observed at lower mass flow rates indicating higher internal leakages in the scroll expander

- The gross mechanical power generated by the expander increased with mass flow rate and source temperature and reached a maximum of **307 W** (T_{source}: **75 °C**).

System performance (ORC mode)



- **Overall cycle efficiency**

$$\eta_{orc,overall} = \frac{\dot{W}_{mech} - \dot{W}_{pp}}{\dot{Q}_{ev}}$$

- **Cycle thermal efficiency**

$$\eta_{orc,thermal} = \frac{\dot{W}_{therm} - \dot{W}_{pp}}{\dot{Q}_{ev}}$$

- At a source temperature of **75 °C**, maximum thermal and overall cycle efficiencies of **3.9%** and **2.1%**, respectively, were achieved. (Pressure ratio 2.1)

Conclusion

HTHP mode

- Maximum compressor isentropic efficiency of **73.4%**
- Higher volumetric efficiencies at lower pressure ratio.
- COP_{el} lies in **3.2 – 6.8** range for temperature lift in 15 –35 K

ORC mode

- Cycle thermal efficiency reached a maximum of **3.9%** overall system efficiency of **2.1%**
- Maximum net power output of **295W (T_{source}: 75 ^{o}C)**
- Maximum expander isentropic efficiency of **43%**

Questions?