Comparison of micro gas turbine heat recovery systems using ORC and trans-critical CO_2 cycle focusing on off-design performance

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- **System modeling**
- **Results**
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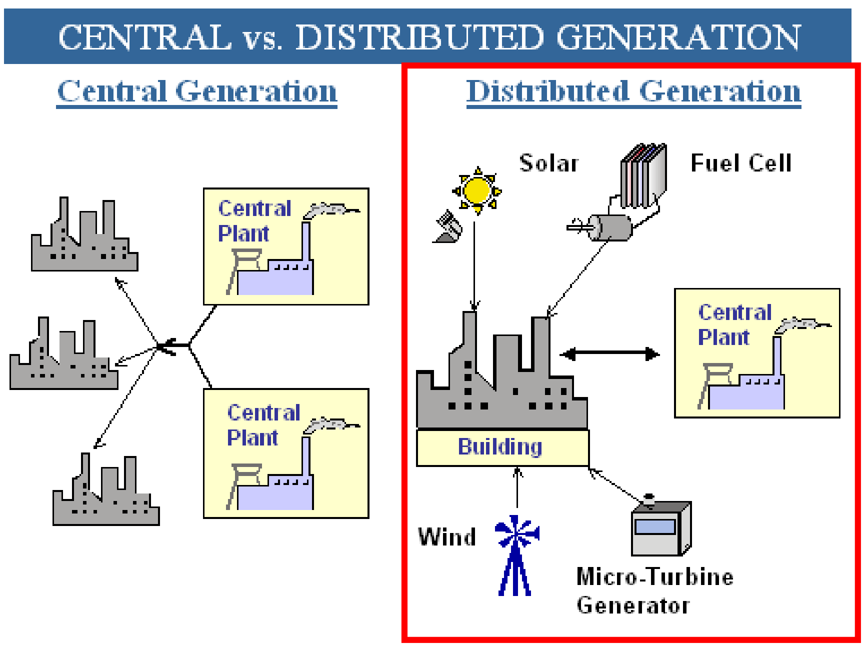
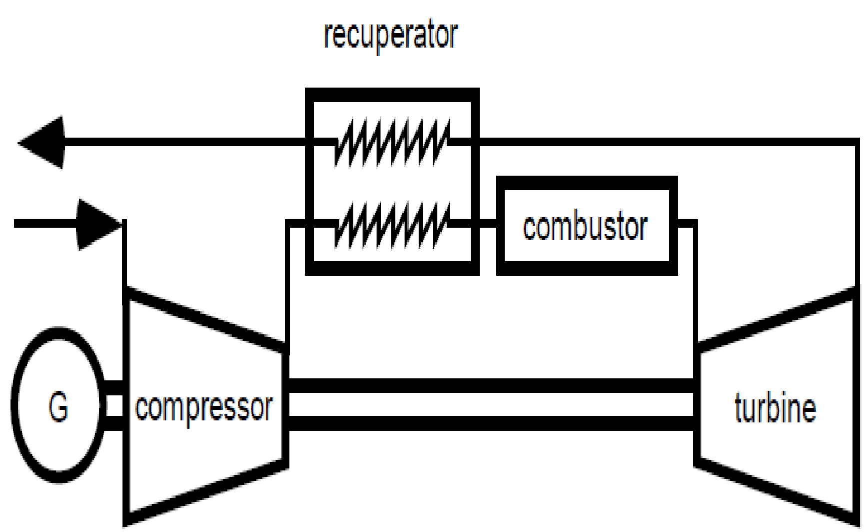
What is a micro gas turbine ?

- Small gas turbine (<300kW)
- Distributed energy resources
- Suitable for combined heat & power (CHP)

✓ Core components
- single-stage compressor
- single-stage turbine
- combustor
- recuperator
- generator





Introduction

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MGT exhaust gas heat recovery

Component	Parameter	Value
Compressor	Pressure ratio [-]	3.6
	Efficiency [%]	79.0
Turbine	Inlet temperature [°C]	828.1
	Efficiency [%]	84.0
Recuperator	Gas outlet temperature [°C]	276.7
	Gas outlet mass flow [kg/s]	0.31
Performance	System power [kW]	28.0
	Efficiency [%]	24.0

▲ Performance of Capstone C30

▲ Capstone C30

- **Capstone C30**
  - **The engine exhausts high temperature gas (276.7°C)**
  - **Generally, the exhaust gas is used to satisfy the heat demand but wasted when there is no heat demand**

➡ **Possibility : supplementary power by adding a bottoming cycle**

Introduction

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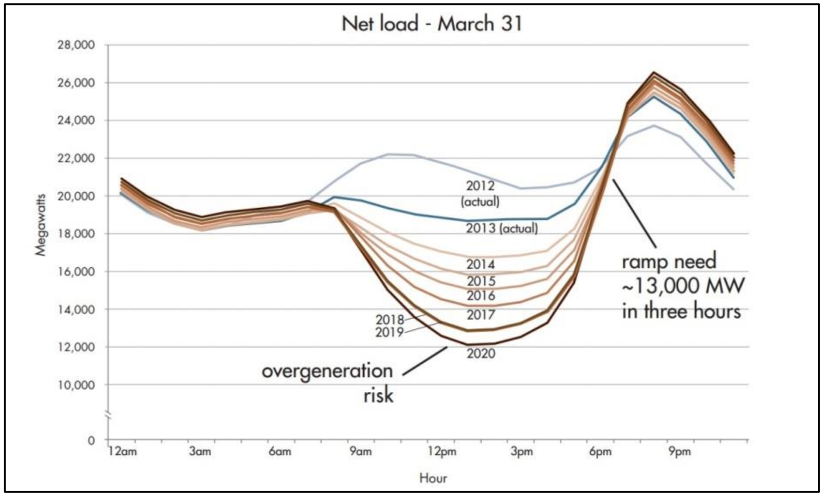
❖ Importance of off-design performance

- **Increasing penetration of renewable energy**



▲ Net load(normal load-renewable power generation) at California

- **Impact of renewable energy sources**
  - **Strong imbalance between demand &supply**
  - **The other generators in the grid system including the MGT will operate at partial loads during a lot of their operating time.**

➡ **Off-design performance of MGT/bottoming cycle package is Important**

Previous works

- **Comparison between ORC and tCO_2 is focused on low temperature applications**
  - **Low grade heat recovery (<160°C)**

    Li et al. "Thermodynamic analysis and comparison between CO2 transcritical power cycles and R245fa organic Rankine cycles for low grade heat to power energy conversion", Applied Thermal Engineering, August 2016
  - **Waste heat recovery from sCO_2 cycle (~120°C)**

    Wang et al. "Exergoeconomic analysis of utilizing the transcritical CO_2 cycle and the ORC for a recompression supercritical CO_2 cycle waste heat recovery: A comparative study", Applied Energy, May 2016
- **Most of the works are interested in design performance only.**
- **Selection of working fluid for High temperature heat source**
  - **For recuperated GT exhaust gas heat (>350°C)→ (Toluene)**

    Cao et al. "Optimum design and thermodynamic analysis of a gas turbine and ORC combined cycle with recuperators",Energy Conversion and Management, May 2016
  - **For externally fired GT exhaust gas heat(400°C) → (Toluene)**

    Camporeale et al. "Cycle configuration analysis and techno-economic sensitivity of biomass externally fired gas turbine with Bottoming ORC" ,Energy Conversion and Management, November 2015

▲ Specifications of commercial ORC

	Manufacturer	Model name	Power output	**Working fluid**	Heat source temp.
Low temp.	Electratherm	Green machine 6500	> 110	**R245fa**	77-116
	GE	Clean energy	125	**R245fa**	121
High temp.	Turboden	TD 6 HR	600	**Silicon oil**	270
	Triogen	WB-1 170 Power	165	**Toluene**	350-530

Introduction

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Research objective

- **Comparison of ORC and Trans-critical CO_2 cycle**

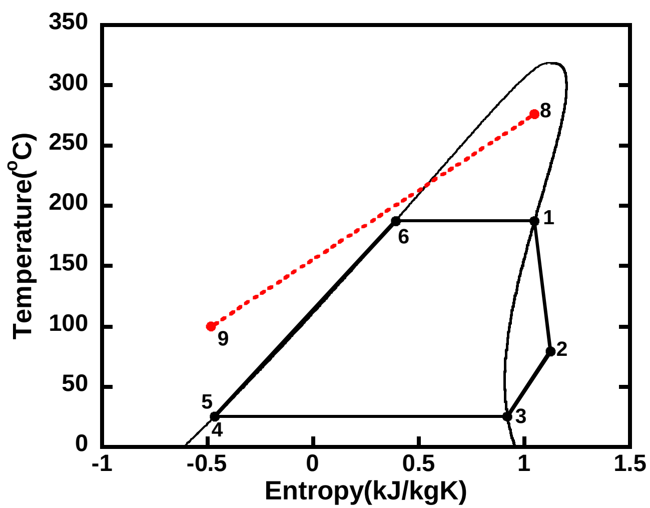
  1. **Performance at full-load condition**

  2. **Performance at part-load condition**

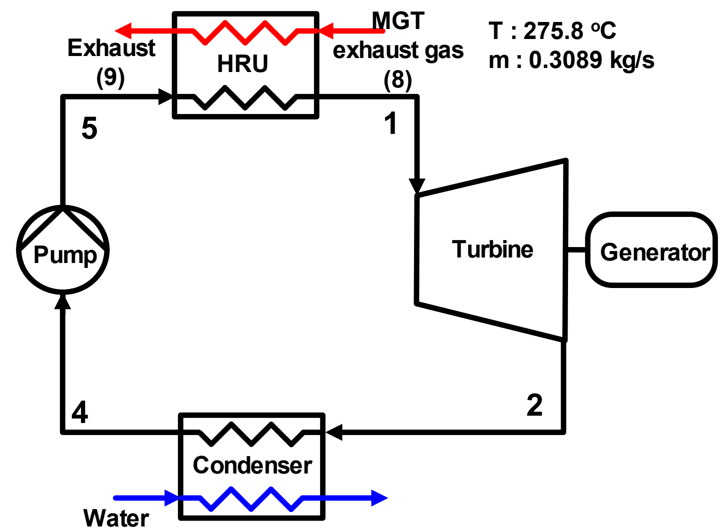
System modeling

Design Modeling

Organic Rankine Cycle



▲ T-S diagram of ORC



▲ Configuration of ORC

- Exhaust gas temperature : 100°C
- Working fluid : Toluene
- Turbine / pump efficiency : 85% / 85%
- Pinch point temperature difference in HRU : 4℃
- Condensation temperature : 25℃ (3.8 kPa)
- Turbine inlet is at saturated vapor
- Turbine inlet pressure is determined to maximize power output → 6.1bar (PR ~ 160)

System modeling

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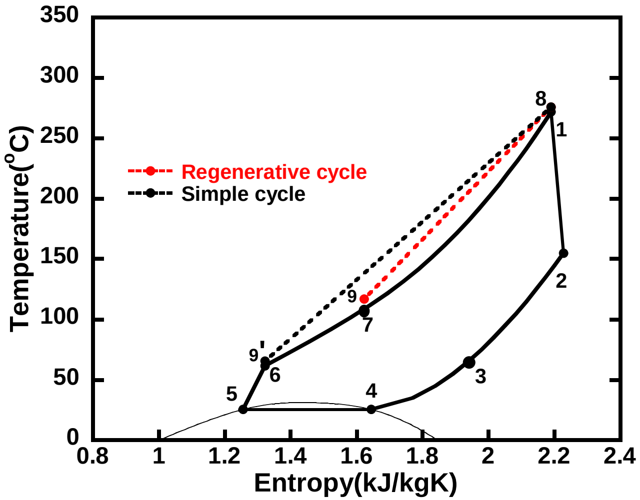
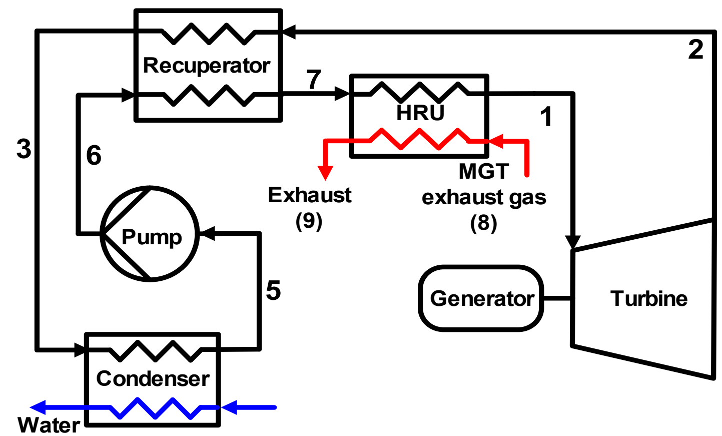
Design Modeling

Trans-critical CO_2 Cycle



▲ T-S diagram of tCO_2

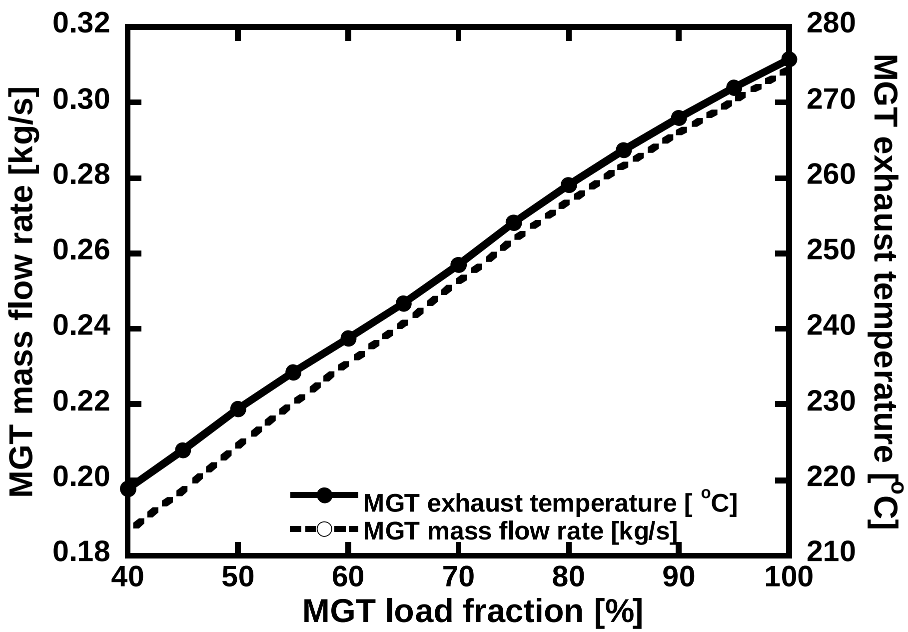


▲ Configuration of tCO_2

- Working fluid : Carbon dioxide
- Turbine / pump efficiency : 85% / 85%
- Pinch point temperature difference in HRU : 4℃
- Condensation temperature : 25℃ (6,470 kPa)
- A regenerator is added to increase mass flow of CO_2 → larger tCO_2 cycle power
- Turbine inlet pressure is determined to maximize power output → 235.3 bar (PR ~ 3.6)

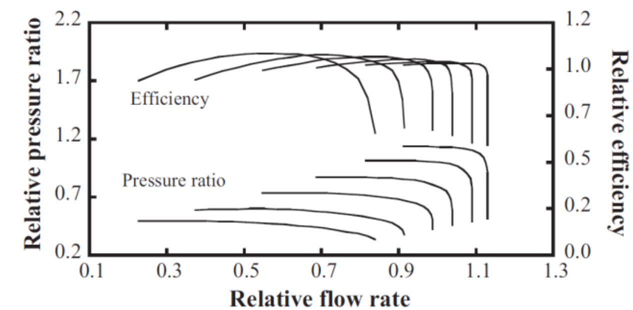
Off-design Modeling

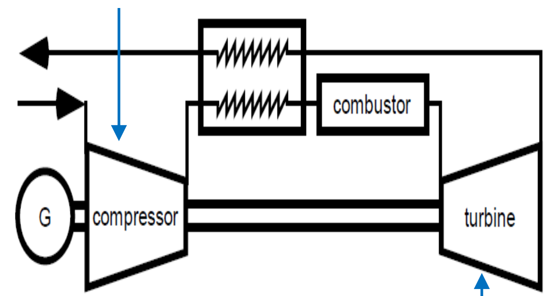
- **Part load data of MGT : exhaust gas flow and temp.**
  – C30 simulation data[1)]



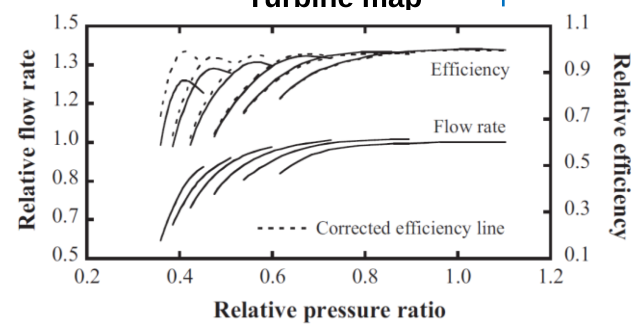
▲ Mass flow rate and exhaust temperature variation of MGT with MGT load fraction

Compressor map





Turbine map



1) Min Jae Kim, Jeong Ho Kim, Tong Seop Kim, (2016). Program development and simulation of dynamic operation of micro gas turbines, Applied Thermal Engineering, Vol. 108, 2016, pp. 122-130.

System modeling

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Off-design Modeling

Heat exchanger

- **Effectiveness-NTU method**

$$\text{Effectiveness}: \varepsilon = \frac{T_{h,i} - T_{h,o}}{T_{h,i} - T_{c,i}}$$

$$\text{Number of transfer unit}: NTU = \frac{UA}{C_{min}} = \frac{1}{C_r - 1}\ln\left(\frac{\varepsilon - 1}{\varepsilon C_r - 1}\right), \text{ where } C_r = \frac{C_{\min}}{C_{\max}}$$

- **Off-design analysis process**

Design

$$(UA)_{design}, \ \varepsilon_{design}$$

$$(UA)_{off} = (UA)_{design}\left(\frac{\dot{m}_{off}}{\dot{m}_{design}}\right)^{0.8}$$

Off-design

$$(NTU)_{off} = \frac{(UA)_{off}}{C_{min}}$$

$$\varepsilon_{off} = \frac{1 - \exp[-(NTU)_{off}(1 - C_r)]}{1 - C_r \exp[-(NTU)_{off}(1 - C_r)]}$$

- **Number of segments**
  - tCO_2 – single segment
  - ORC – two segments (economizer(preheater)/evaporator)

System modeling

Off-design Modeling

Turbine

Stodola's ellipse

$$\text{Flow coefficient} : \Phi_{design} = \frac{\dot{m}_{in,design}\sqrt{T_{in,design}}}{P_{in,design}}$$

$$\text{Stodola's constant} : Y_{design} = \frac{P_{in,design}^2 - P_{out,design}^2}{P_{in,design}^2 \Phi_{design}^2}$$

Turbine efficiency correction[2)]

$$\eta_{off} = \eta_{design} \sin\left[0.5\pi\left(\frac{\dot{m}_{in,off}}{\dot{m}_{in,design}}\frac{\rho_{in,design}}{\rho_{in,off}}\right)^{0.1}\right]$$

Off-design analysis process

Design

$$\Phi_{design},\ Y_{design}$$

$$Y_{off} = Y_{design} = const.$$

$$\Phi_{off} = \frac{\dot{m}_{in,off}\sqrt{T_{in,off}}}{P_{in,off}}$$

Off-design

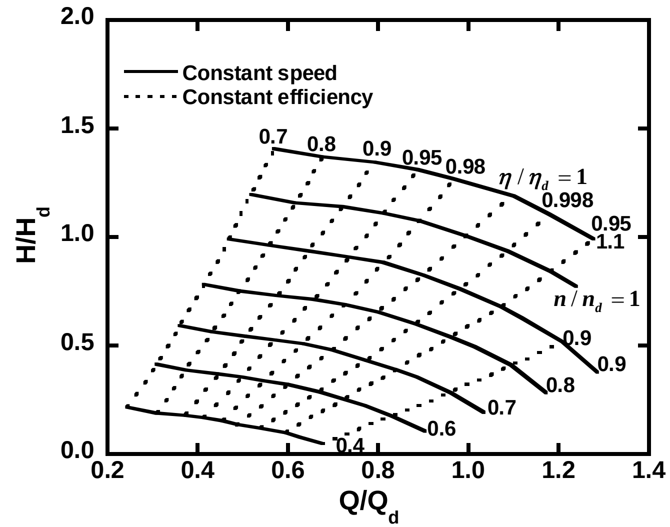
$$P_{in,off} = \sqrt{\dot{m}_{in,off}^2 T_{in,off} Y_{design} + P_{out,off}^2}$$

2) Keeley KR. A theoretical investigation of the part-load characteristics of LP steam turbine stages. CEGB memorandum RD/L/ES0817/M88. Central Electrical Generating Board, UK; 1988.

System modeling

Off-design Modeling

- Pump
  - Performance map is used

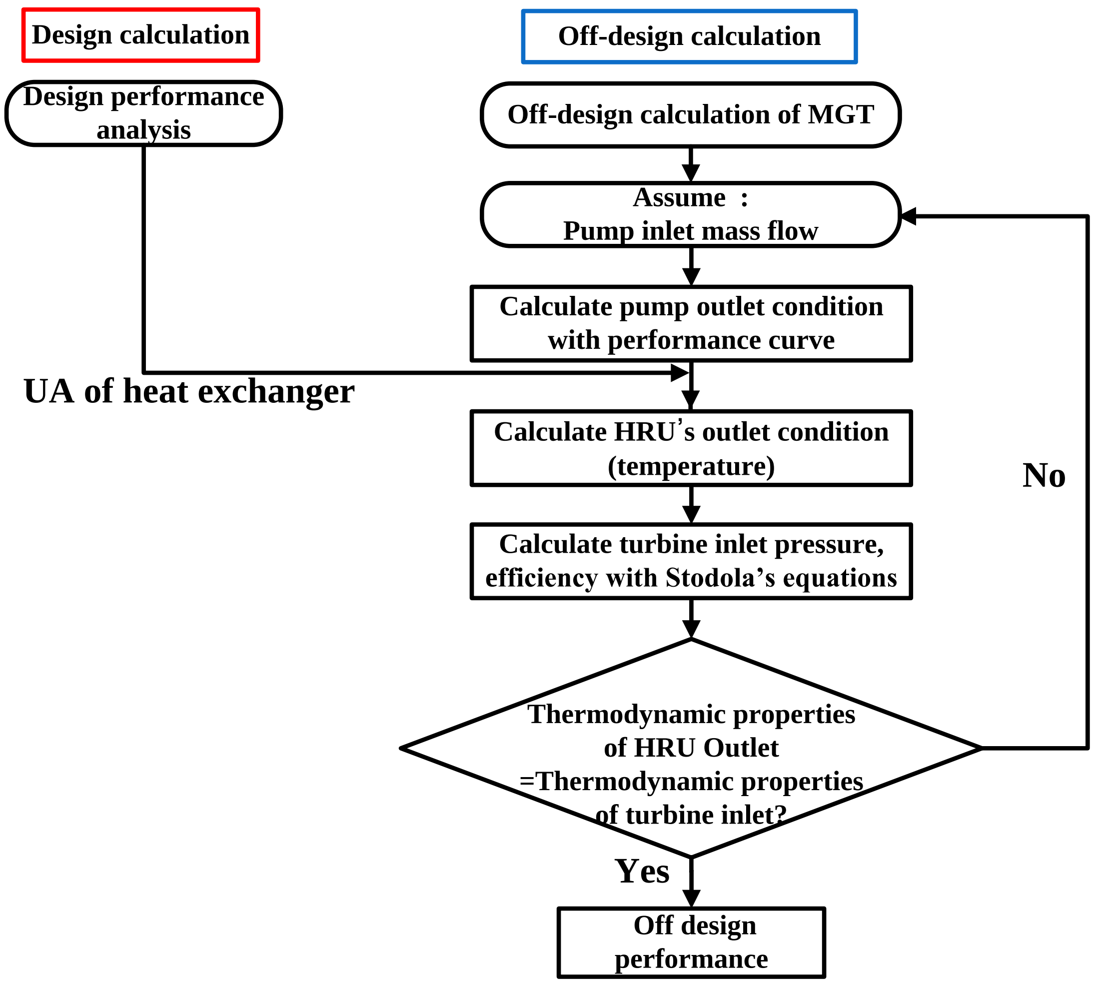


  - Simulation of variable speed operation
    - tCO_2
      - ✓ Calculation process for each MGT part load condition.
        - For each rotational speed, a single point that satisfies the matching among pump, HRU and turbine is determined.
        - The calculation is repeated for every speed, and a maximum power points is decided → the working point for the specific MGT power.
    - ORC
      - ✓ For each MGT part load condition
        - A single rotational speed exists because turbine inlet condition is fixed (saturated vapor)

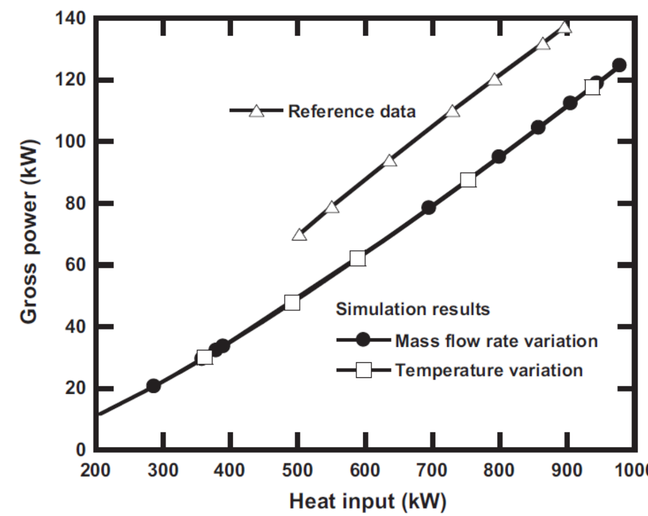
System modeling

Performance analysis

Simulation process



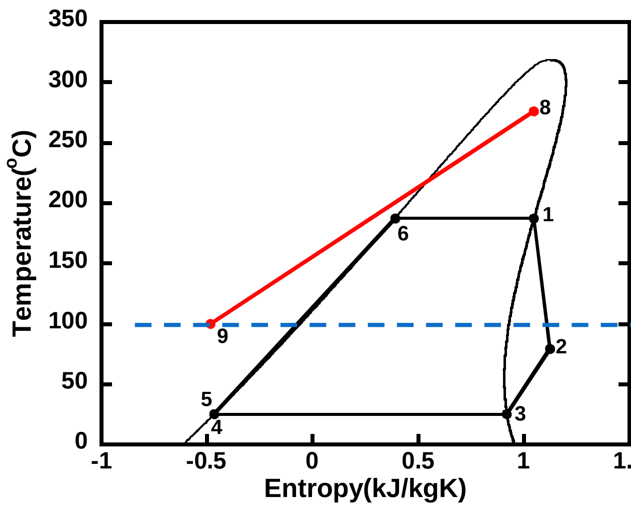
- **Modelling validation**



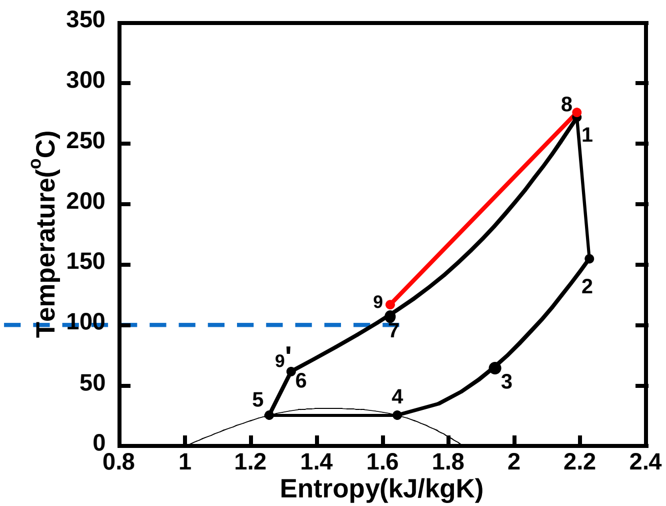
In Seop Kim, Tong Seop Kim, Jong Jun Lee, (2017). Off-design performance analysis of organic Rankine cycle using real operation data from a heat source plant, Energy Conversion and Management, Vol. 133, Issue 1, Feb. 2017, pp. 284-29.

Results

Performance at the design point



▲ T-S diagram of ORC



▲ T-S diagram of tCO_2 cycle

	ORC	tCO_2
Turbine inlet temperature [°C]	187.4	271.8
Turbine inlet pressure [MPa]	0.61	23.53
Cycle power output [kW]	12.85	12.18
Net cycle power output [kW]	40.85	40.18
Net cycle efficiency [%]	34.87	34.30

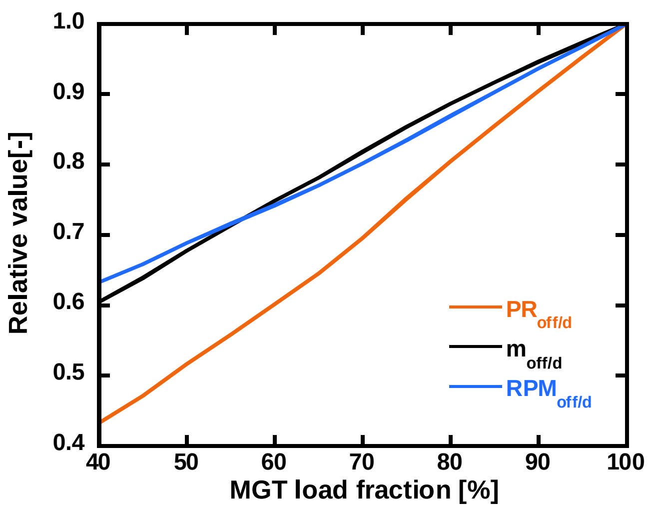
- MGT exhaust heat ~ 95kW
- Bottoming cycle efficiency ~13%
- Bottoming cycles add ~45% power

- **ORC recovers more heat at the HRU, and produces slightly larger power**

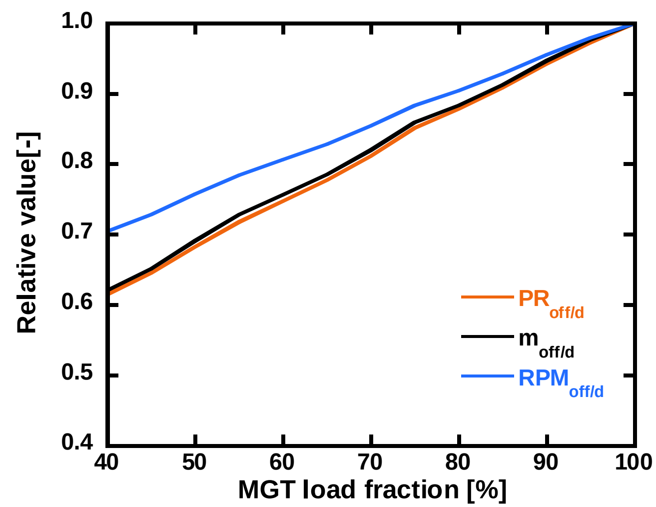
Performance at the off-design points

✓ General tendency

- **MGT load fraction ⬇**
  - → MGT exhaust gas temp. & mass flow ⬇
  - → Mass flow rate of the bottoming cycle ⬇
  - → Turbine inlet pressure ⬇
  - → Bottoming cycle power ⬇



▲ Variation of operating parameters of ORC with MGT load fraction



▲ Variation of operating parameters of tCO_2 with MGT load fraction

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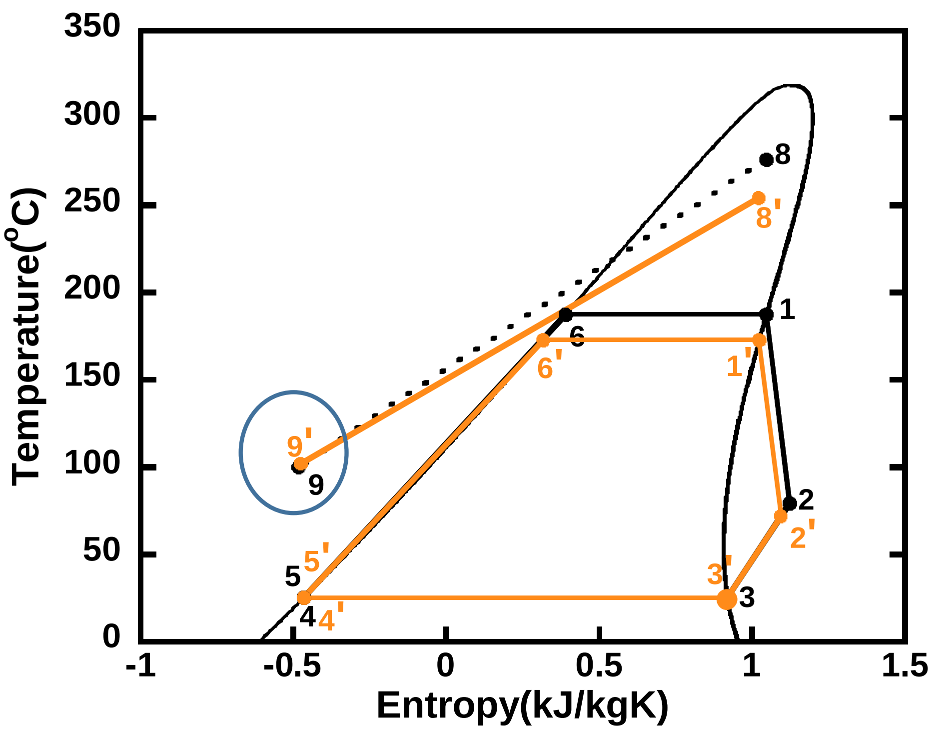
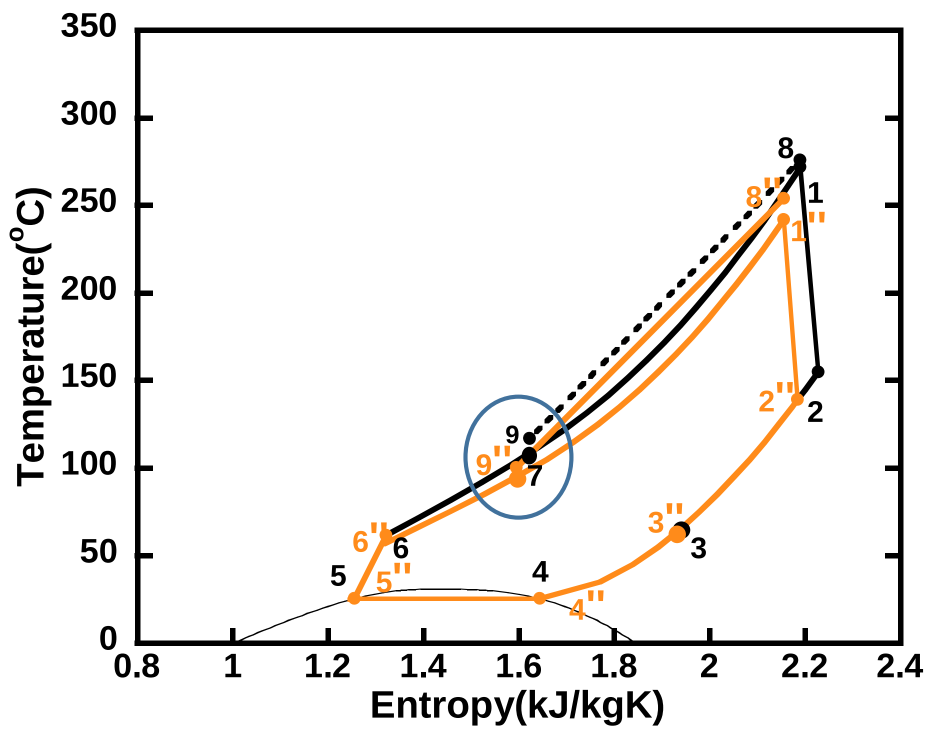
Performance at the off-design points

✓ Comparison of operating point changes



▲ T-S diagram of ORC at 75% MGT load

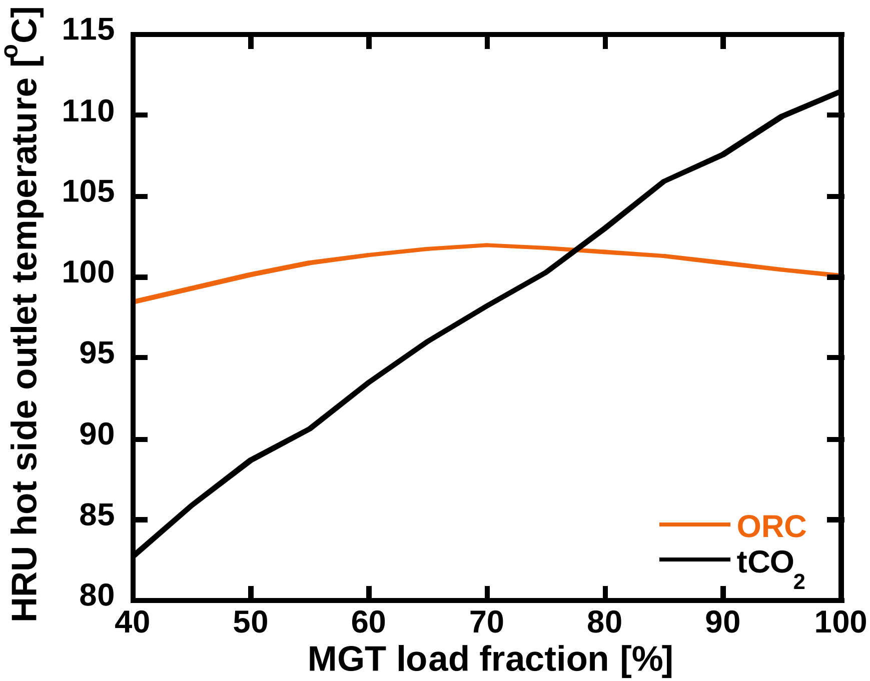


▲ T-S diagram of tCO_2 cycle at 75% MGT load

- tCO2 shows a larger drop in the gas exit temperature (T9) at the HRU

Performance at the off-design points

✓ Heat recovery performance



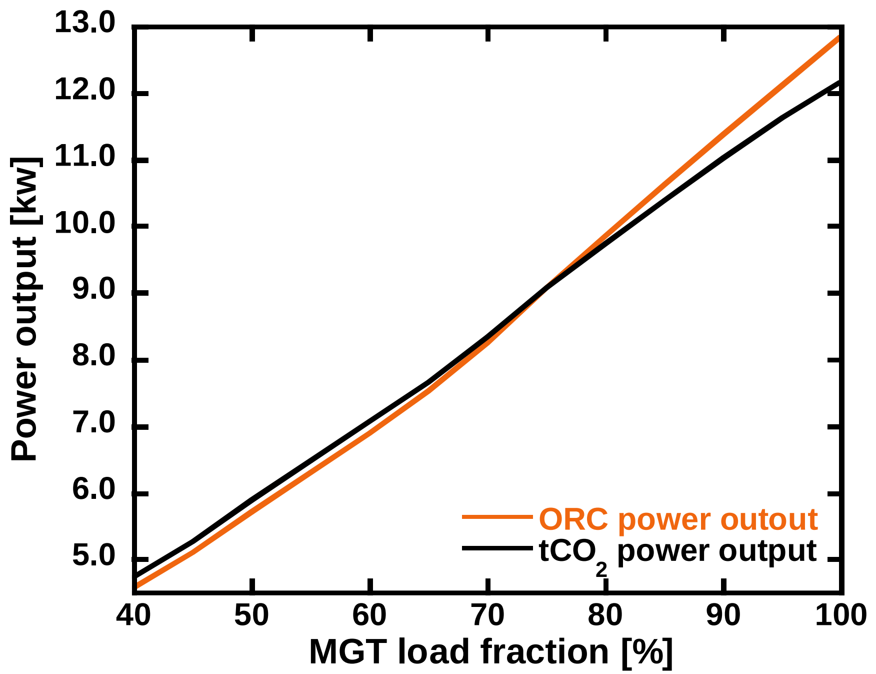
▲ HRU hot side outlet temperature

- **HRU exit gas temperature is reversed about at 75% MGT power**
  → HRU heat recovery becomes larger for the tCO_2 cycle

Results

Performance at the off-design points

✓ Bottoming cycle power



▲ Variation of power output of bottoming cycles with MGT load fraction

- **Power variation with MGT power is steeper for ORC**
- **Power production reversed about at 75% MGT power**

Conclusion

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- **Design performance of an ORC using toluene and a recuperated tCO2 was compared: ORC produces slightly larger power (5.5%).**

- **An operation simulation tool has been set up using off-design models for components (pump, HRU and turbine), and operation strategy was provided.**

- **The reduction rate of the heat recovery performance of the ORC is larger in comparison to tCO2; tCO2 produces more power in the MGT power range less than 75%.**

- **A suitable system (ORC or tCO2) should be selected considering the operating environment (near full load or mostly at part loads).**

Thank you.