111年度 廢熱與廢冷回收技術應用研討會

有機朗肯迴路：一種負碳方式應用於低溫熱能之發電系統

Organic Rankine cycle: The challenge of a negative-carbon approach in power generation from low-temperature waste heat

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Warnings from global warming

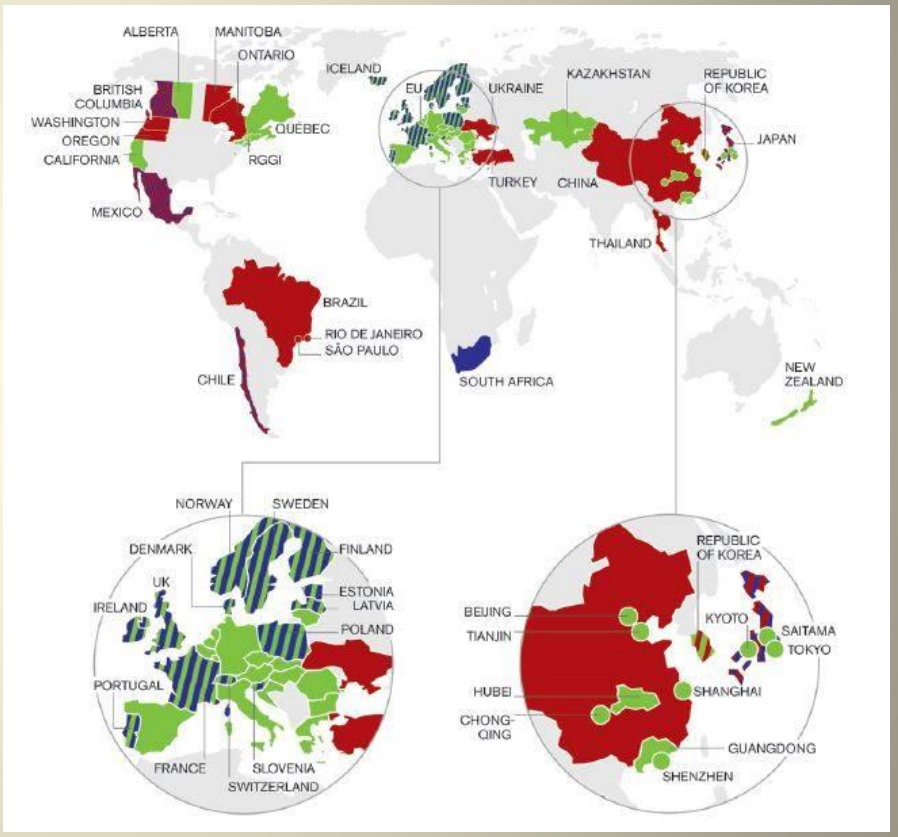
- Svalbard Global Seed Vault in Norway-- Arctic stronghold of world's seeds flooded after permafrost melts.

- Fast-growing moss is turning Antarctica green!

- BUT, *Donald Trump* proclaimed withdrew the US from the *Paris climate accord*!!!!

Carbon tax & emission trading

Source: D.G. Victor and
D. Cullenward, 2007



Source: Carbon pricing watching, 2015, Ecofys

Think about This!

- Suppose the engine efficiency is around 35%; it means 65% of waste heat is dissipated to ambient.
- Assume ORC recovery efficiency is 15%.

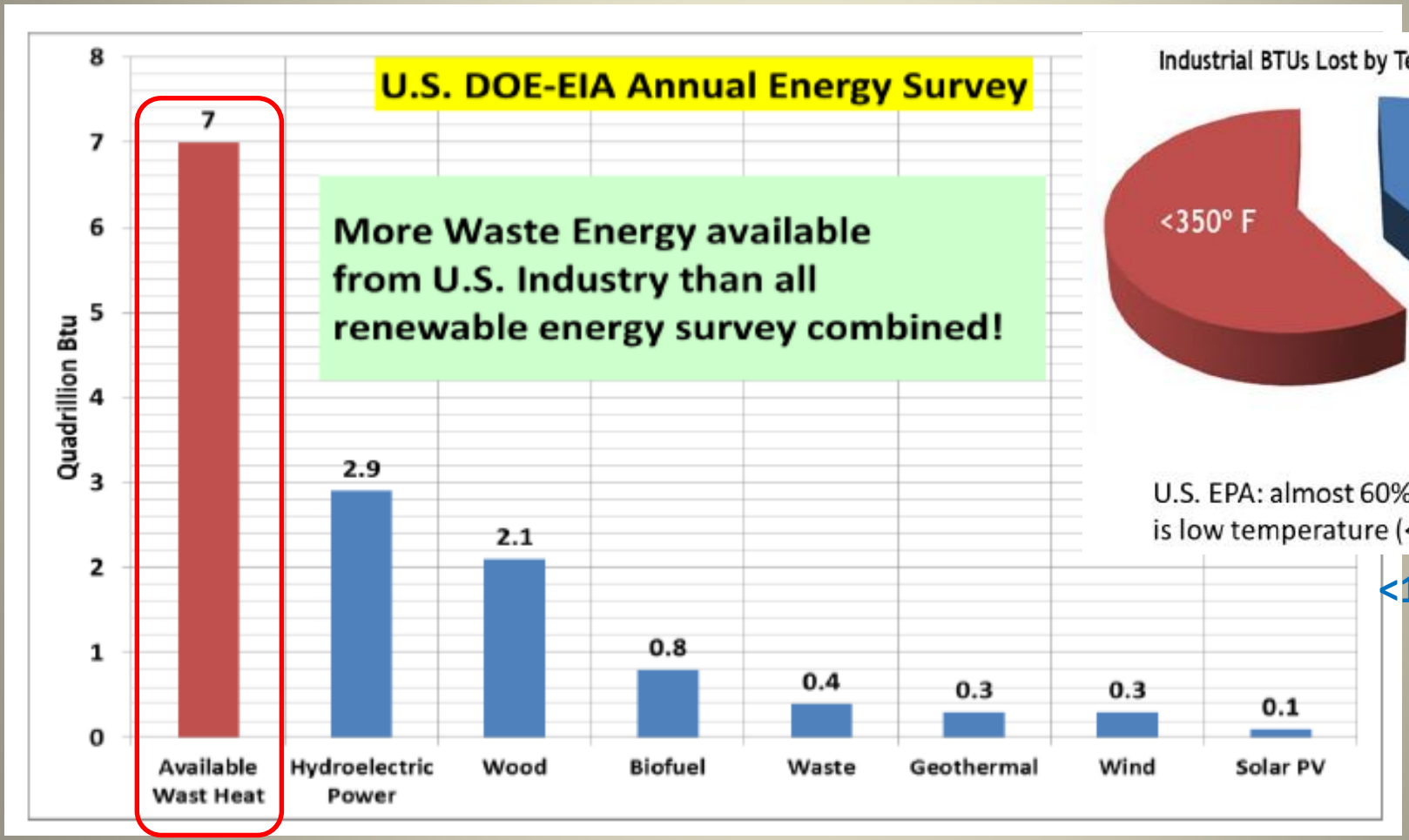
65% of waste heat x 15% of ORC efficiency ≈ extra 10% of power.
That is, it can reduce about 1/3 of fuel consumption!

New York

Taipei

➔ 負碳方式之發電系統

Huge amount of industrial waste heat



1 Quadrillion Btu ≈ 1 x 10^{15} kJ

Background in Organic Rankine Cycle

Power Production from
Low Temperature Heat

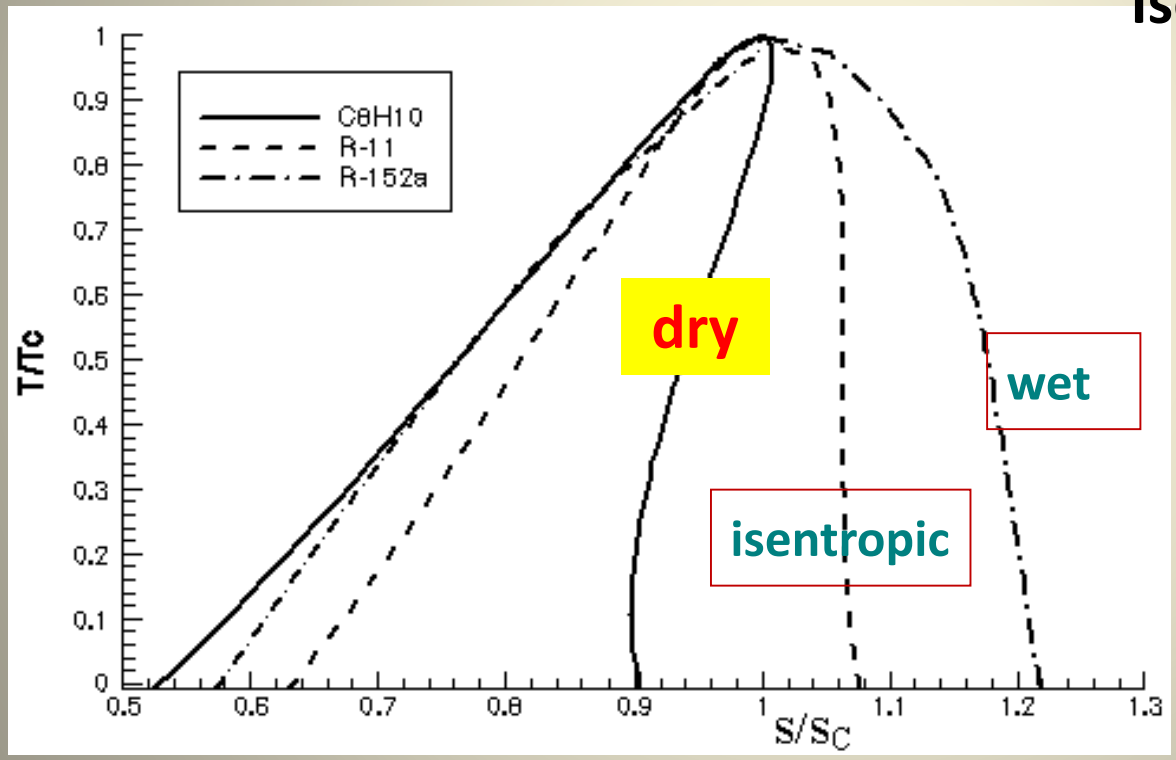
Initiator of the idea

Saturated curves of working fluid

Dry: $\left(\frac{ds}{dT}\right)_{x=1.0} > 0$

Isentropic: $\left(\frac{ds}{dT}\right)_{x=1.0} \cong 0$

Wet: $\left(\frac{ds}{dT}\right)_{x=1.0} < 0$

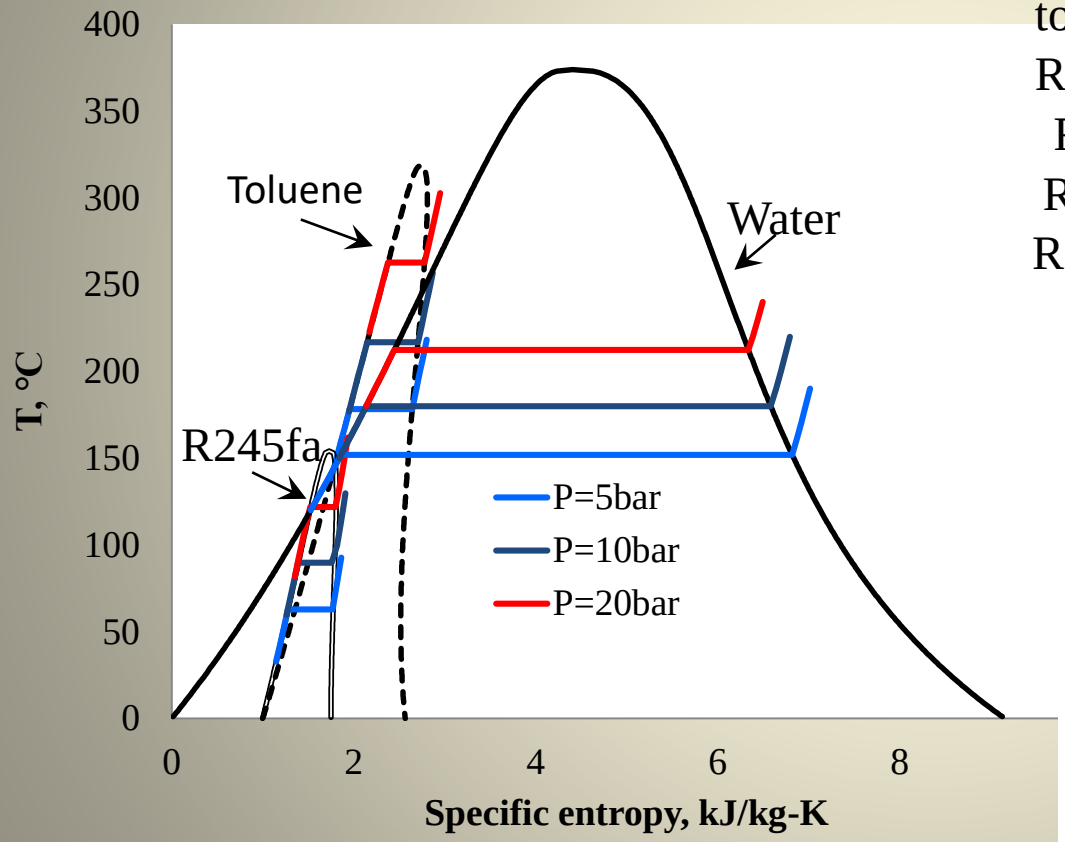


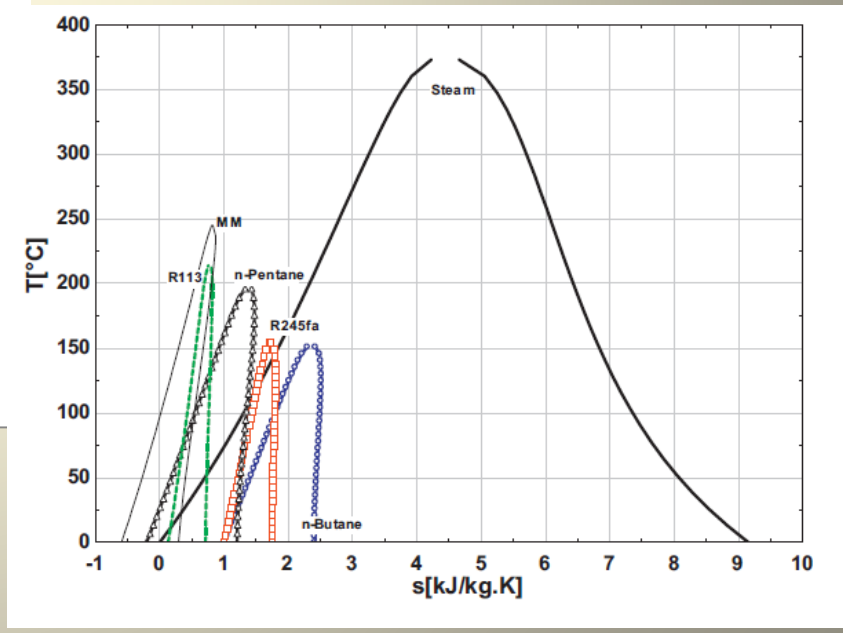
So many choice in fluids – Not just water, air, A/C refrigerants!

ENERGY, Vol. 22, No. 7, 1997, pp. 661-667.

Saturated curve: water vs. organic fluids

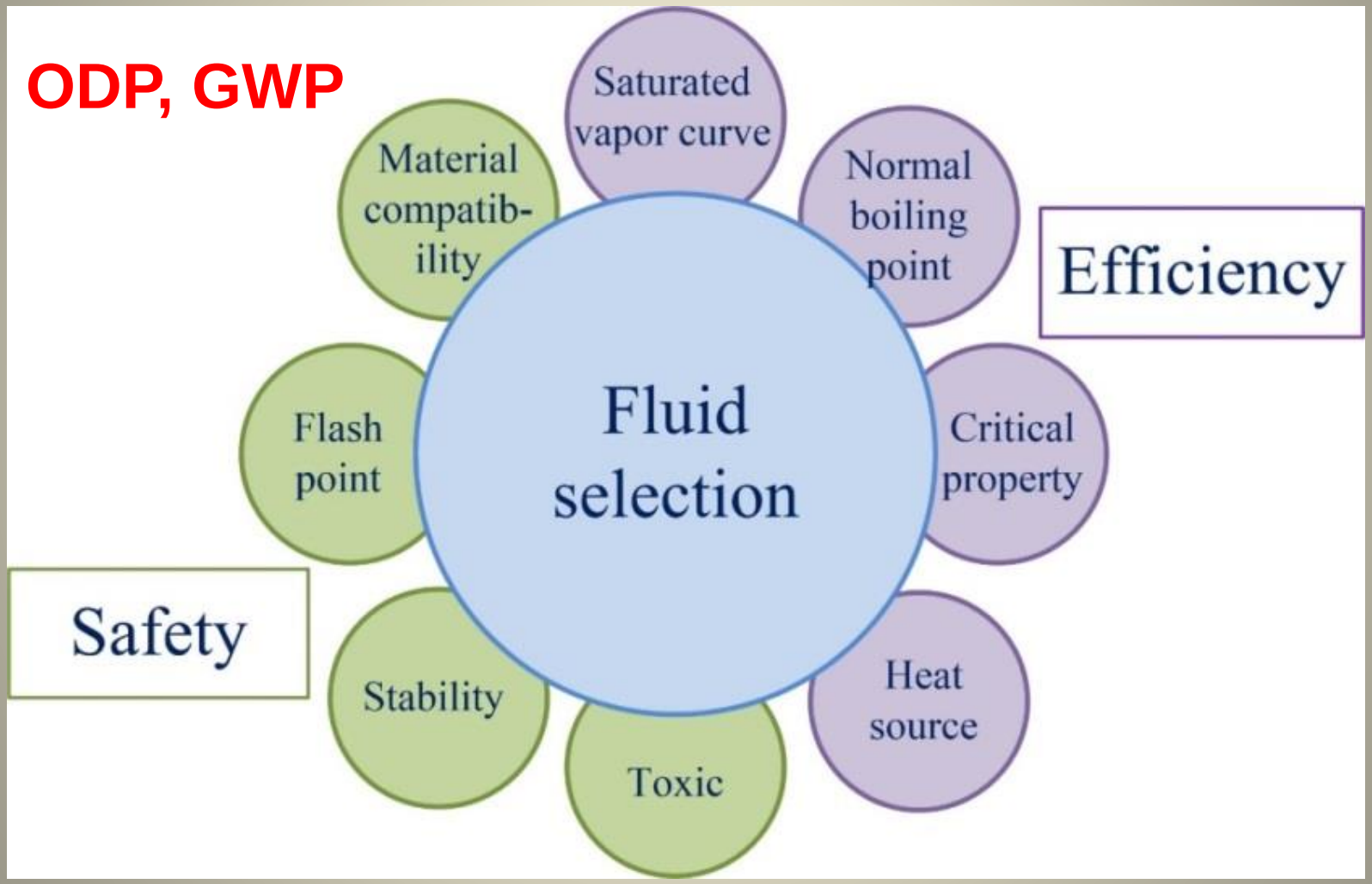
Fluid	Pressure	Saturation temp.
water	10 bar	179.9 ℃
toluene		216.8 ℃
R245fa		89.7 ℃
R123		111.2 ℃
R134a		39.4 ℃
R227ea		53.4 ℃





Organic Fluids vs. Water

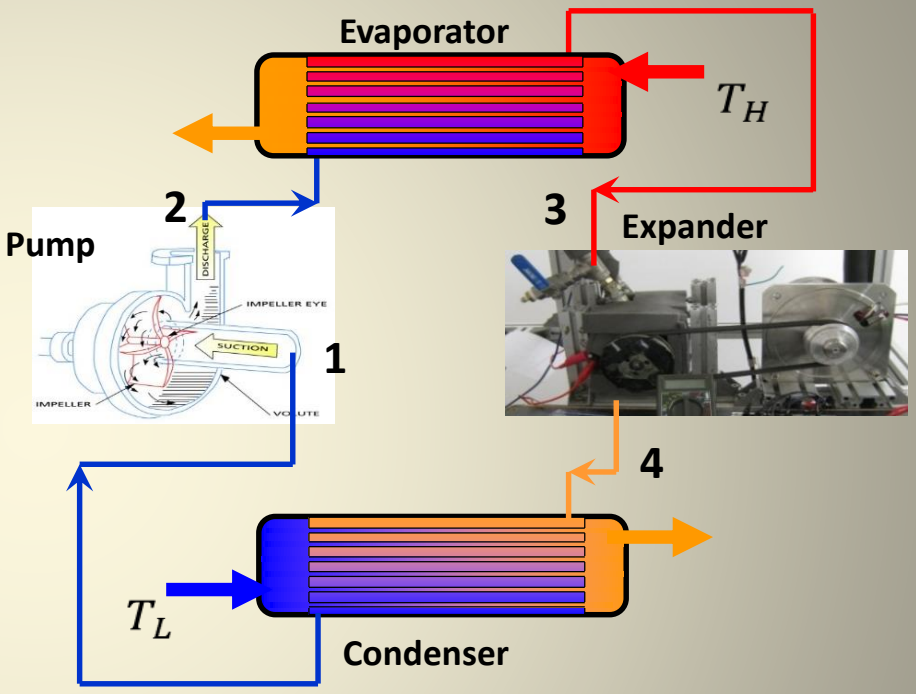
Concerns in the use of fluid



Other concerns: ecology, economics, etc.

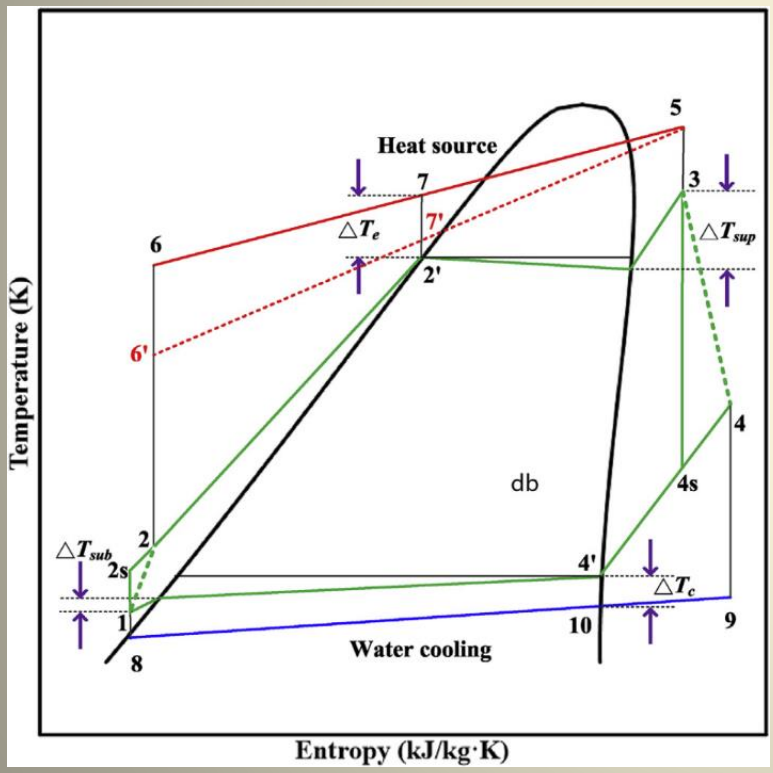
Organic Rankine Cycle (ORC)

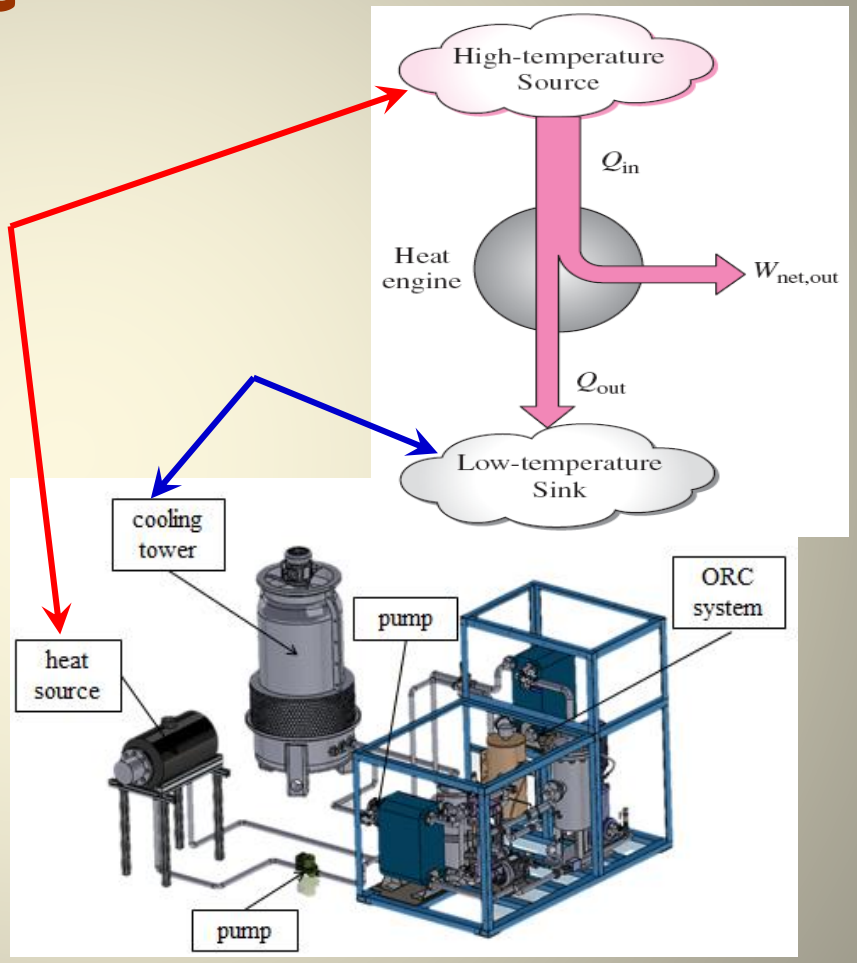
- ORCs are primarily used for **low-temperature heat sources recovery,** such as OTEC, geothermal or waste heat, etc.



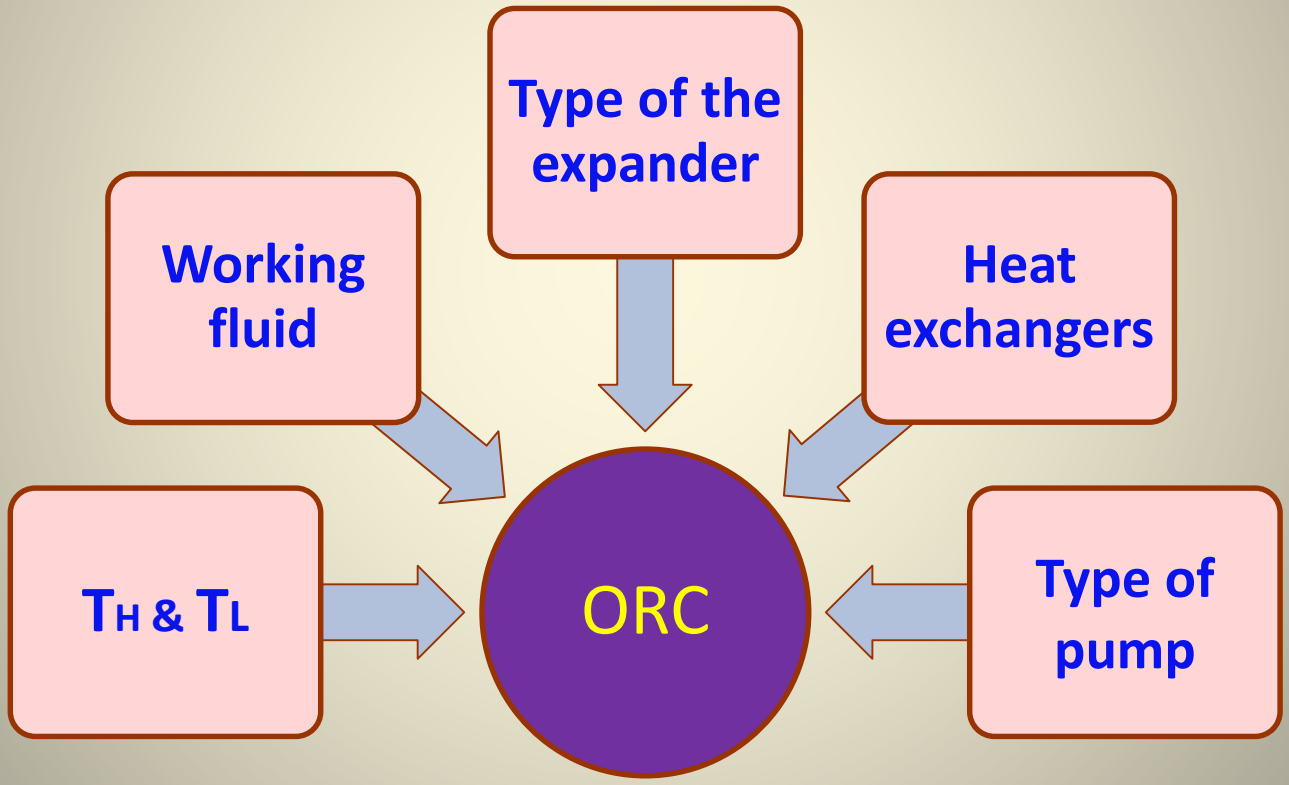
- ORCs use the **fluids** that can be selected to **best match wide temperature spectrum of heat source and heat sink.**

Generic T-s diagram vs. ORC schematic

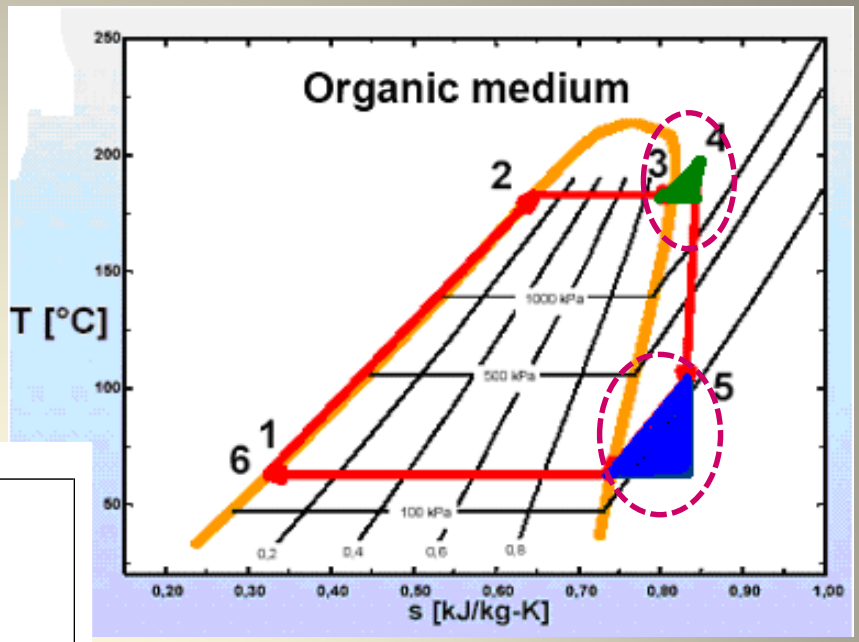


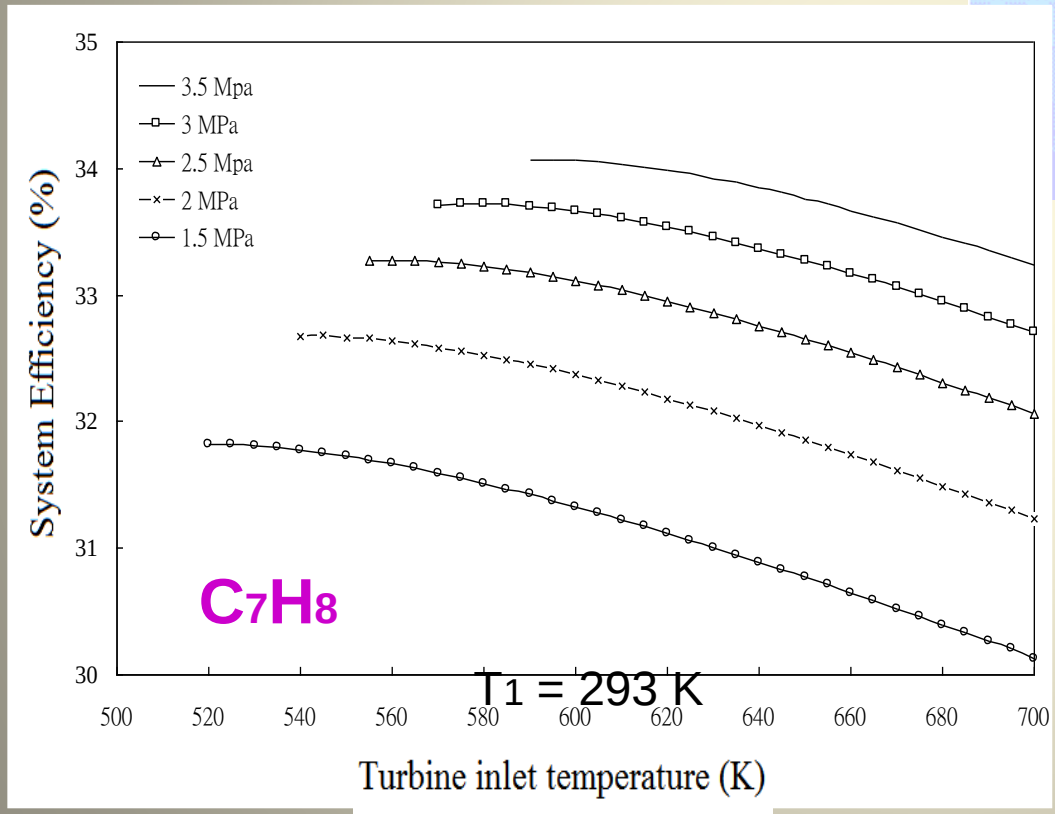


What are related with ORC?



Theoretical effect of superheating to ORC using dry fluids





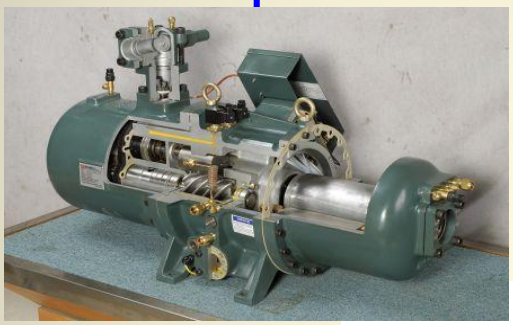
- Greater turbine T_{in} → greater superheating → less system efficiency!
- No superheat needed because no condensation during expansion

Energy Conversion and Management, Vol. 42, 2001, pp. 539-553.

Types of expander

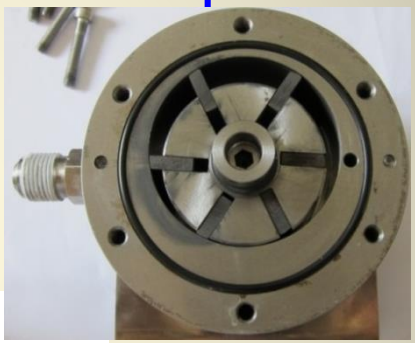
- Expander
  - Dynamic
    - Radial inflow turbine

  - Positive-Displacement
    - Twin screw

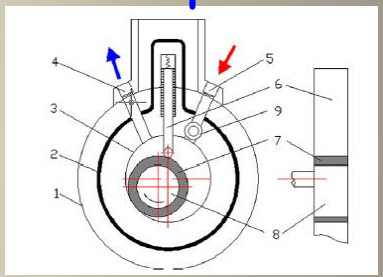


    - Single screw

    - Multi-vane



    - Rolling-piston



    - Scroll

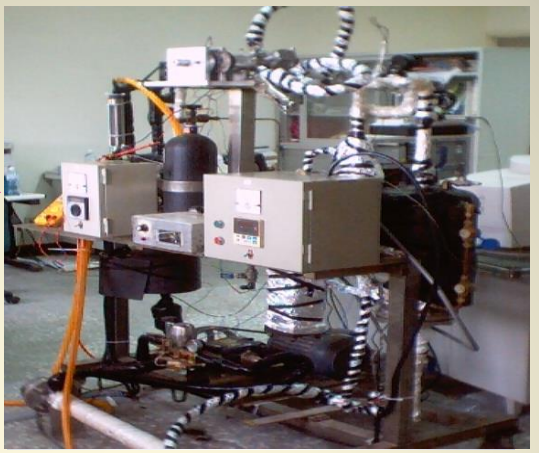
    - Piston

Power	Suitable expander
< 2kWe	Multi-vane
1-10kWe	Scroll, Multi-vane
10-100kWe	Screw, Turbine
>100kWe	Turbine

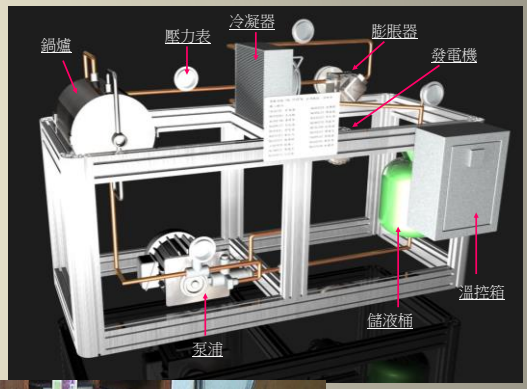
Source: Qiu et al., 2011

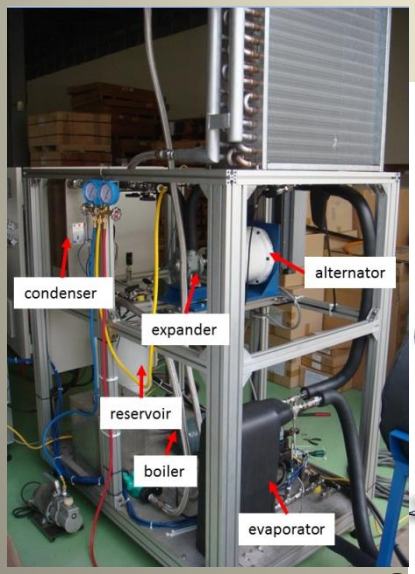
Developed ORCs in our laboratory

Gen. 1

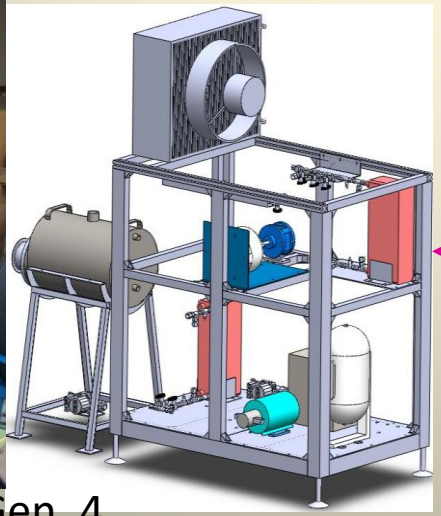


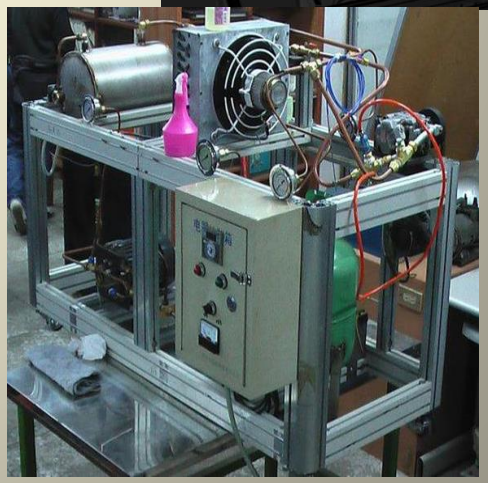
Gen. 2





Gen. 4



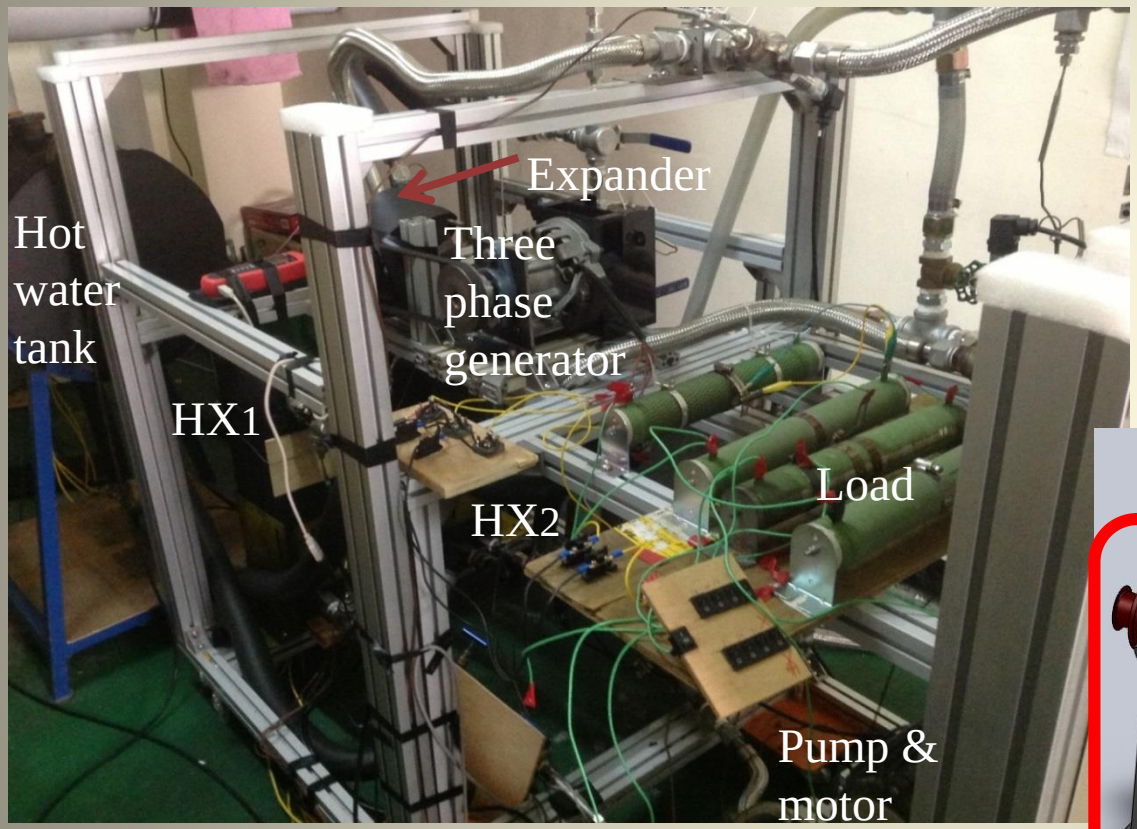


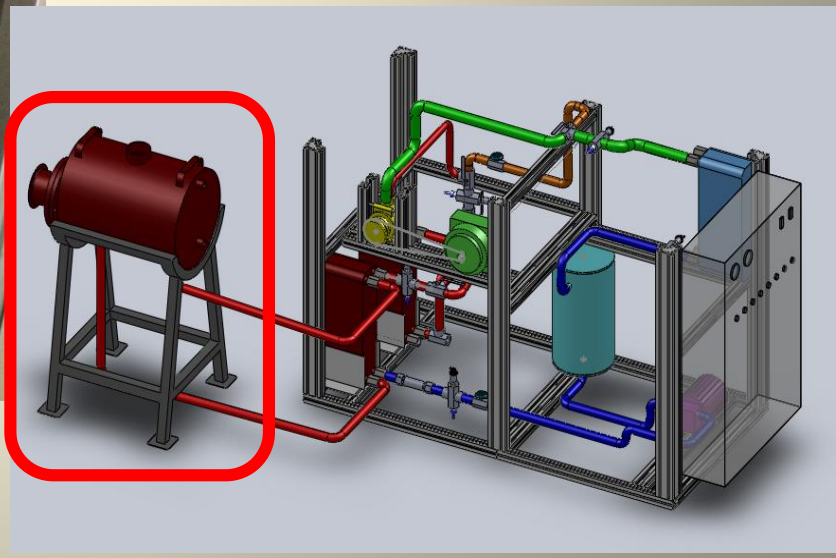
Gen. 3

Gen. 5 ORC – 2 kW

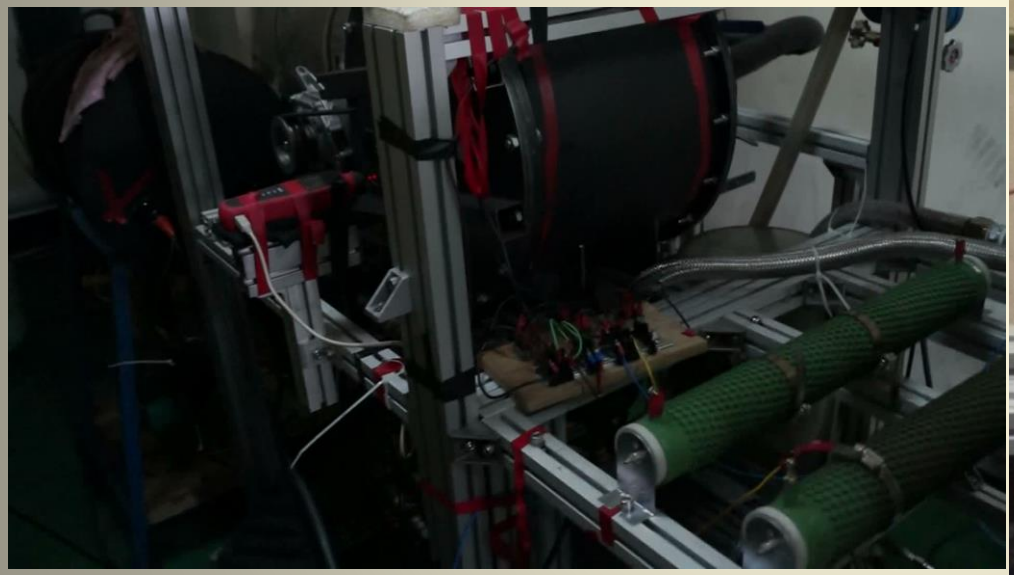
(KNT-020)

Gen. 5 experiment facility (KNT-020)



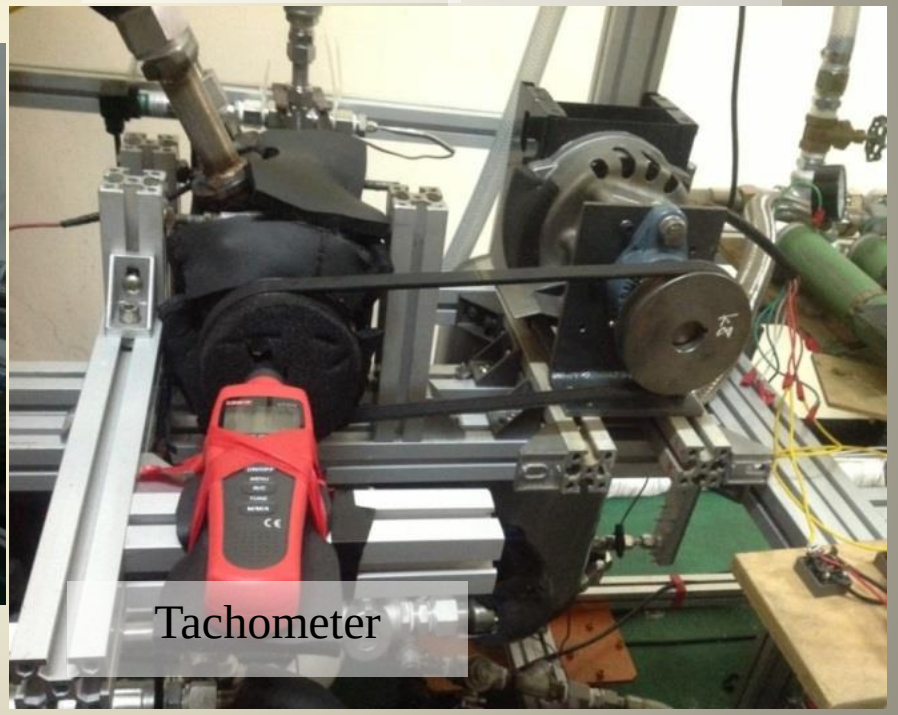


Pumping and power generation for Gen. 5 ORC (KNT-020)



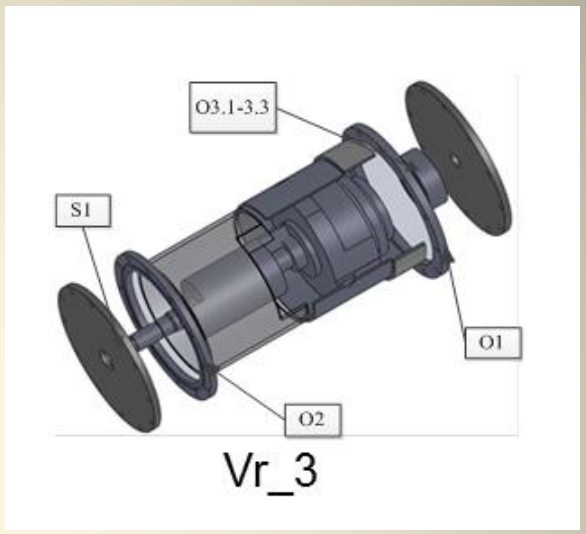
Expander

Generator

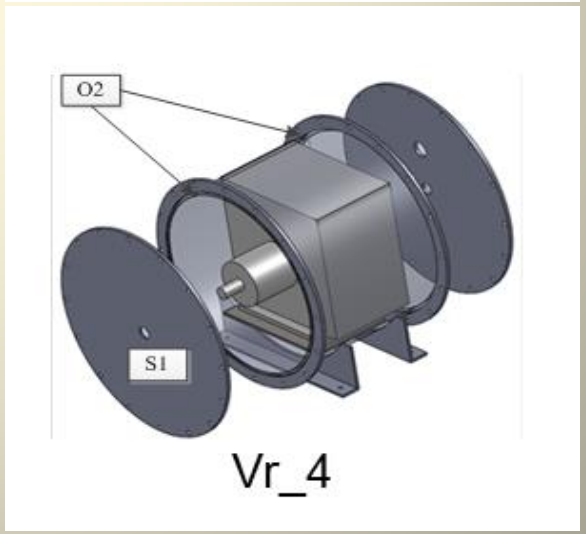


Scroll expanders for Gen. 5 ORC

	Vr : 2.12 R_b : 3.21 mm P_t : 20.17 mm t : 4.58 mm H : 33 mm V_{ei} : 40817 mm^3
	Vr : 2.95 R_b : 2.59 mm P_t : 16.27 mm t : 4 mm H : 41 mm V_{ei} : 35005 mm^3
	Vr : 4.05 R_b : 3.262 mm P_t : 20.8 mm t : 4.5 mm H : 28 mm V_{ei} : 34210 mm^3



Vr_3

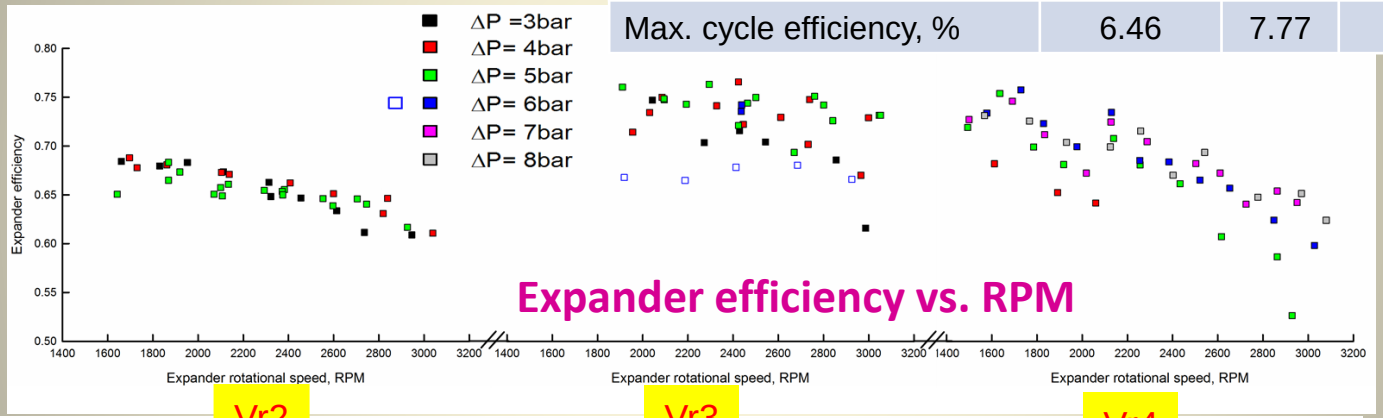


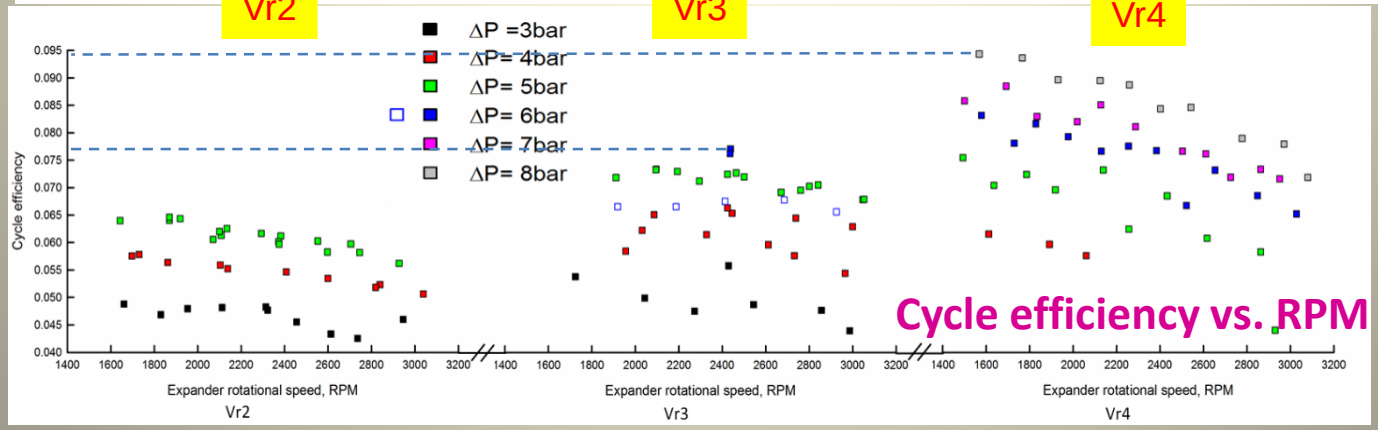
Vr_4

Performance achievement

Superheating at expander inlet: 3±1°C

	Vr2	Vr3	Vr4
Cycle pressure difference, bar	3~5 ±0.15	3~6 ±0.15	4~8 ±0.15
Max. expander efficiency, %	68.8	76.3	73.1
Max. cycle efficiency, %	6.46	7.77	9.44



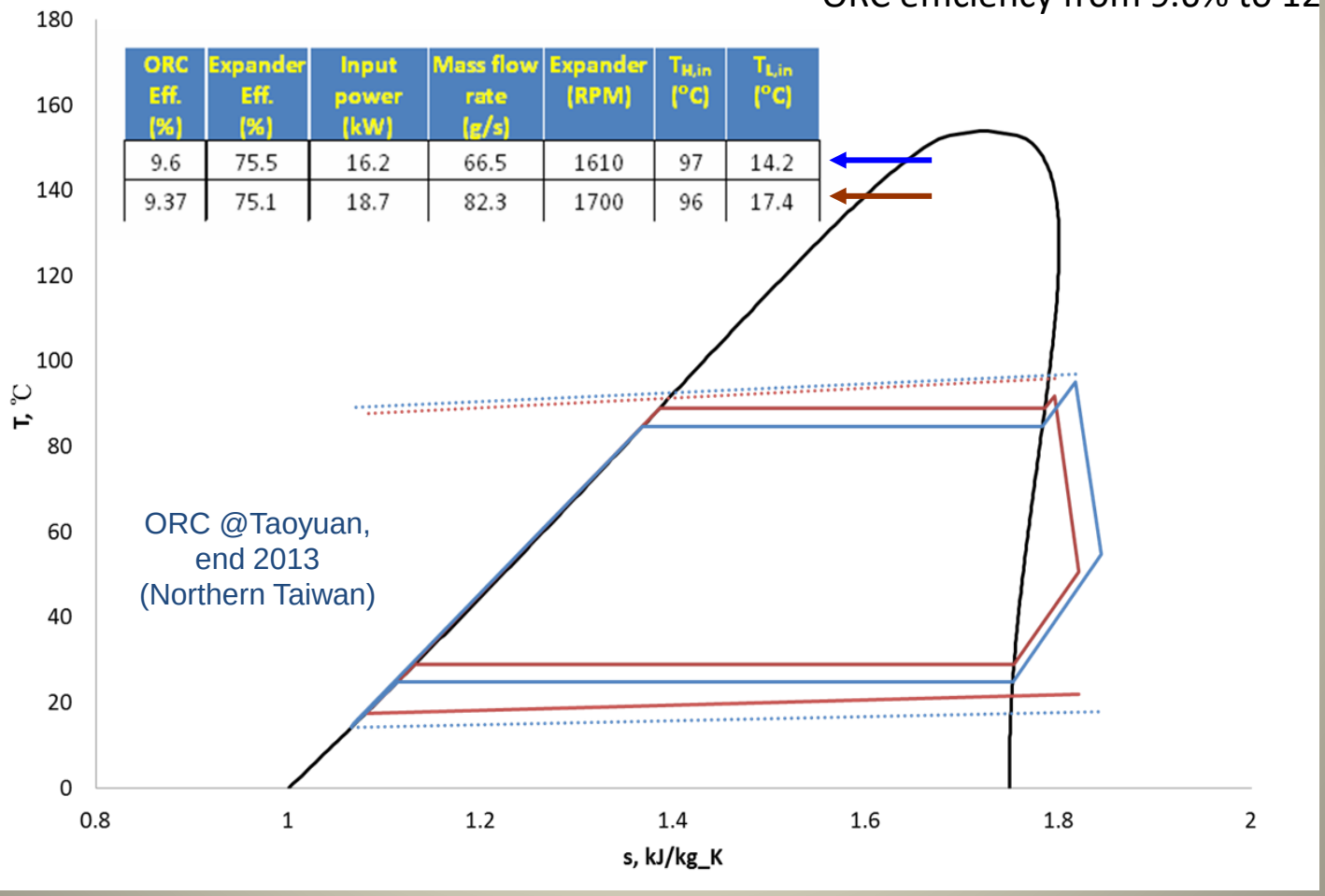


Applied Energy, Vol. 155, 1 October **2015**, pp.150-159.

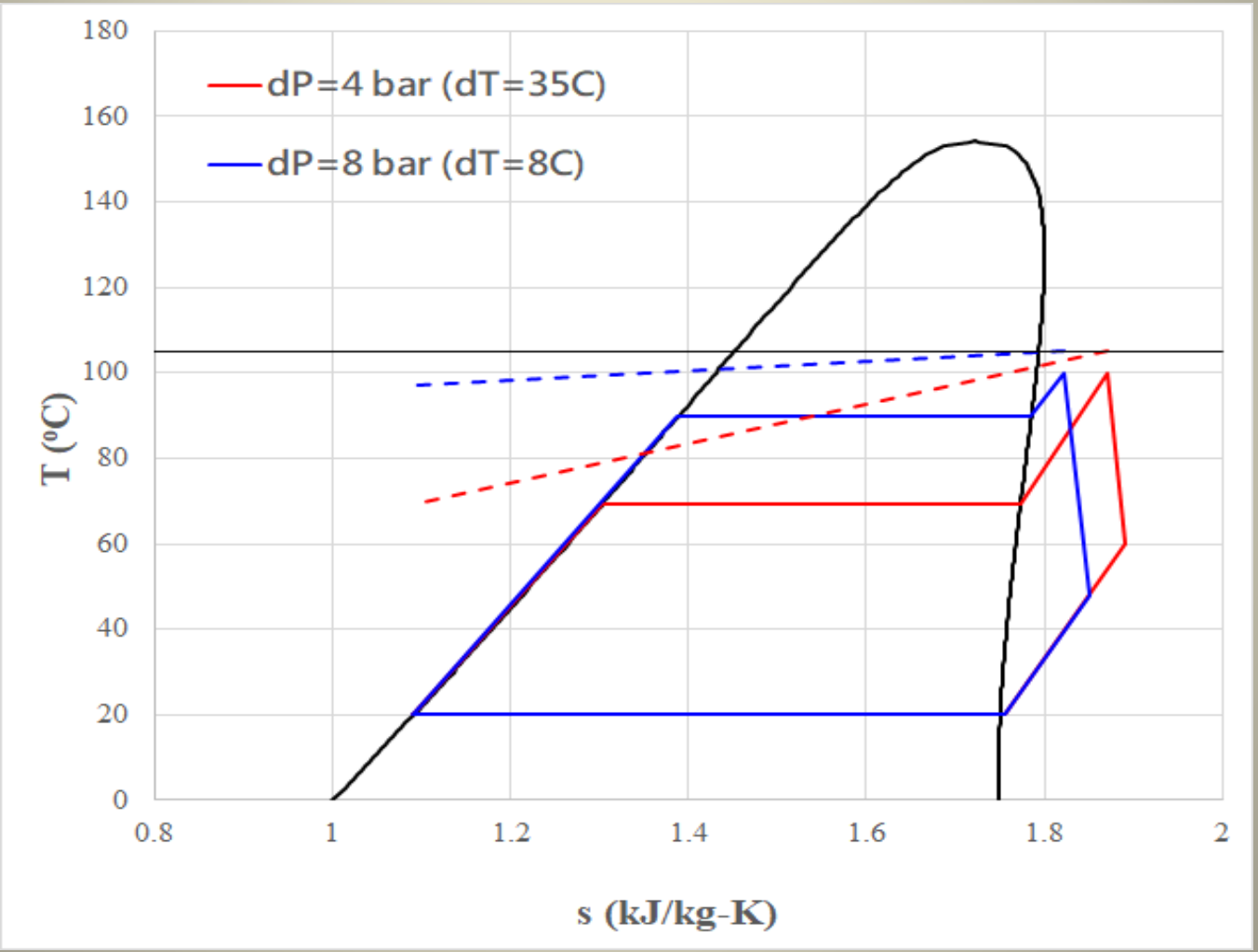
Sample results – Vr4

- Ideal ORC efficiency = 14.42%
- Carnot efficiency = 22%
- Regeneration **could enhance** the ORC efficiency from 9.6% to 12%.

ORC Eff. (%)	Expander Eff. (%)	Input power (kW)	Mass flow rate (g/s)	Expander (RPM)	$T_{H,in}$ (°C)	$T_{L,in}$ (°C)
9.6	75.5	16.2	66.5	1610	97	14.2
9.37	75.1	18.7	82.3	1700	96	17.4



The system and the heat source



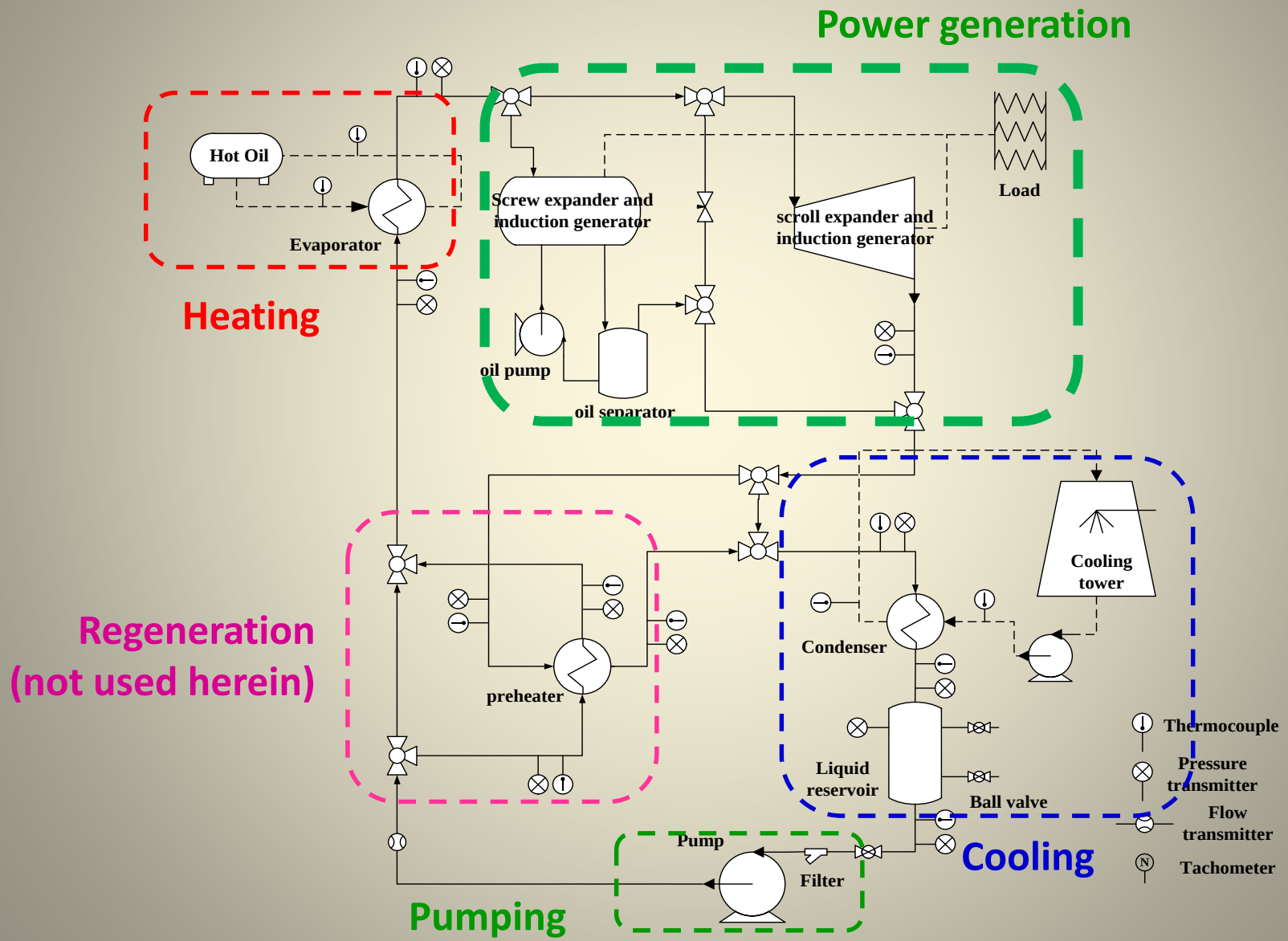
Gen. 6 ORC – 3 kW

(KNT-030)

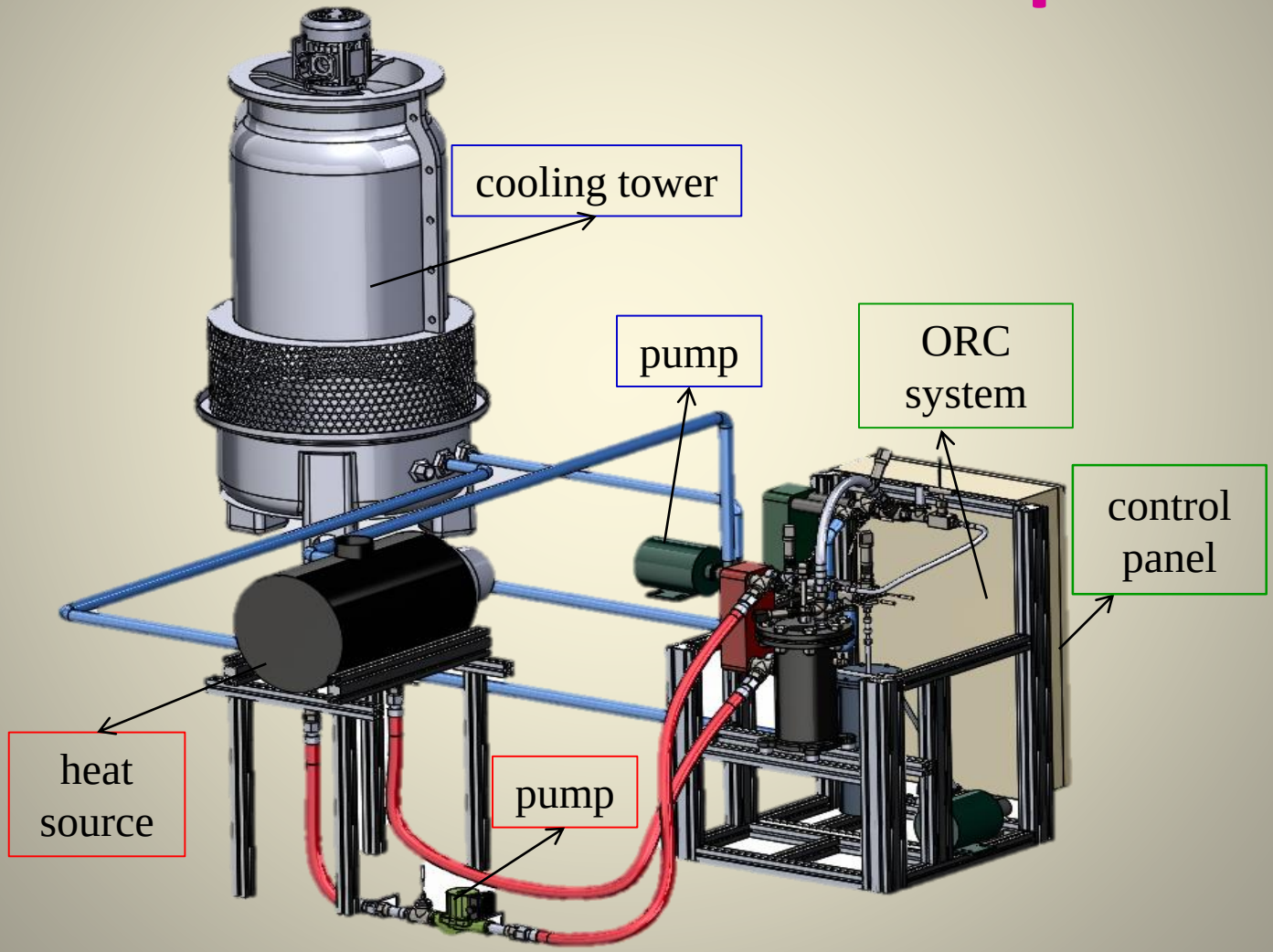
Present Scope

- **Modularized 3~10kWe ORC (micro ~ small)**
- **Heat sources:**
  - **< 120℃ of liquid or**
  - **≅ 1atm of steam**
  - **< 160℃ hot exhaust gas**
- **Ensuring safety**
- **The challenge in the simplicity and difficulty for low-temperature and low-pressure**

KNT-030 & KNT-100

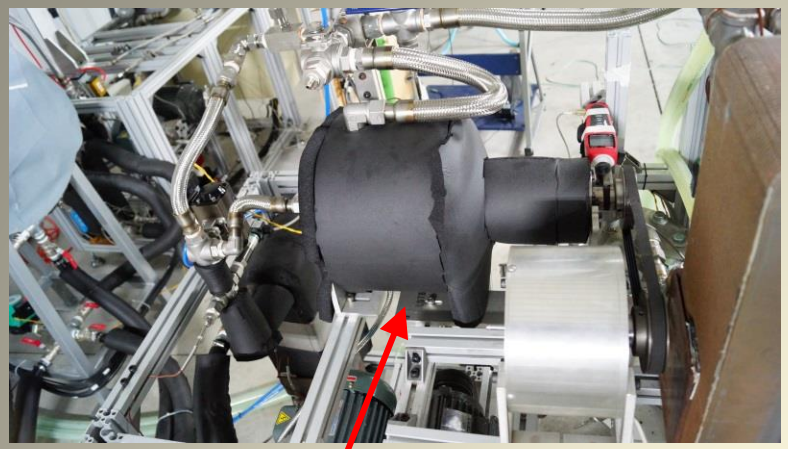


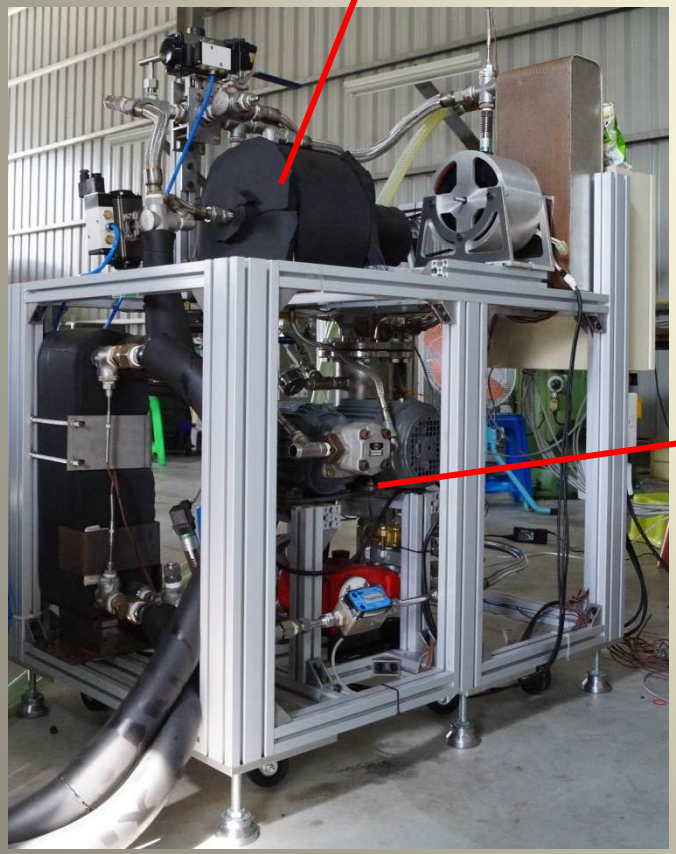
Schematic ORC experimental platform

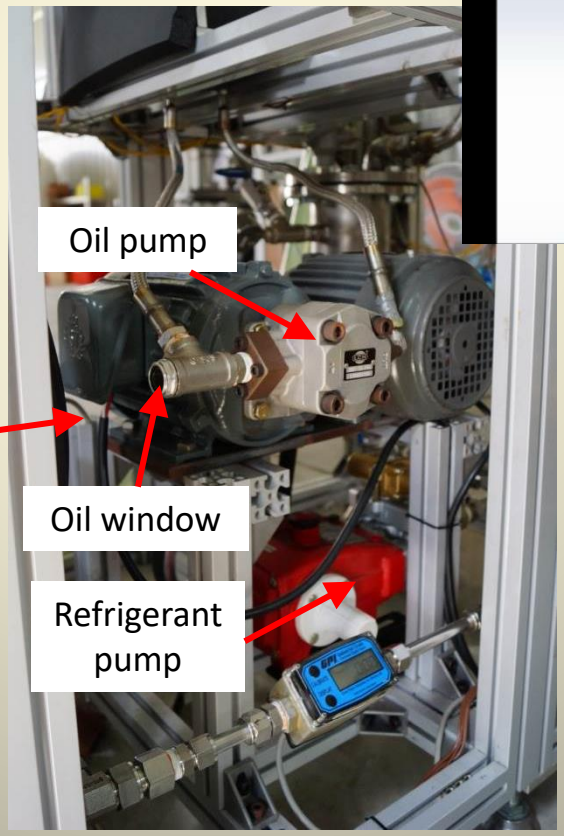


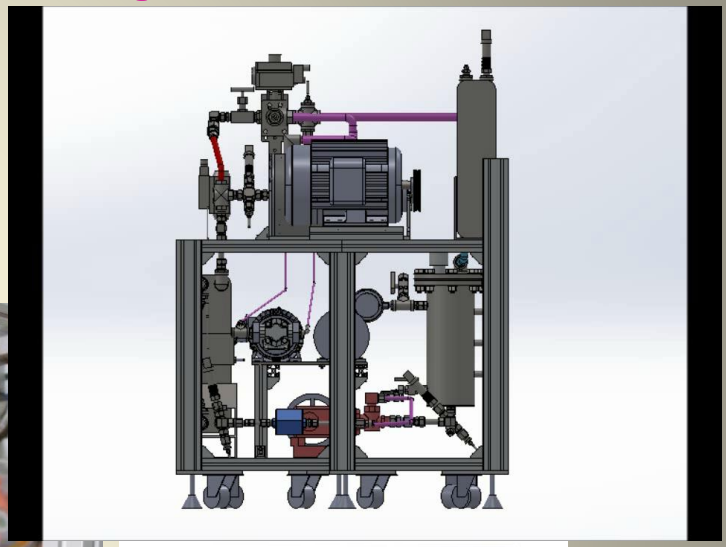
Gen. 6 experiment ORC loop

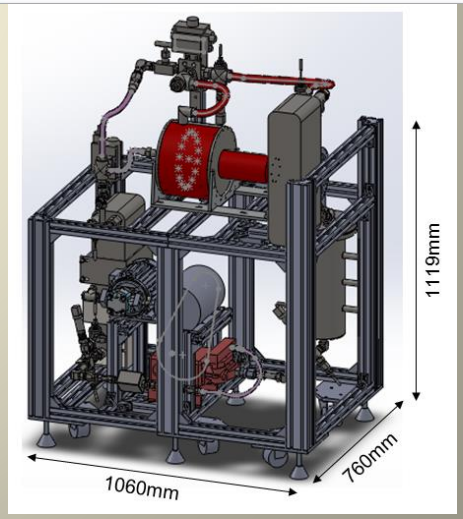
Expander-generator set







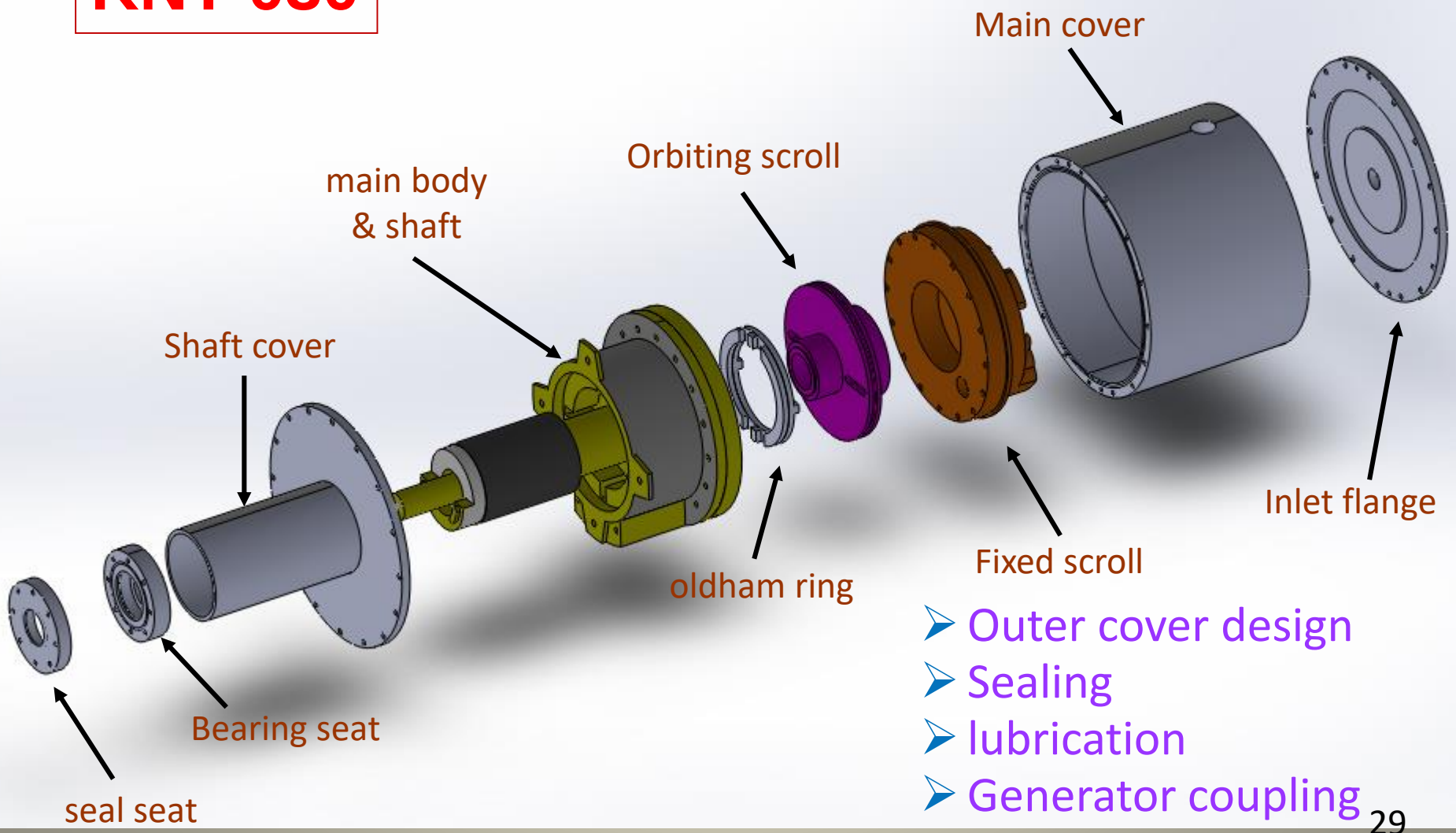




Modified scroll expander (Vr3)

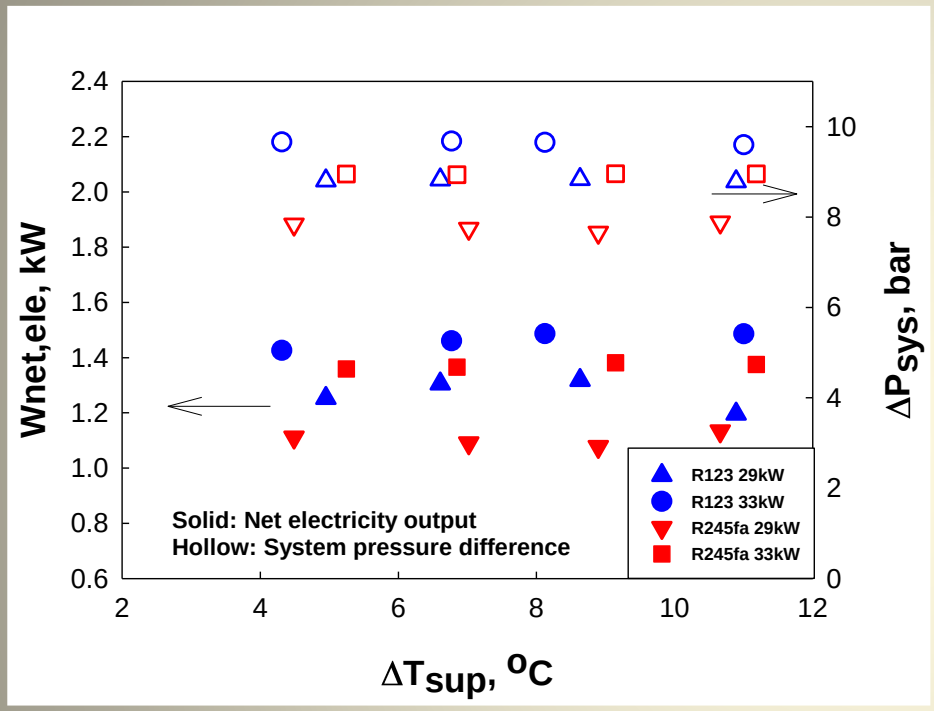
Applied Thermal Engineering, Vol. 73, **2014**, pp. 1444-1452.

KNT-030

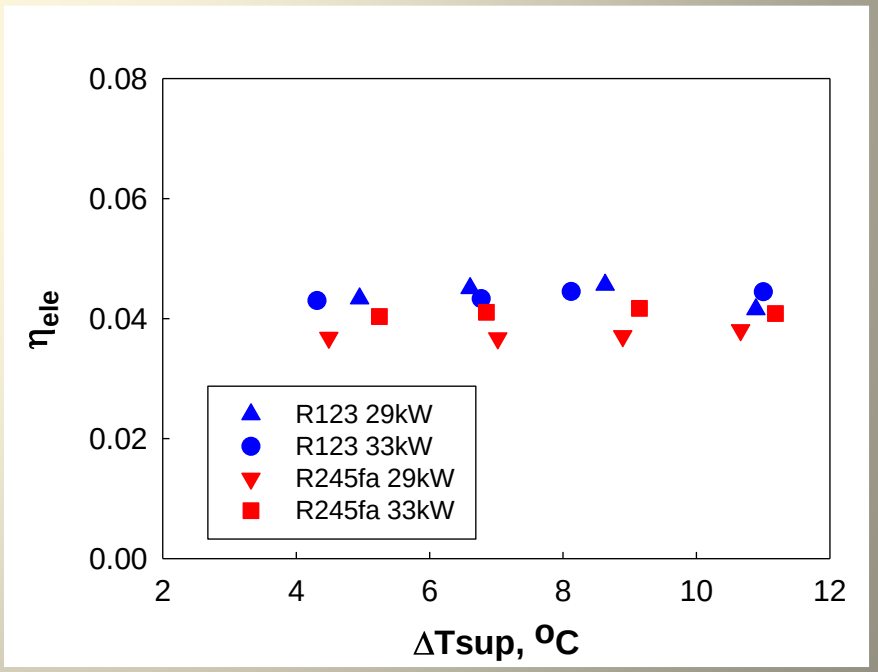


- Outer cover design
- Sealing
- lubrication
- Generator coupling

Operation characteristic of a R245fa-based KNT030 ORC



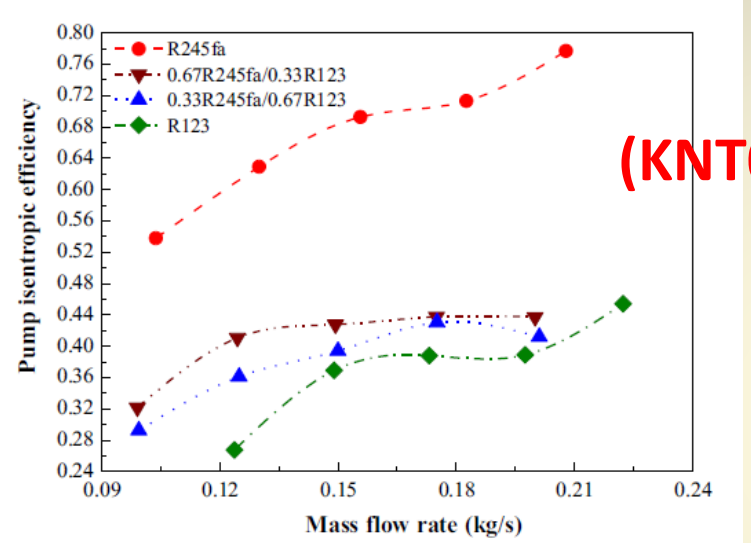
- Expander eff.=60~70%
- Generator eff.= 60~70%
- Pump isentropic eff.=20~40%



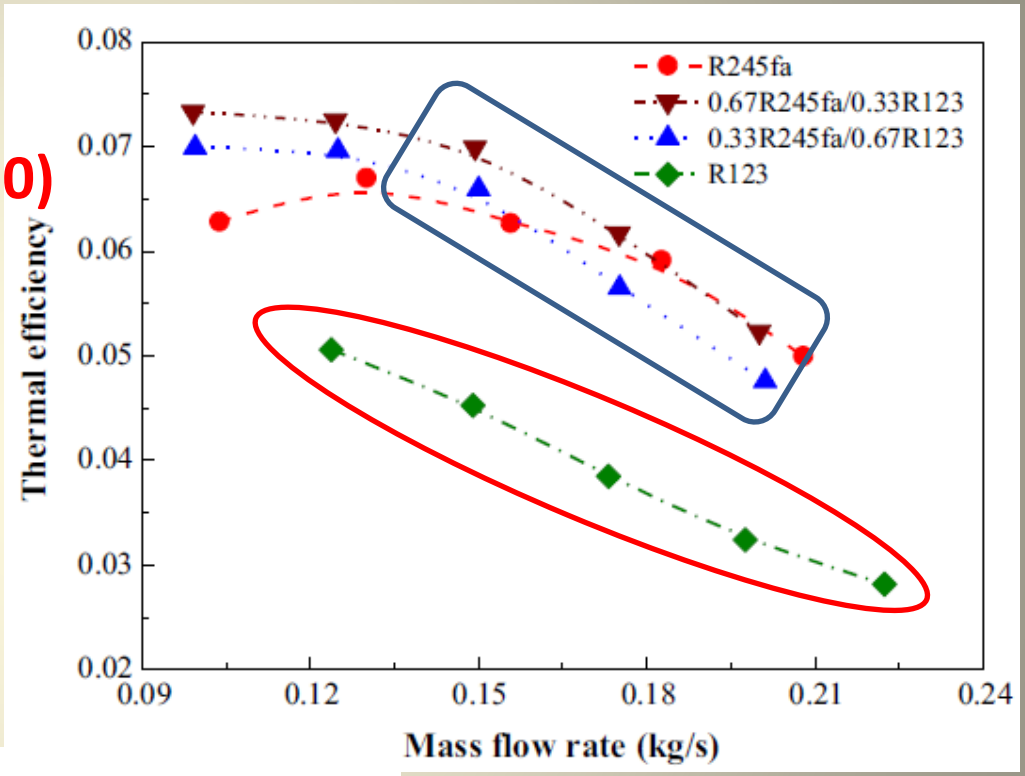
- Net electricity and ΔP_{sys} vs. ΔT_{sup}
- T_H=100°C

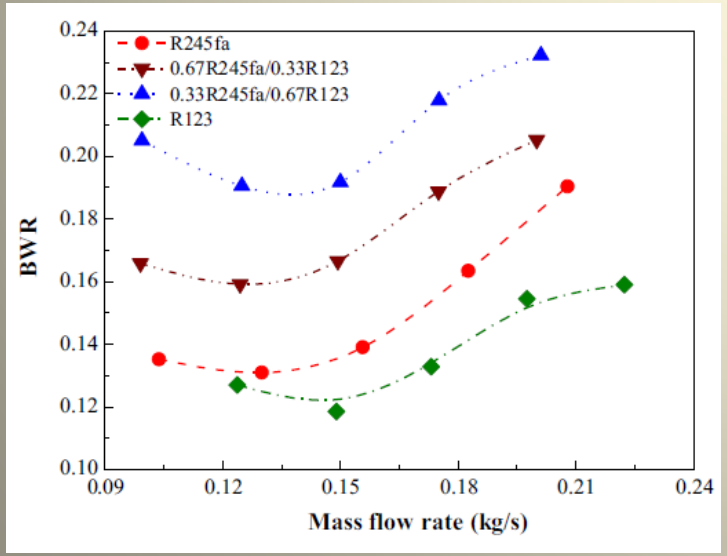
Energy Conversion and Management, Vol. 144, 2017 pp. 153–163.

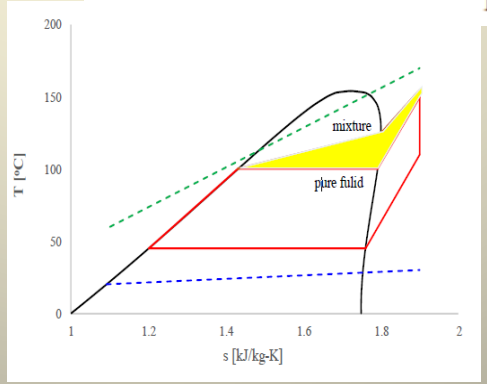
Operation characteristic of ORC using R245fa, R123 and their mixtures



(KNT030)

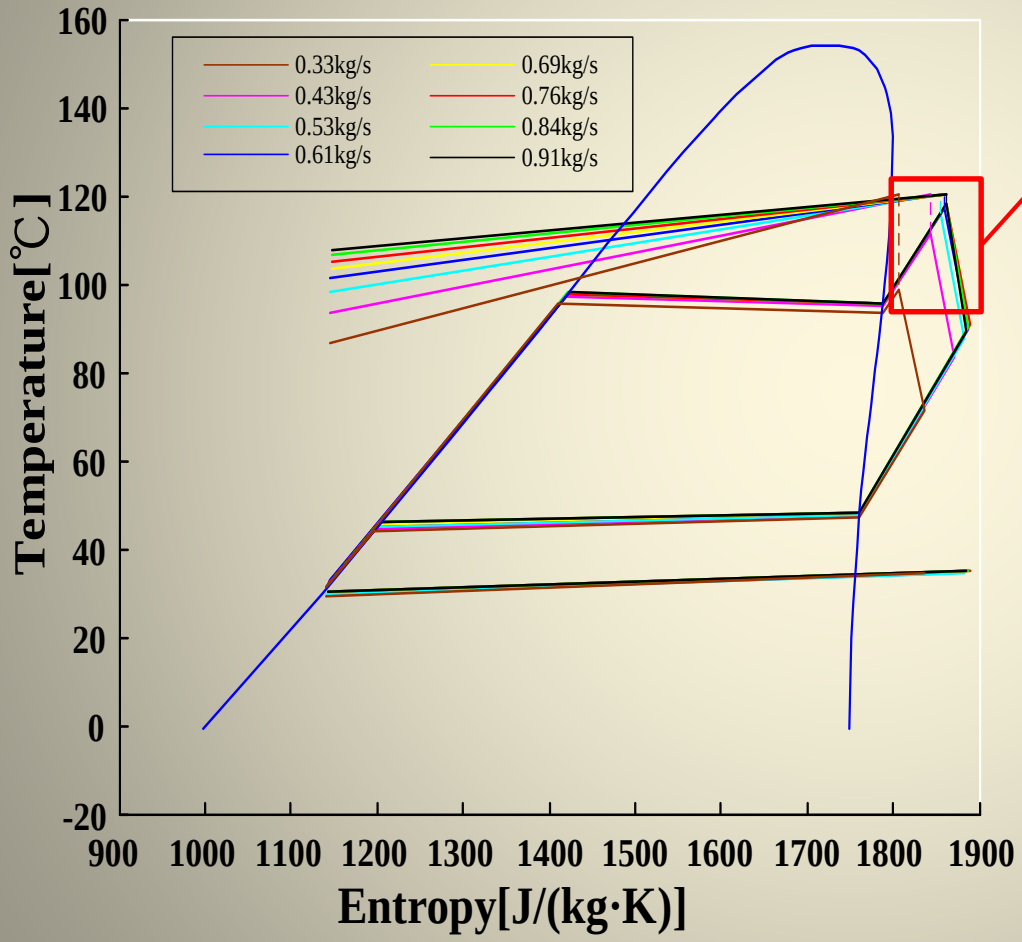




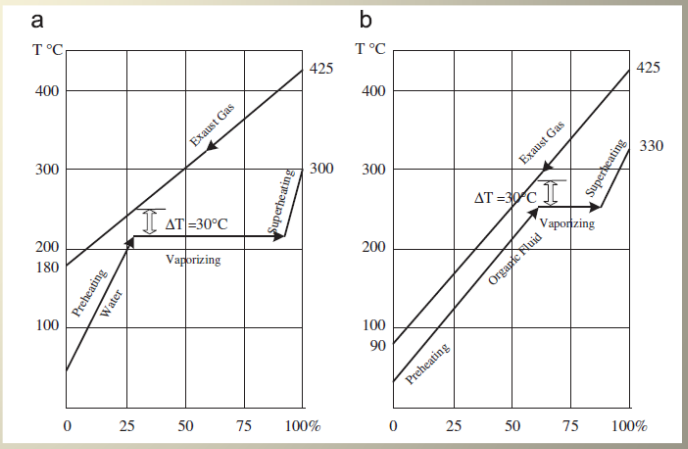


Energy, Vol. 133, 2017, pp. 636-651.

To pursue for large ΔT_H

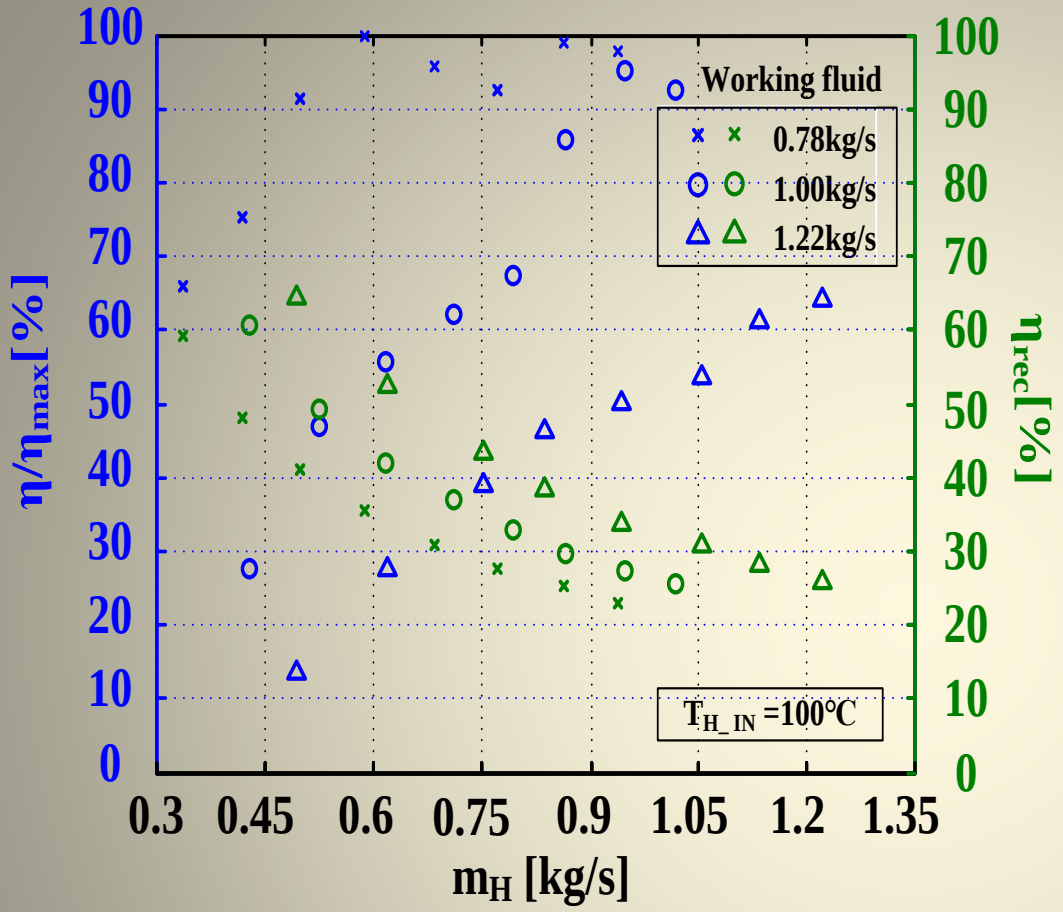


Smaller ΔT_H **Greater ΔT_H**



Source: Larjola J., Int. J. Production Economics, 1995.

ENERGY, Vol. 149, 2018, pp. 566-576.



Heat recovery

ENERGY, Vol. 172, April 1, **2019**, pp. 391-400.

Inlet T of Heat source	100℃	110℃	120℃
η_{max}	1.87%	2.89%	3.03%

η= net electricity / heat supply

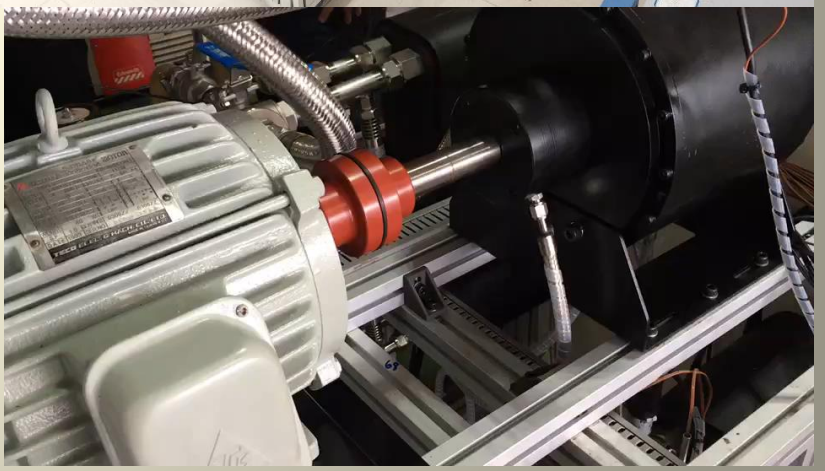
η_{max} : maximum of η

η_{rec} : heat recovery efficiency

$\eta_{rec}= (T_{H\_IN}-T_{H\_OUT})/(T_{H\_IN}-T_{H,ref})$; $T_{H,ref}$ =60C

m_H: mass flowrate of heat source

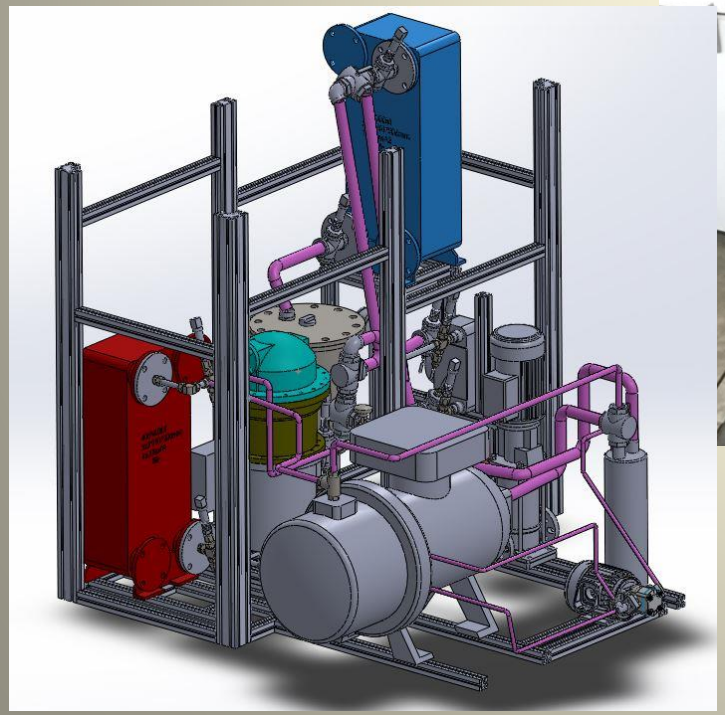
3 kW ORC products



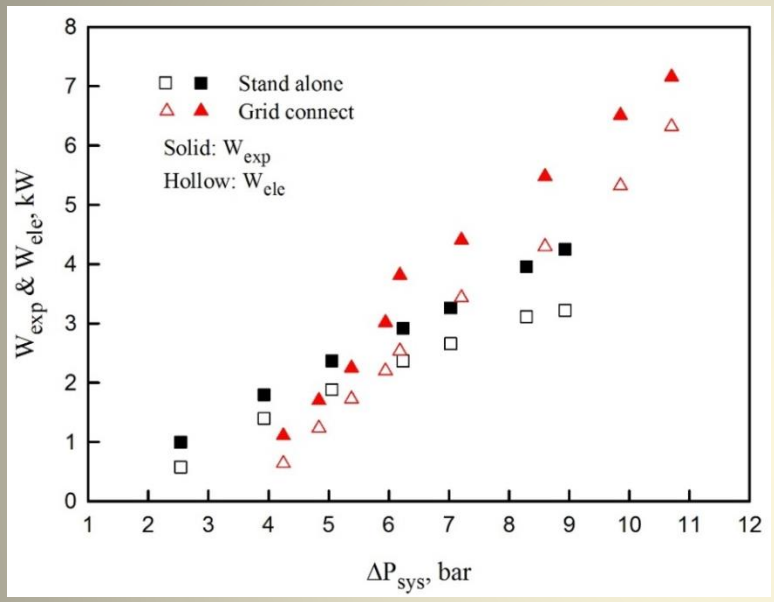
Gen. 7 ORC

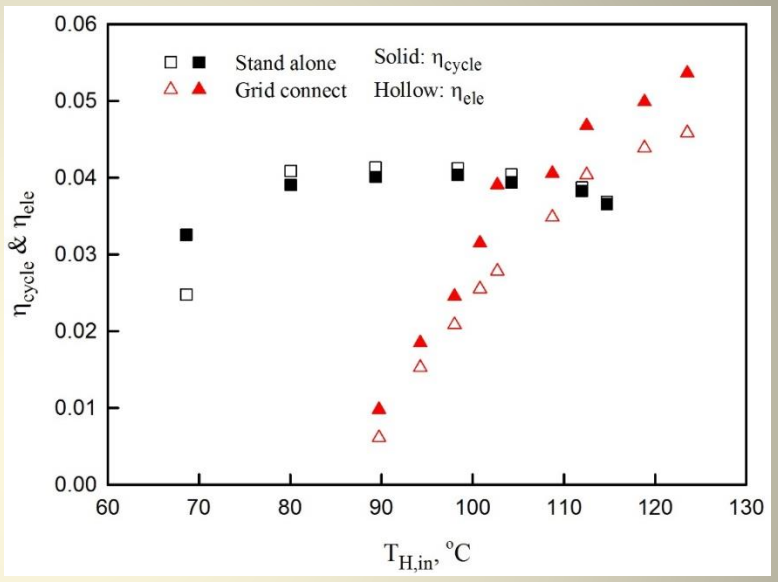
(KNT100-1)

Gen. 7 Experiment facility (KNT100-1)

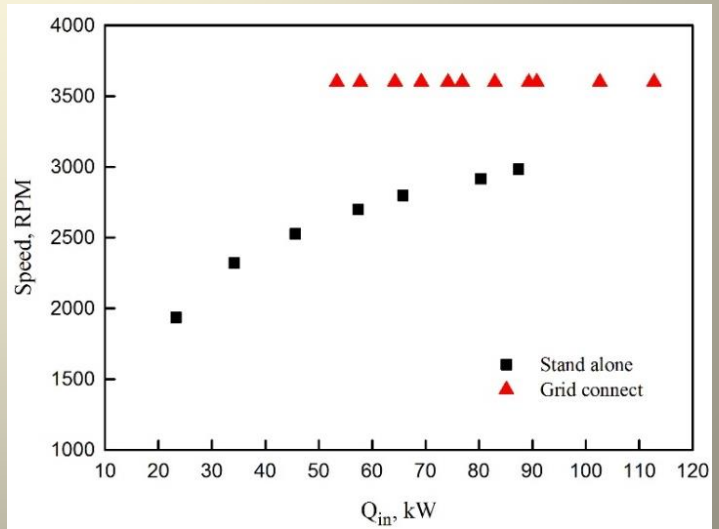


Characteristic of KNT100-1 -- influence of heat source

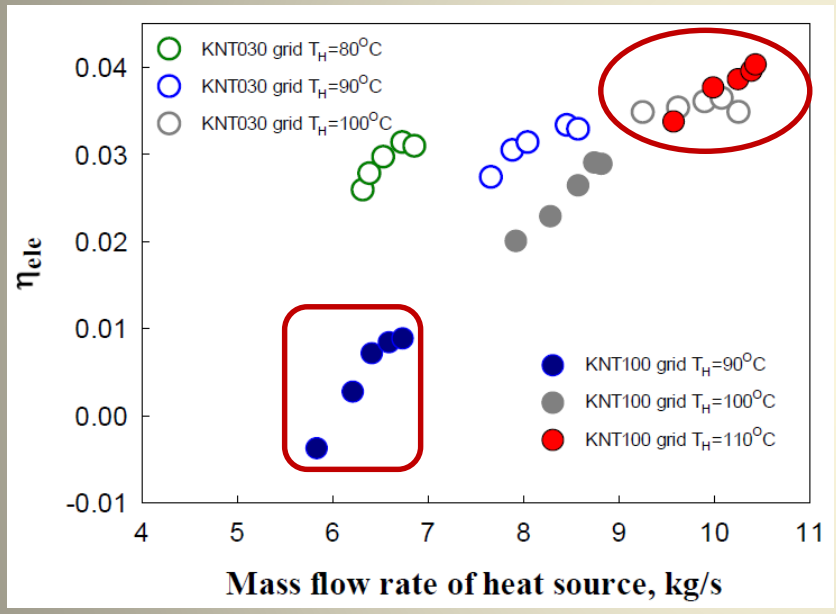


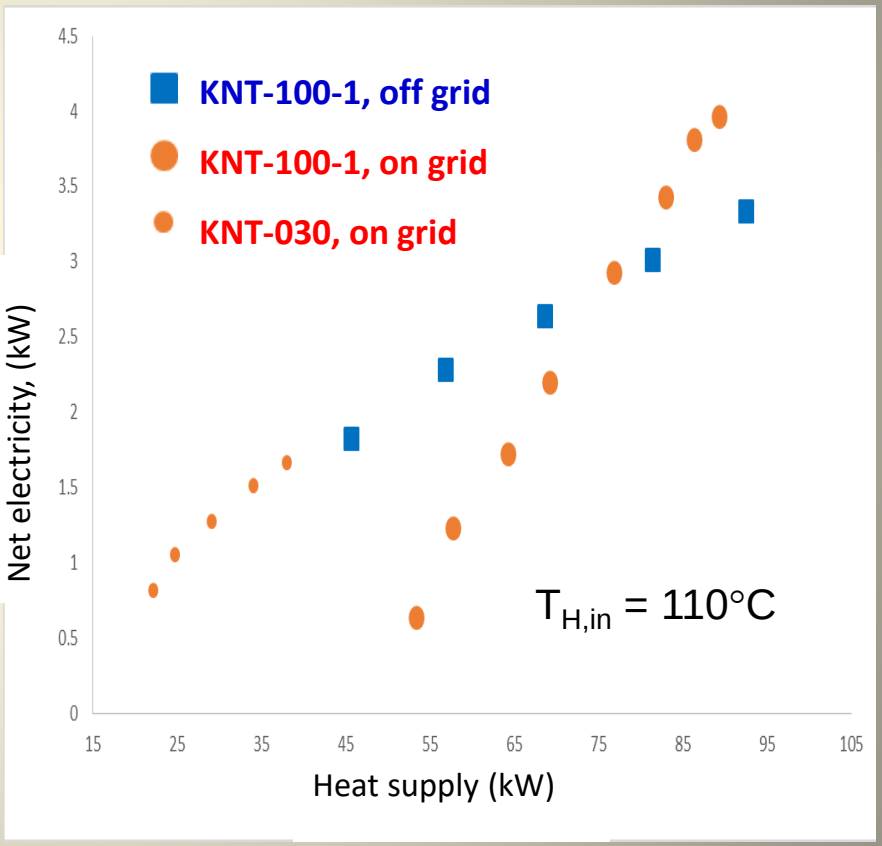


For stand alone, rotational speed will be influenced by the heat source.



R245fa-based KNT030 and KNT100-1: stand alone and grid connect



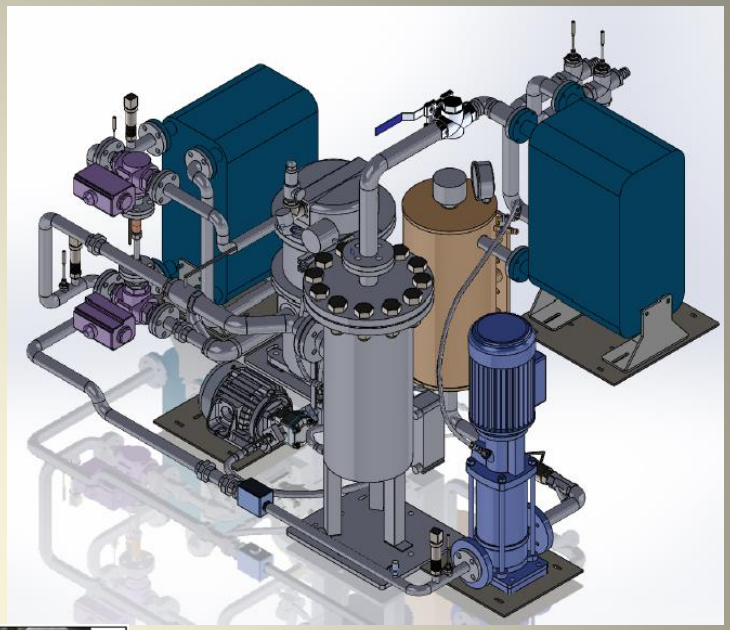


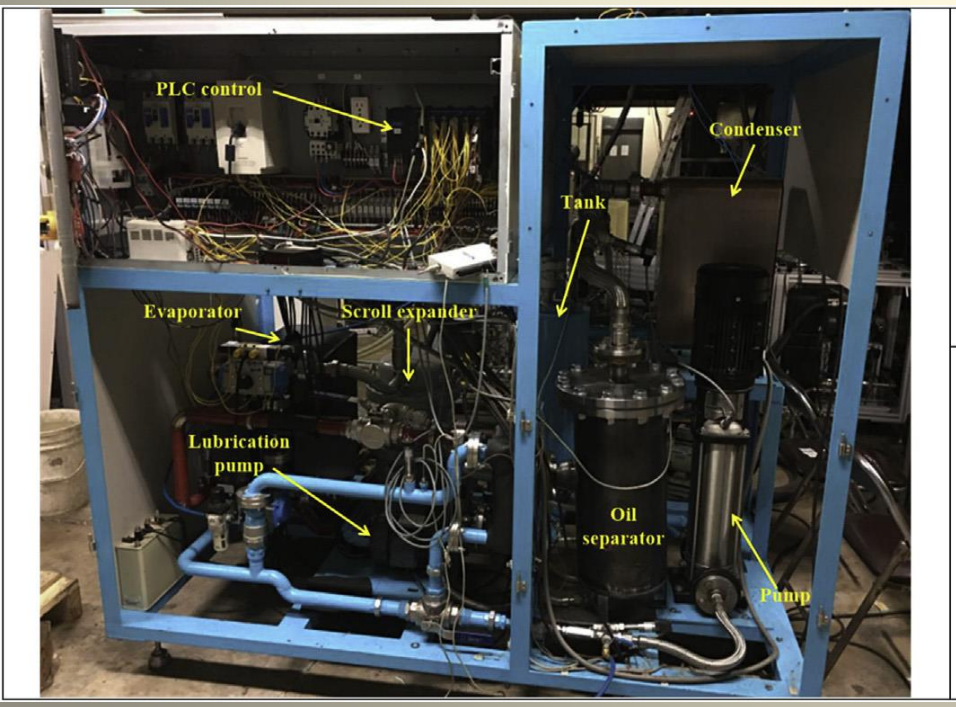
ENERGY, December 2017, 141: 1239-1253.

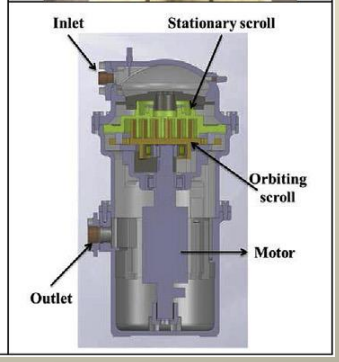
Updated and good results from KNT100-2

10kWe ORC

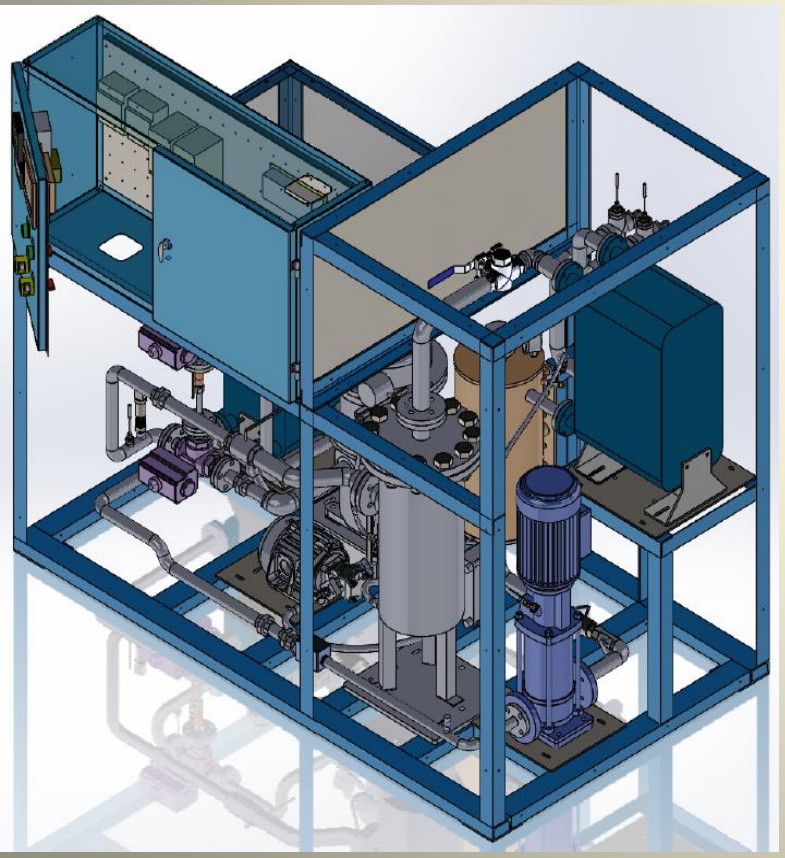
KNT100-2





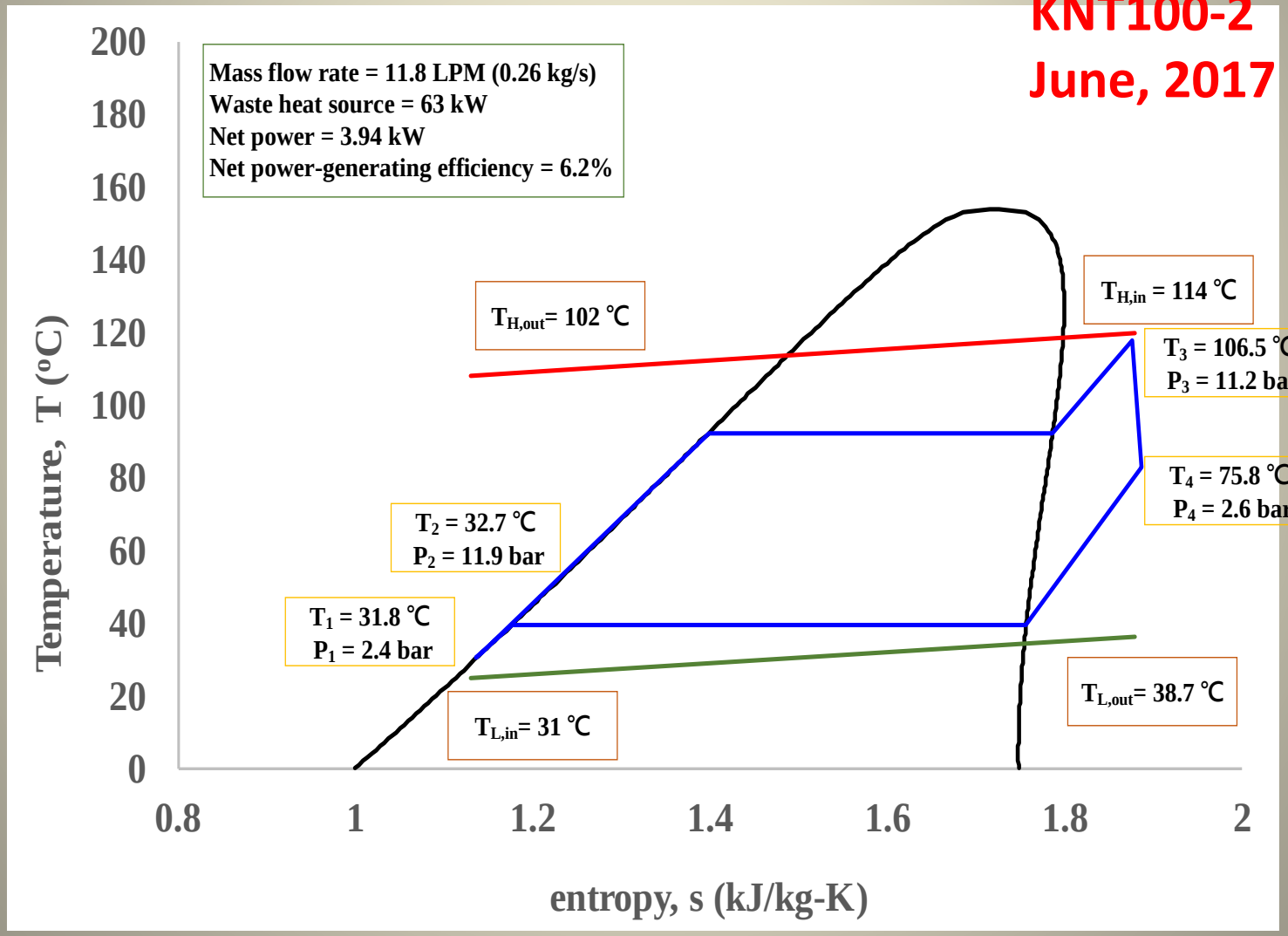


10kWe prototype ORC



ENERGY, Vol. 177 (April, **2019**), pp. 94-105.

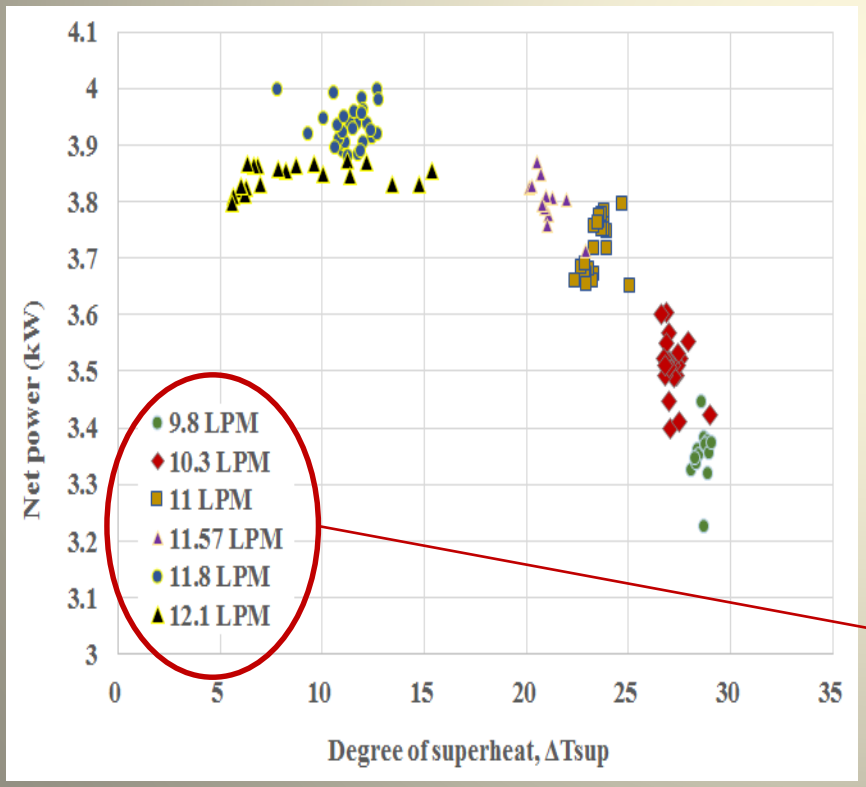
Sample operation

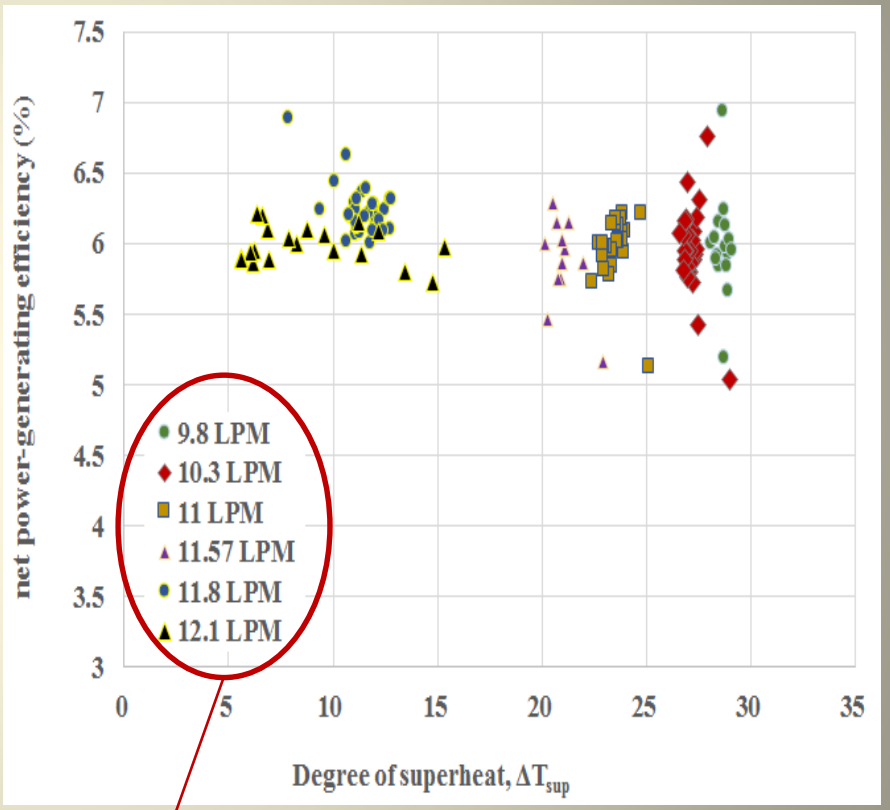


Influence of superheating to net electricity generation and efficiency

KNT100-2
June 2017

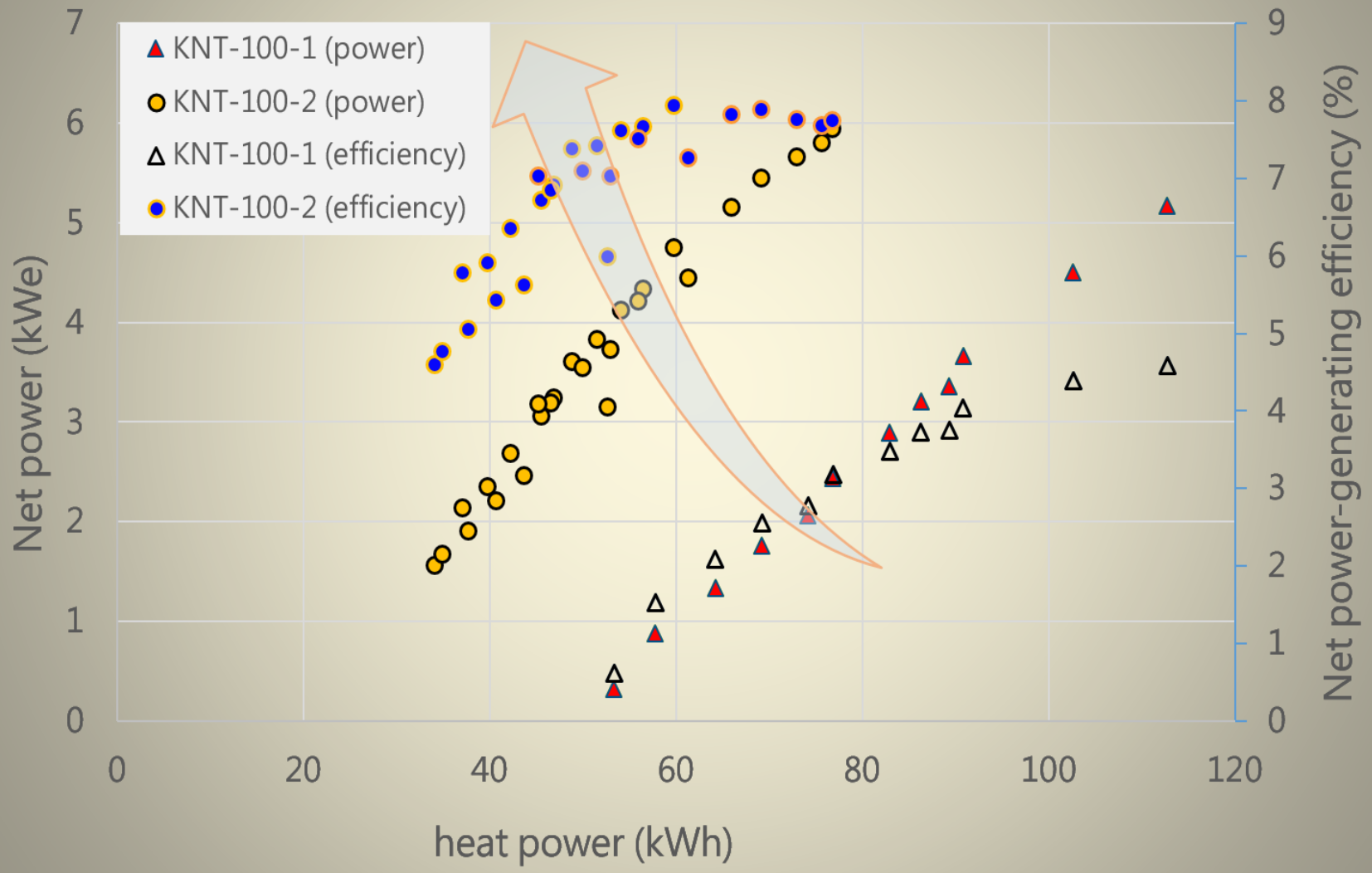
$T_{L,in}$=31°C,
$T_{H,in}$=110±5°C





Flow rate of working fluid at the exit of pump

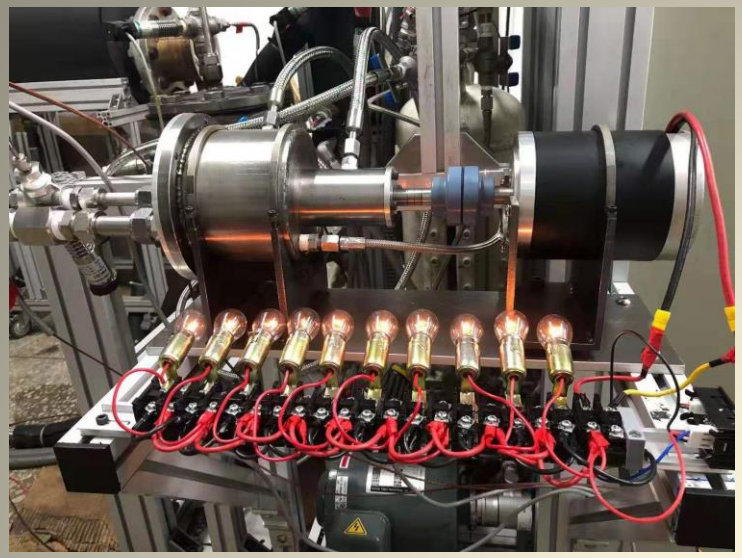
Most updated KNT-100-2 results



Like a pony pulls a horse-drawn carriage!

300 W ORC unit

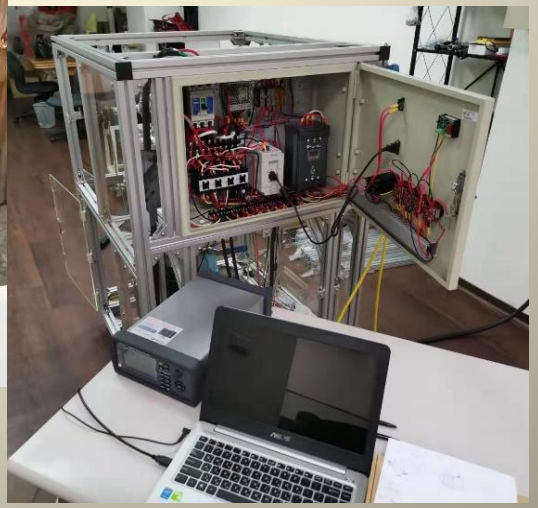
(with City Univ. of Hong Kong)



Scroll expander and generator

Ver 2

Ver 1

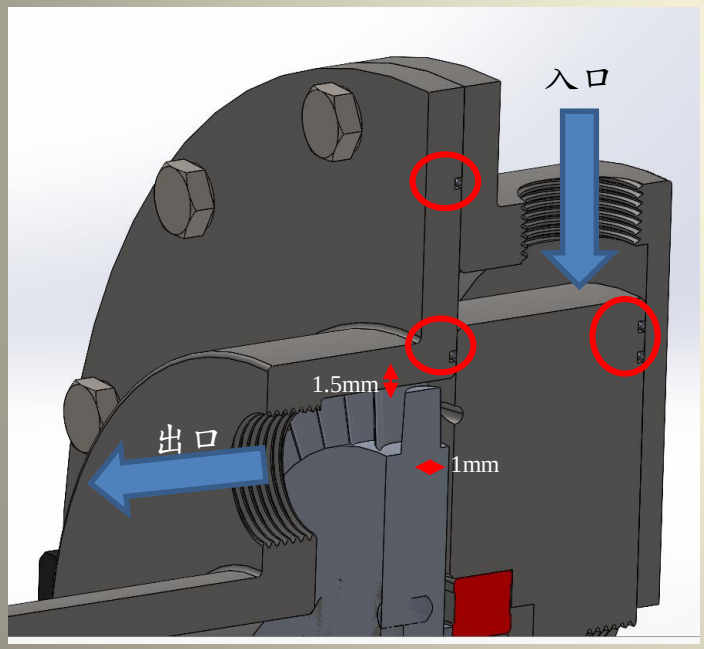


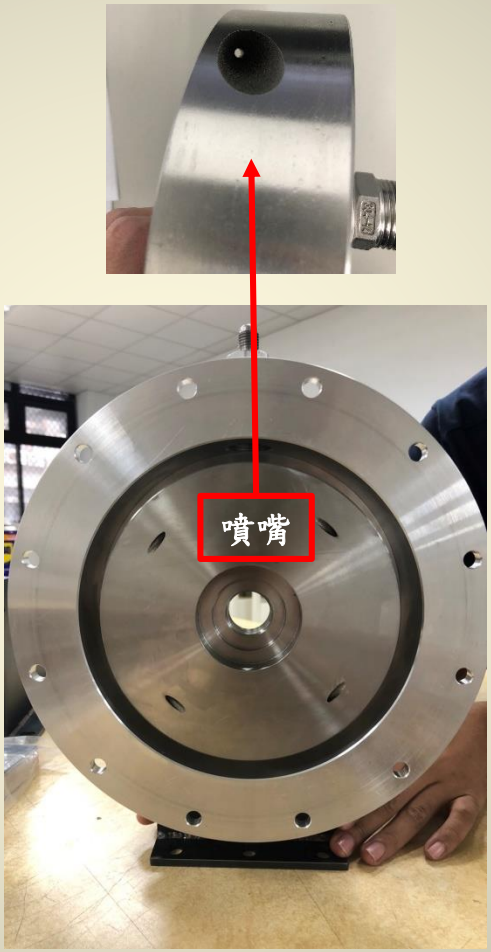
Turbine as expander of ORC (current progress)

Why turbine?

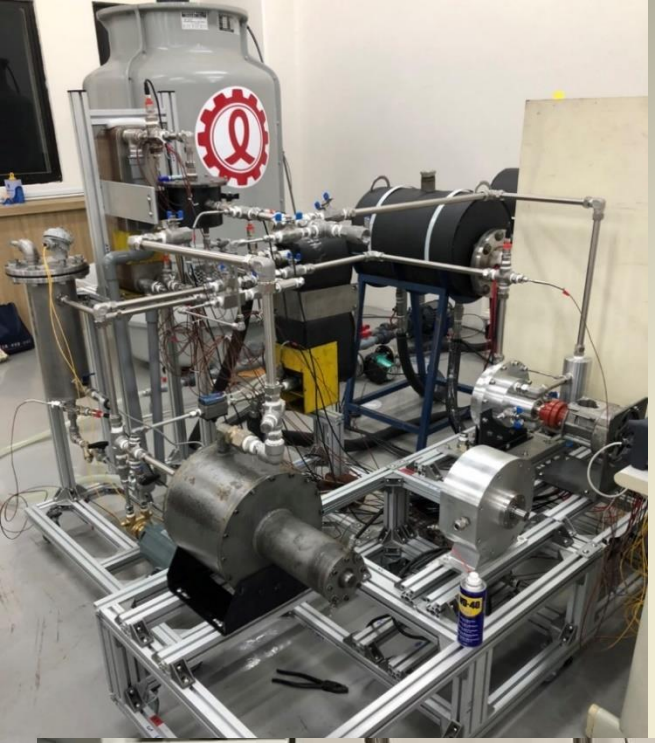
- Scroll expanders are no more practical for the proposed unit of scale > 10 kW!
- Our applications: Low temperature of the heat source; pressure is relatively low as well.
- One stage or two stage of turbine is enough. It means simple and low cost!

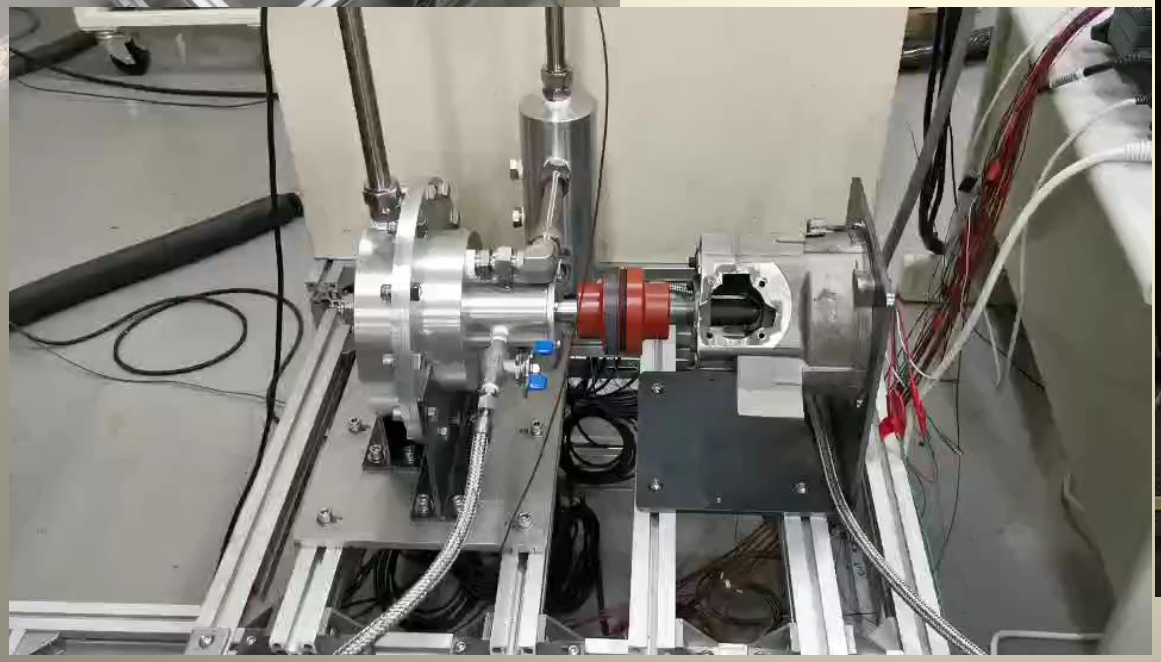
渦輪機加工結果

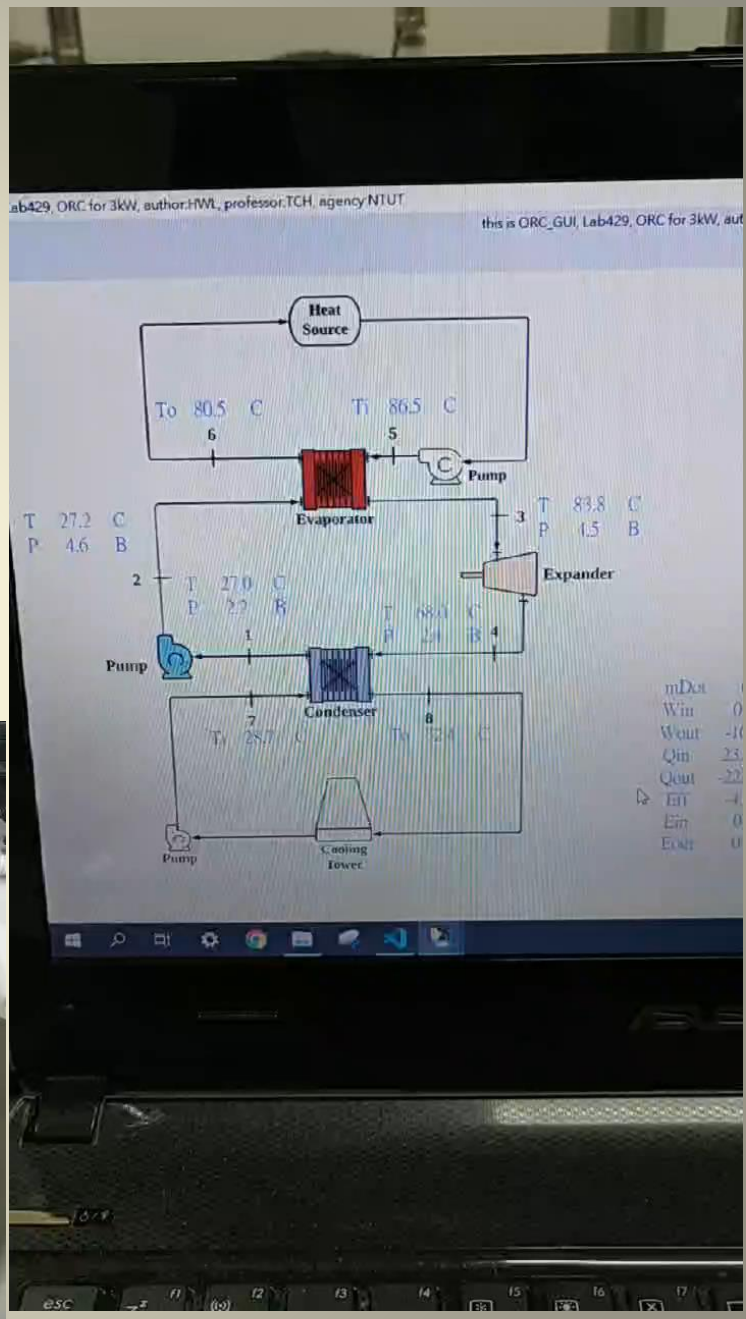




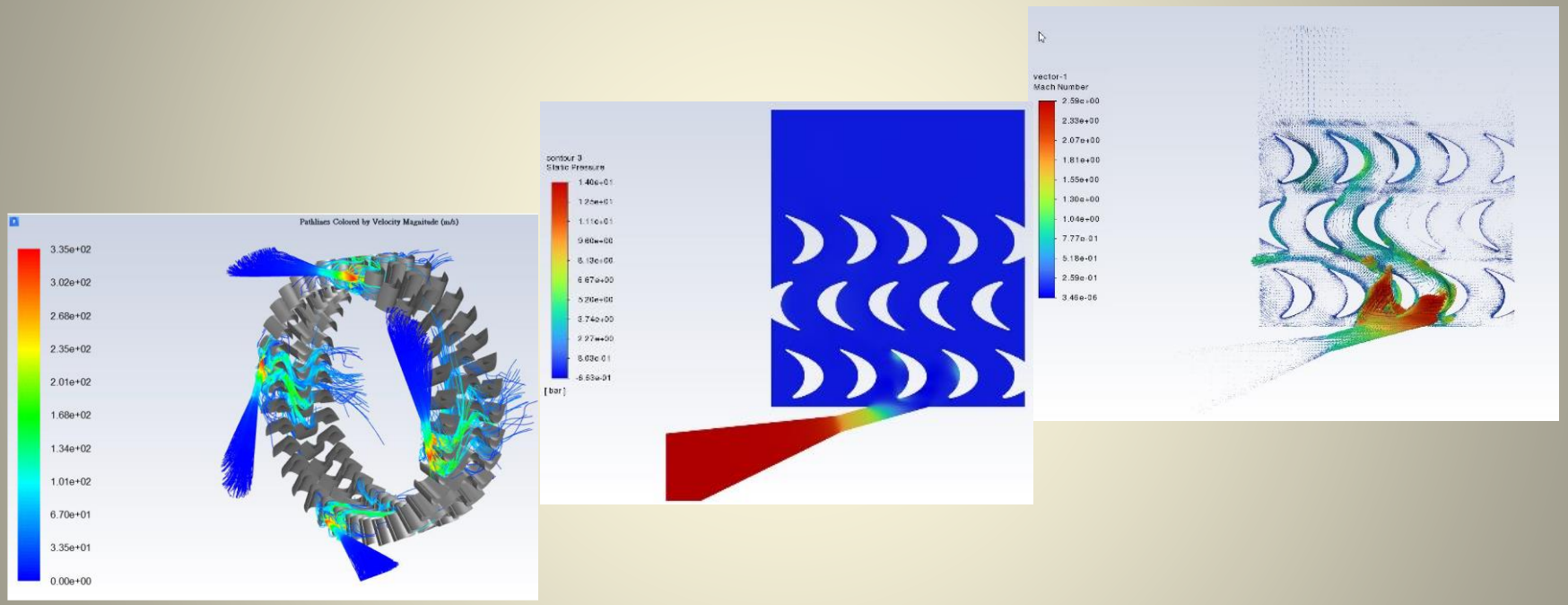
渦輪式 ORC






Heat Source
To 80.5 C
Ti 86.5 C
6
5
Pump
Evaporator
T 27.2 C
P 4.6 B
3
T 83.8 C
P 4.5 B
Expander
2
T 27.0 C
P 2.2 B
1
4
Pump
Condenser
7
8
Pump
Cooling Tower

雙級渦輪機設計中



雙級渦輪機設計 (CFD) -- 左：速度場；中：壓力場；右：Mach #

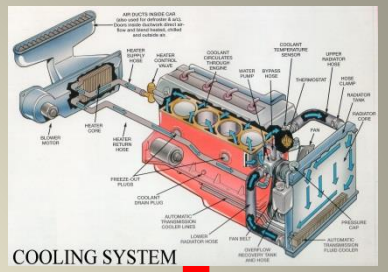
Where are the heat sources: T_H and T_H-T_L

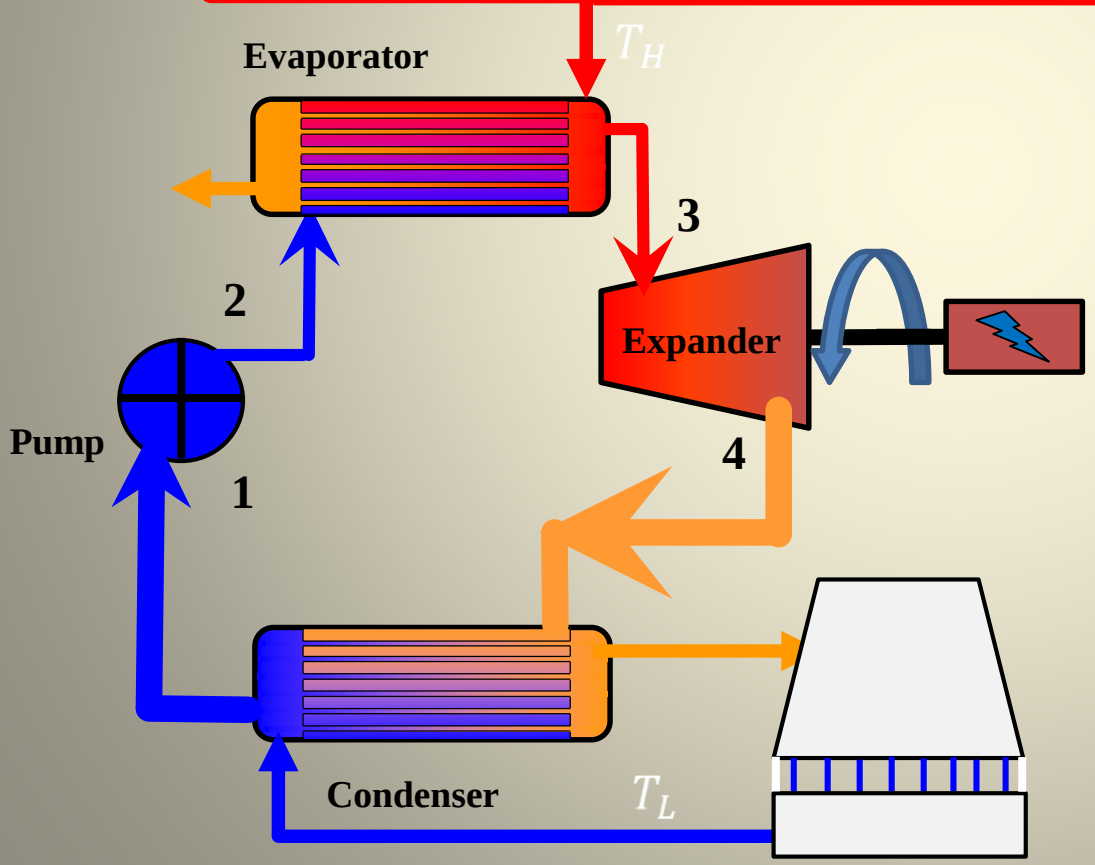
Heat sources for ORC

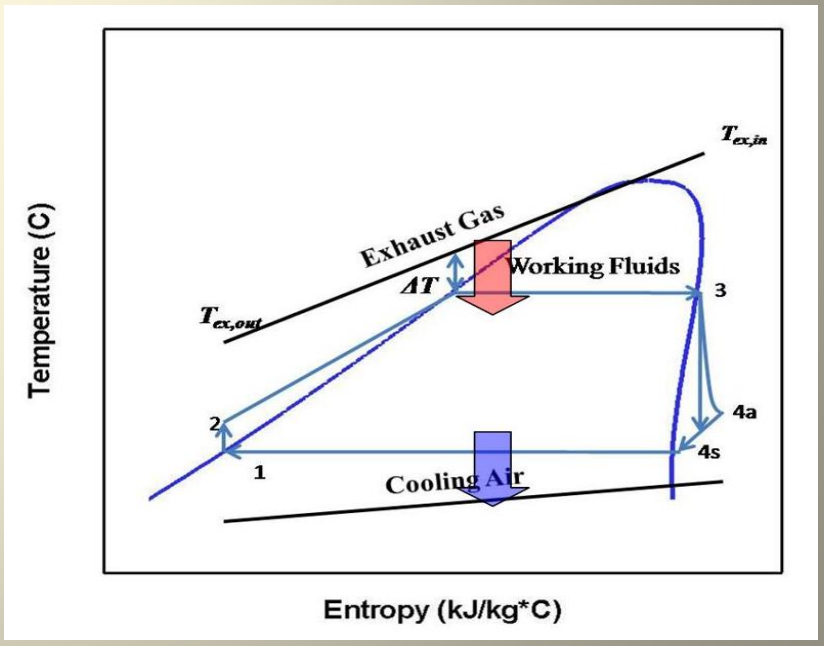
or

or

or







Waste heat exists anywhere

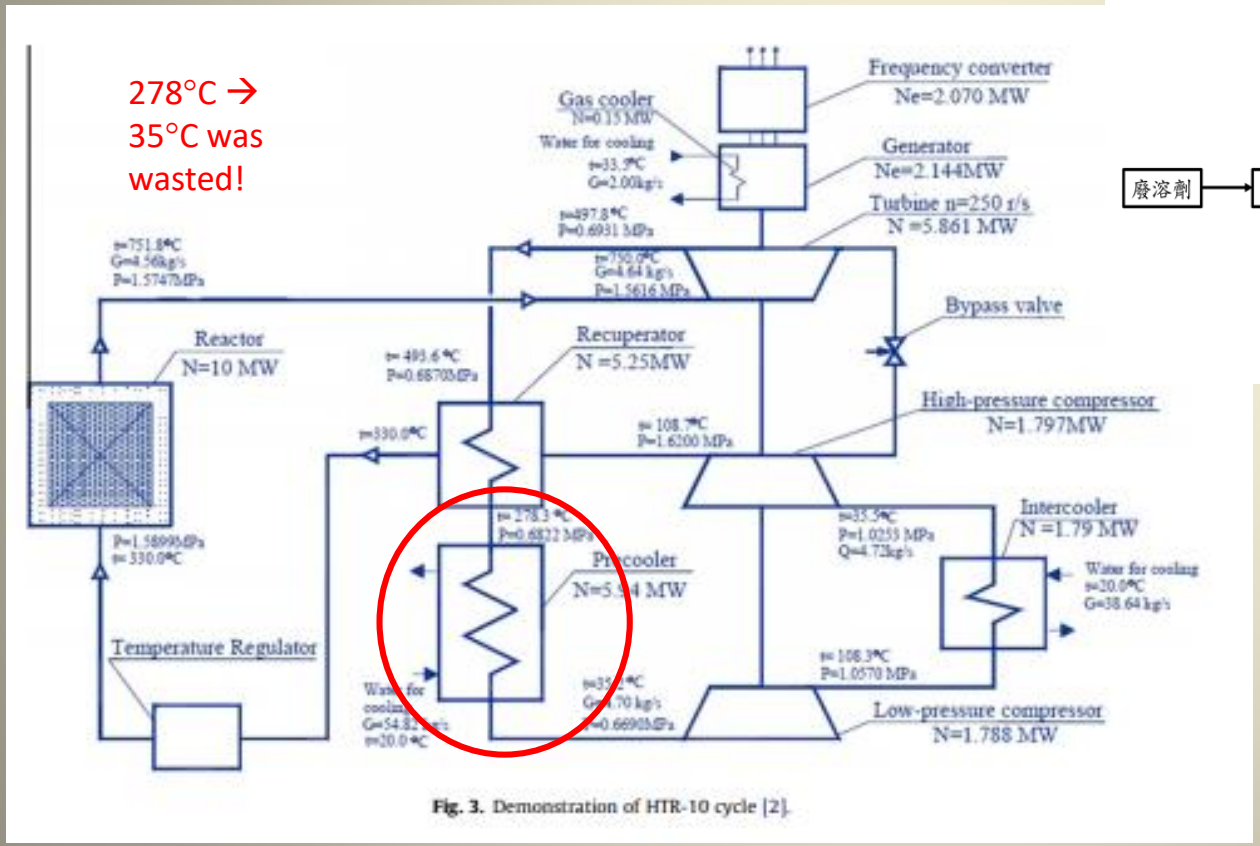
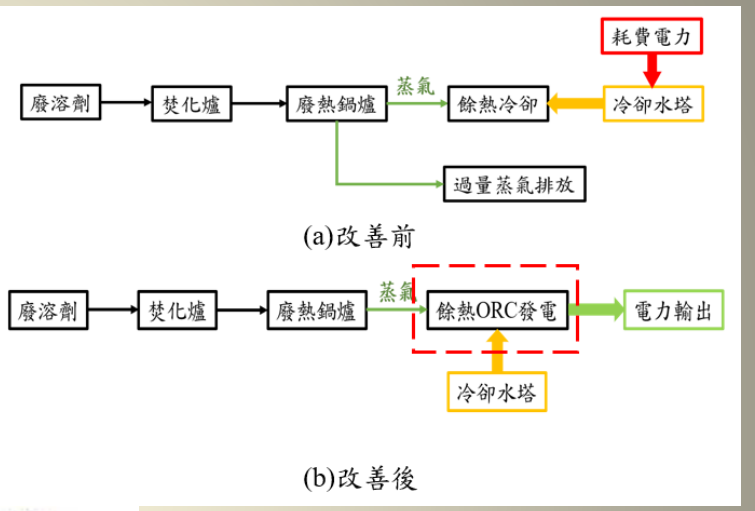


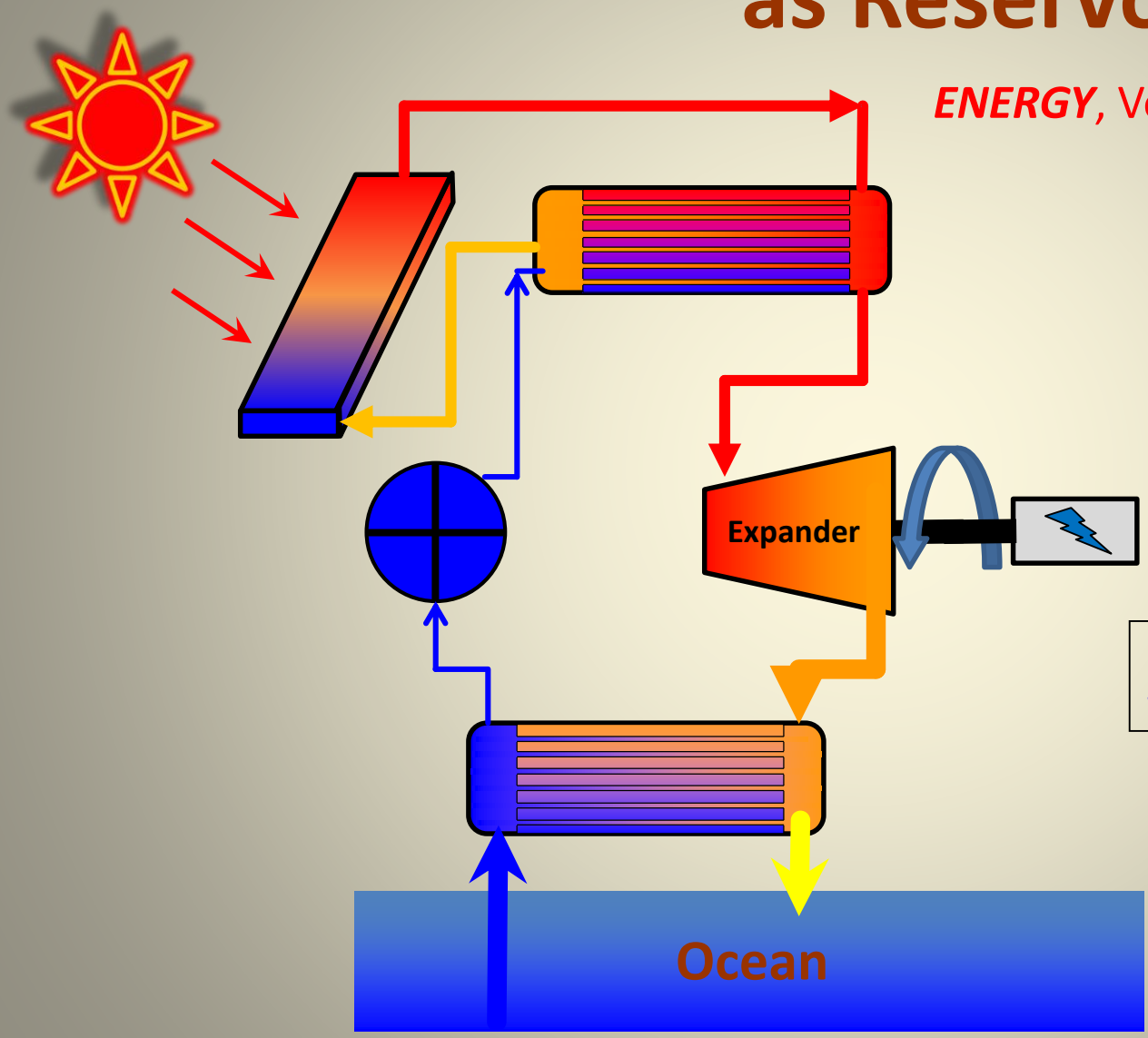
Fig. 3. Demonstration of HTR-10 cycle [2].



Applied Energy, Vol. 99, November 2012, pp. 183–191.

Integrated Solar and OTEC as Reservoir of ORC

ENERGY, Vol. 35, pp. 1403–1411, 2010.



OTEC:

Very small ΔT

→ low efficiency

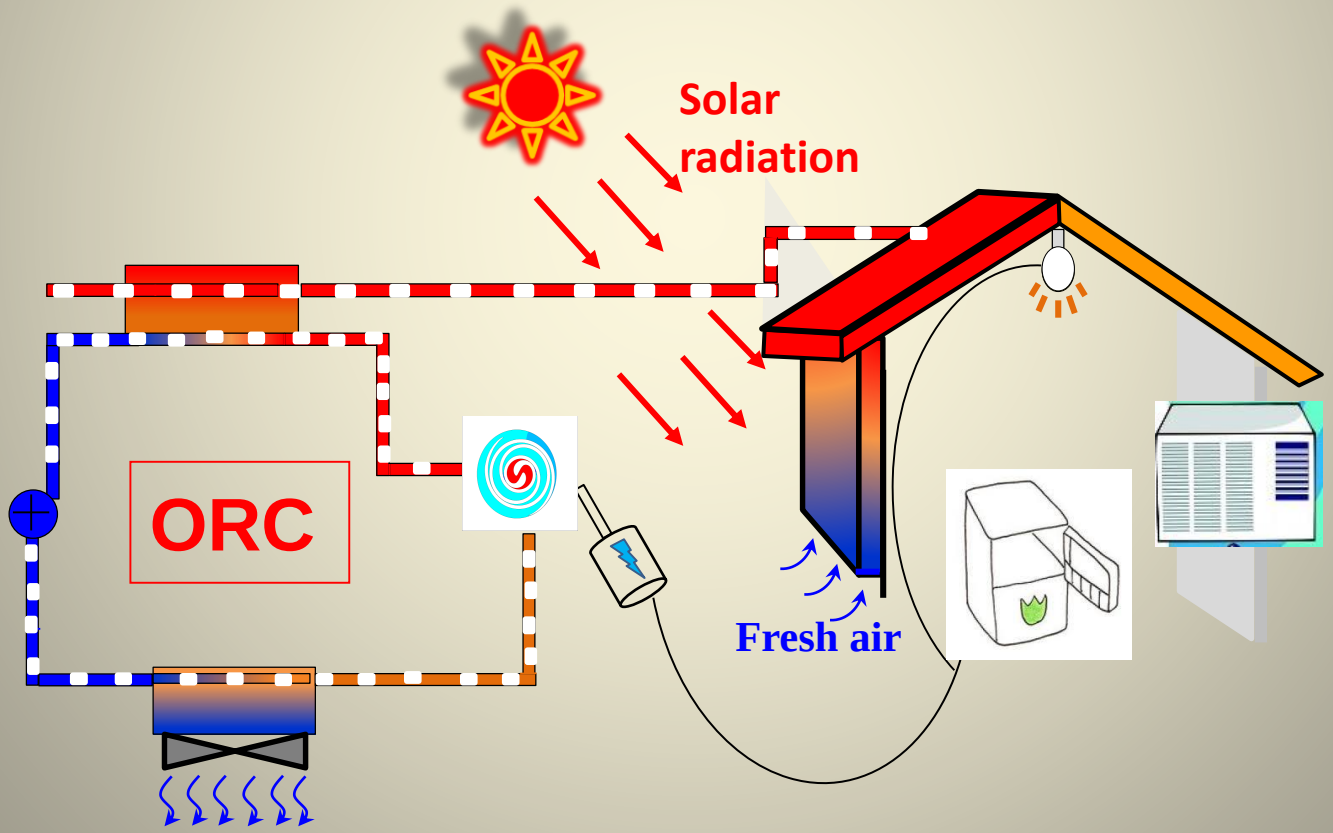
→ high cost

➔ Instead of OTEC, shallow water is good for heat sink.

8 · OECD **EFFECTIVE CARBON RATES** 2021

https://www.oecd.org/tax/tax-policy/effective-carbon-rates-2021-brochure.pdf

Passive solar thermal collection design for ORC application & isolation for indoor



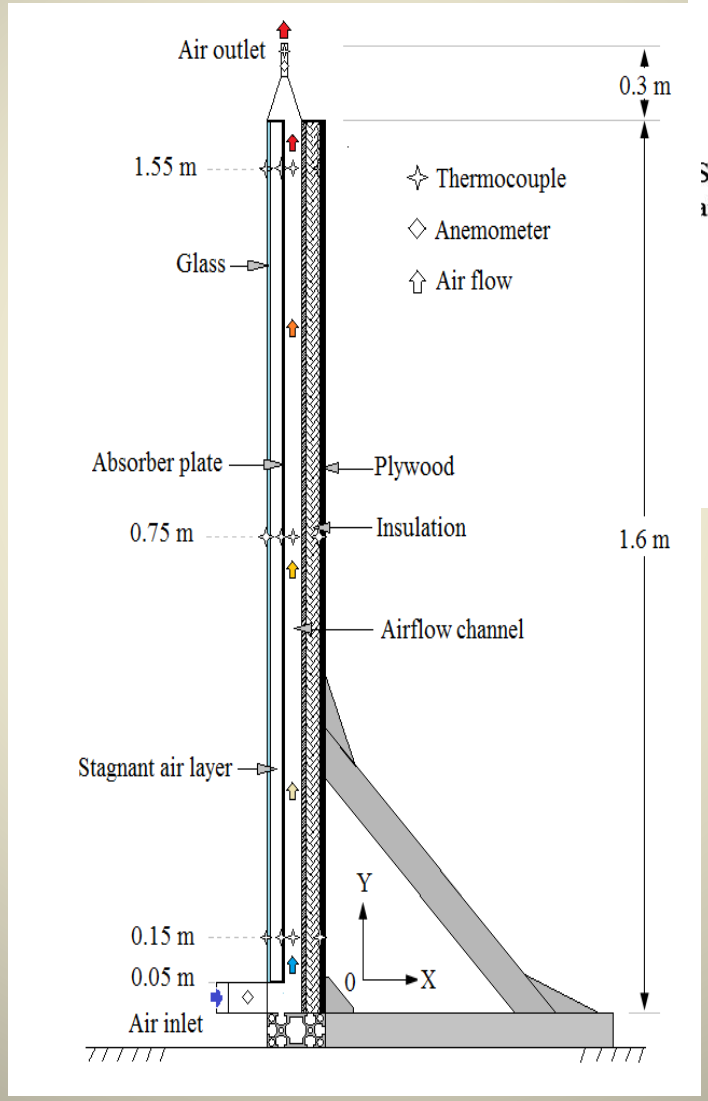
Driving force = net buoyancy force.
It is employed to overcome the friction along the flow path.

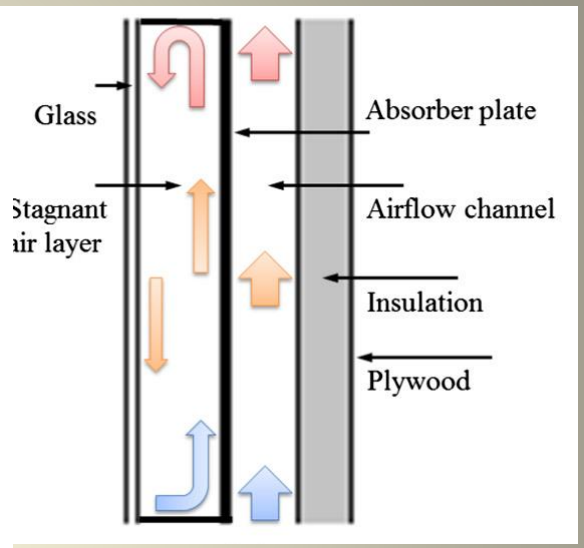
$$\int_{\text{cold } path} \rho g dy - \int_{\text{hot } path} \rho g dy = \sum_{\text{i}} \int_{path\ \text{i}} \frac{1}{2} f_r \rho V^2 dy$$

Longer path ➔ stronger buoyancy force!!

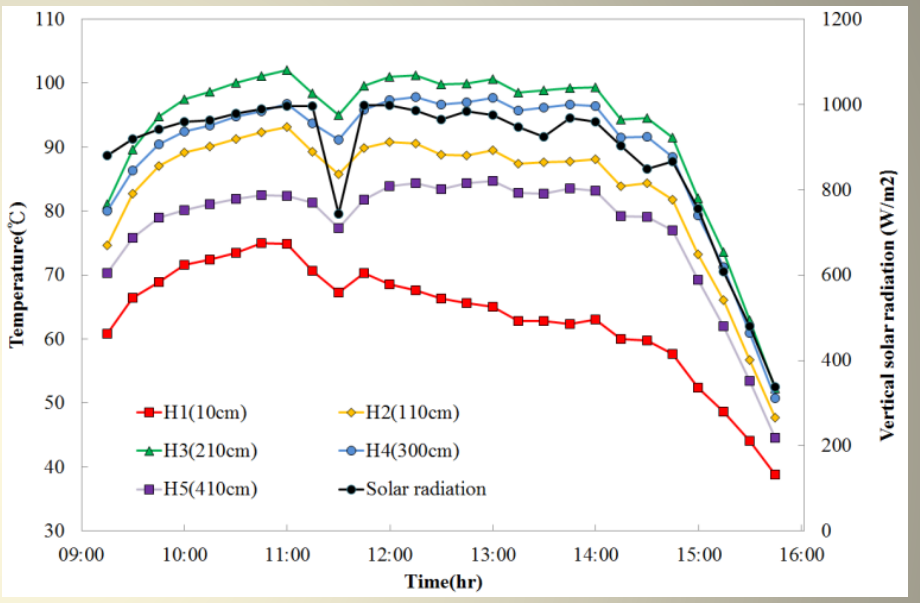
廣義而言：任何可以直接照射到太陽的空間皆可！

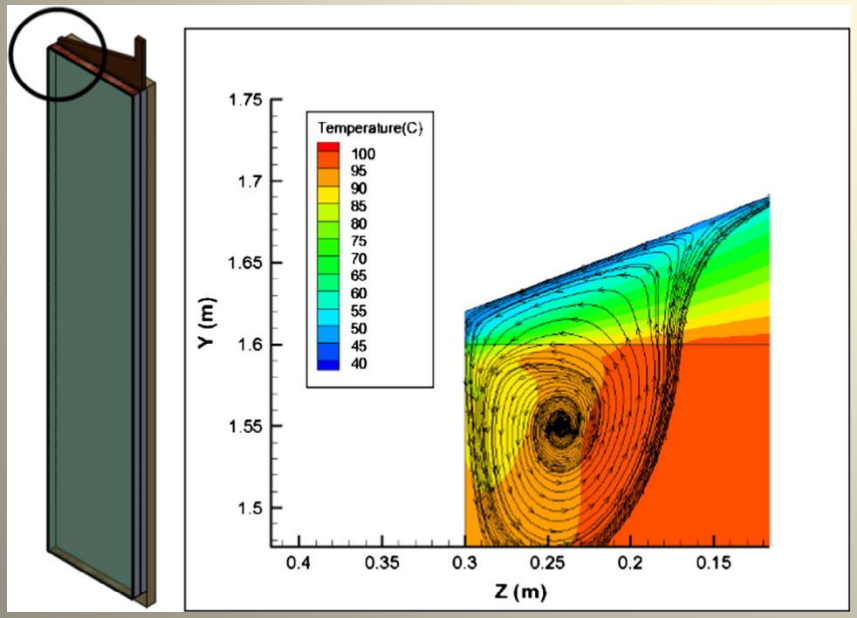
Experiments in solar building





Experiment condition & flow phenomenon

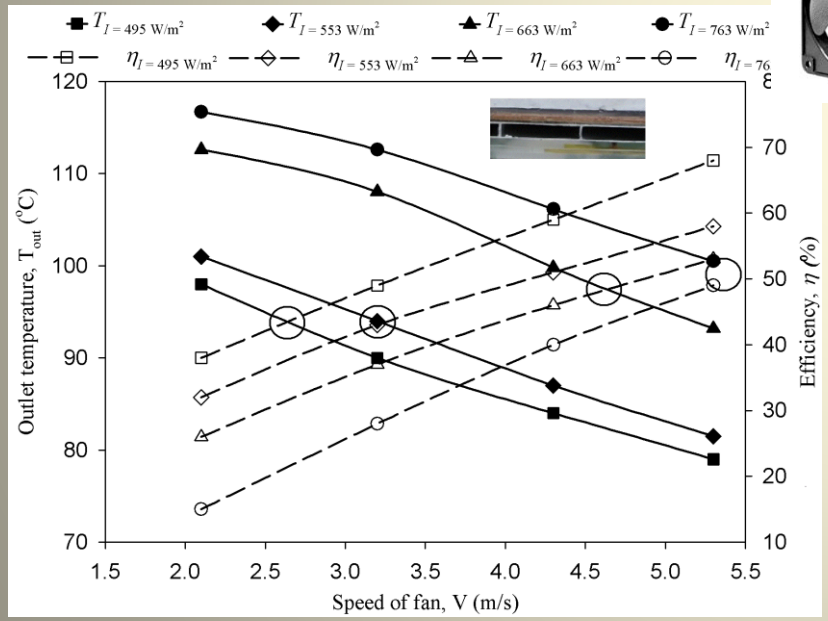


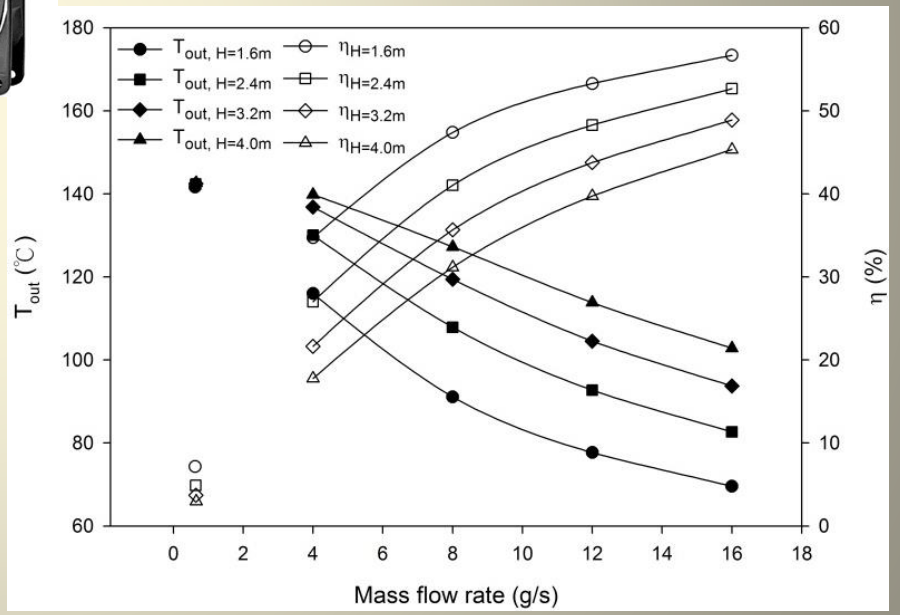


Experiment data

- Mixed convection is preferable

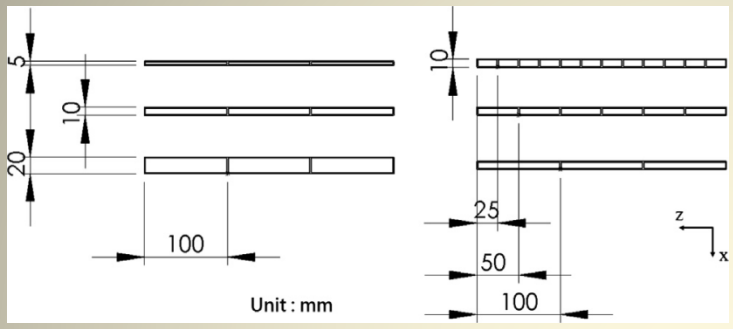
Applied Energy, Vol. 154, 15 September **2015**, pp.651-662.



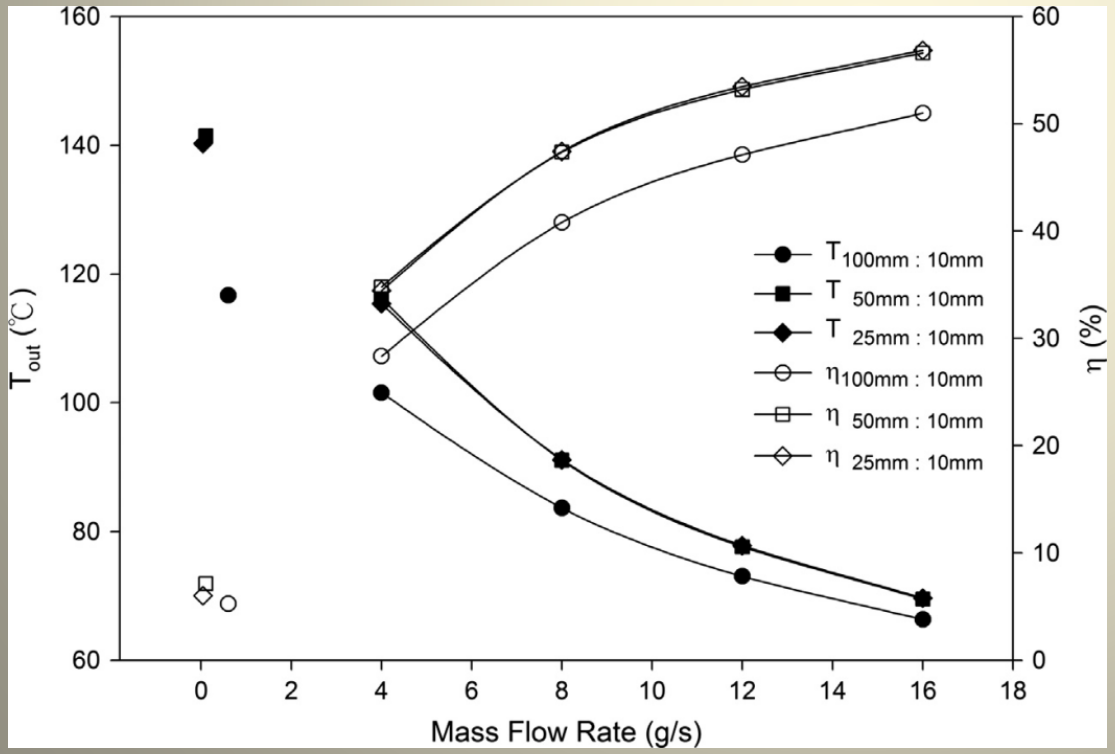


The outlet temperature and efficiency versus mass flow rate at different height of the device.

Experiment data

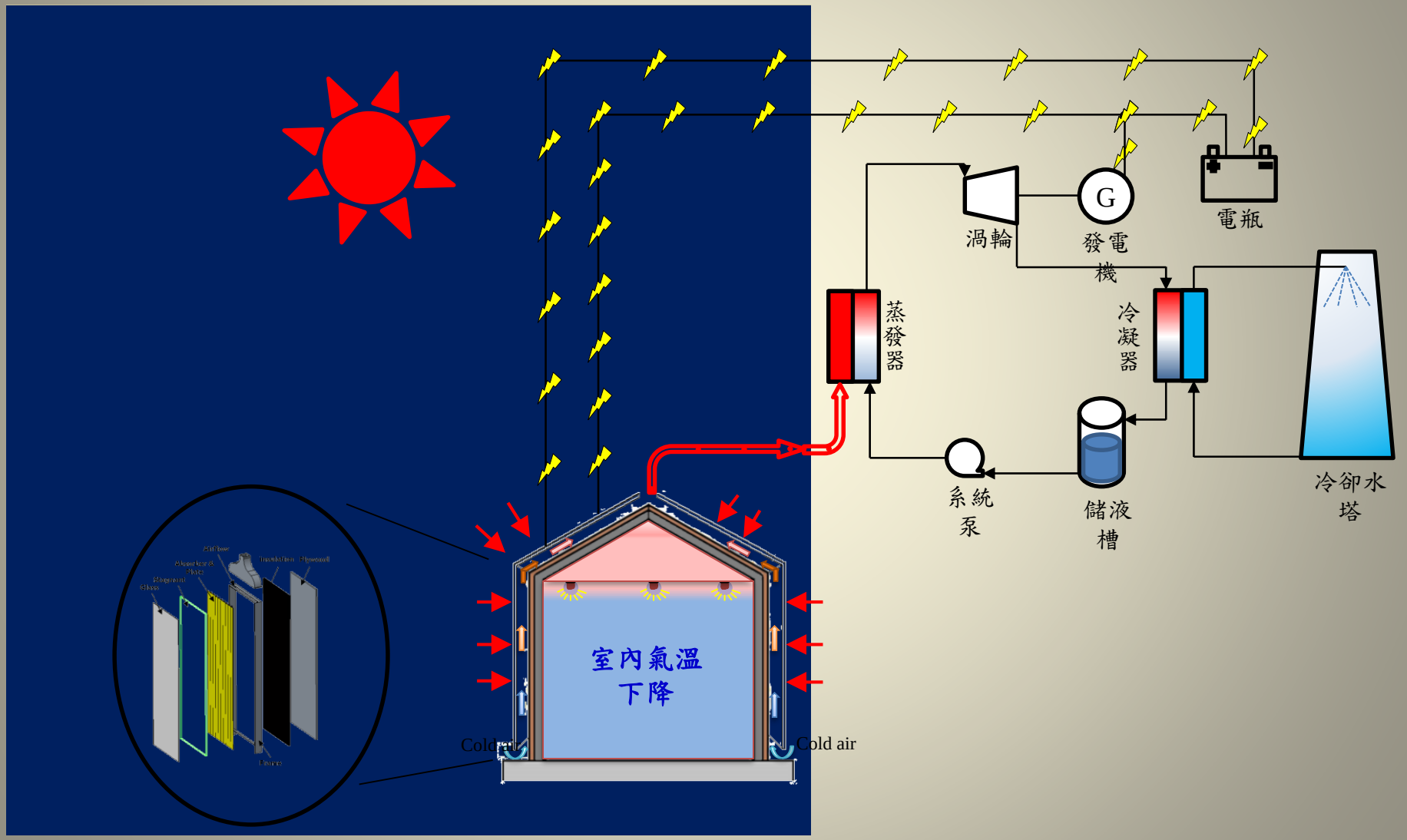


cross section and associate size of rectangular-tube

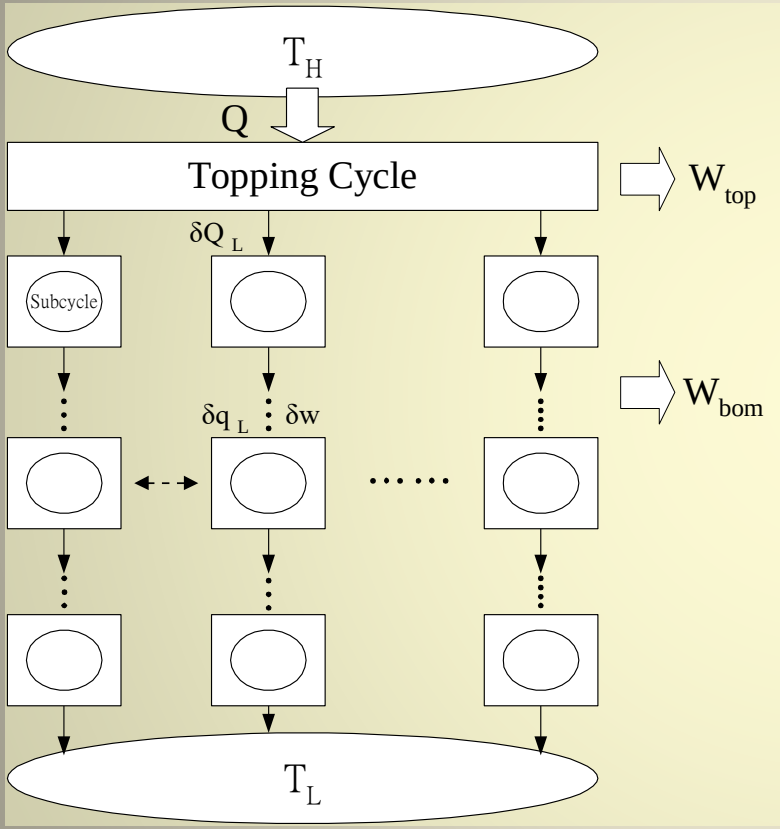


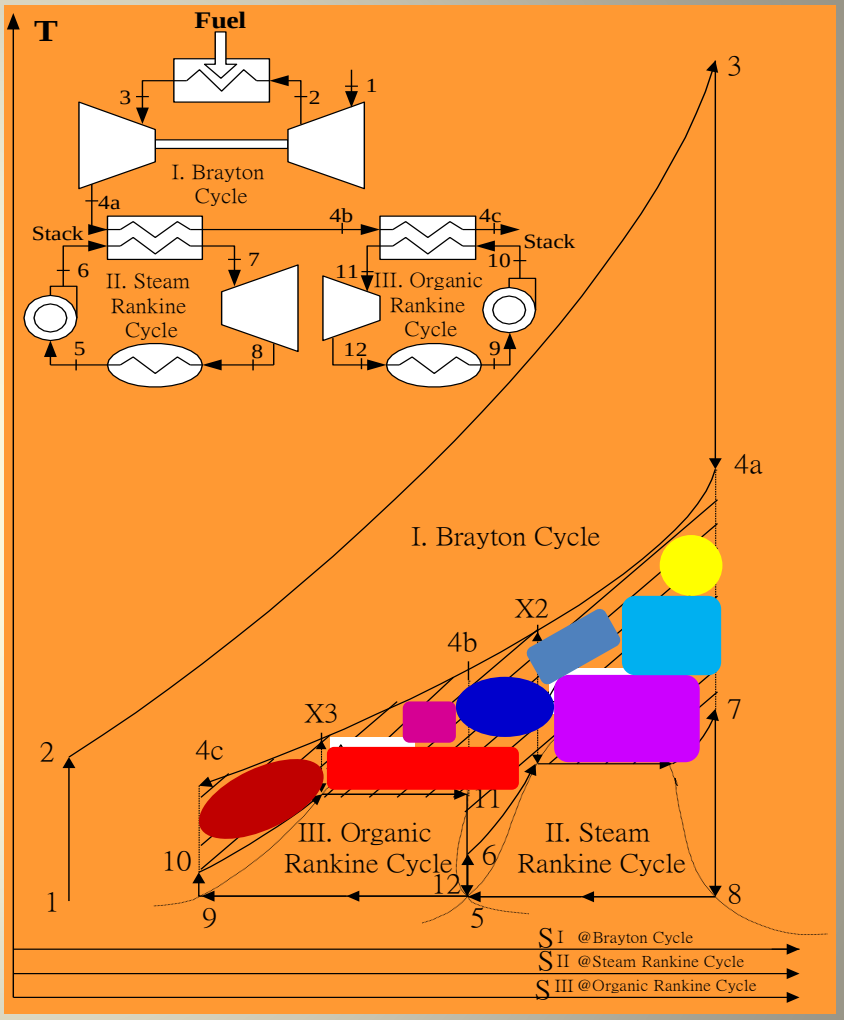
Outlet temperature and efficiency versus air flow rate for three aspect ratios of flow channel

結合產能與儲能



Multi-Cycle to Enhance the Efficiency

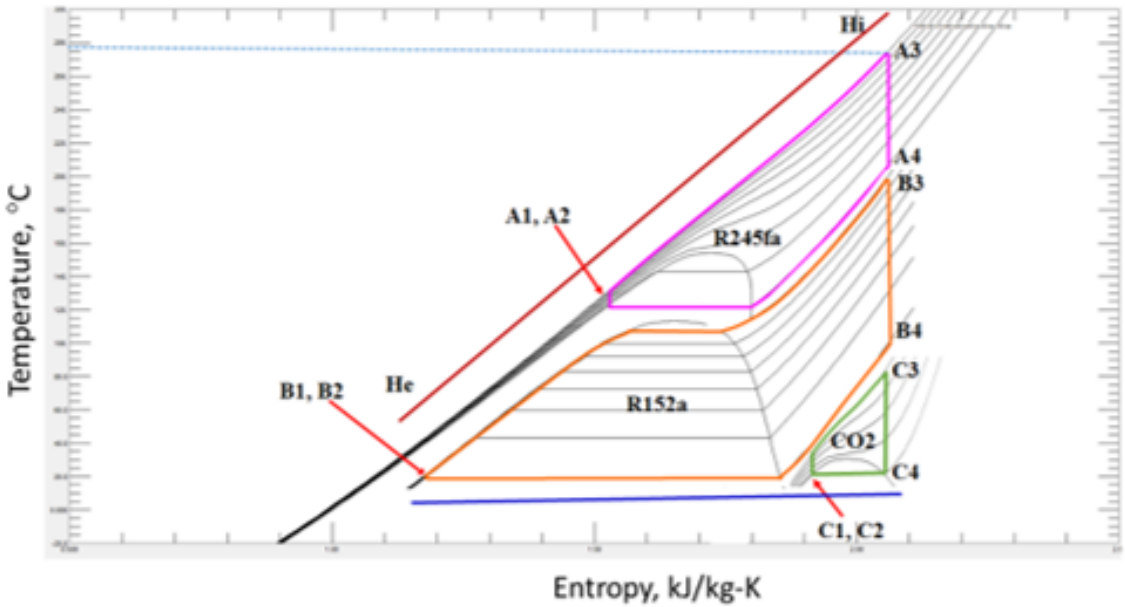




ASME *Journal of Engineering for Gas Turbines and Power,* Vol. 124, 2002, pp. 429-436.

Case Studies in Thermal Engineering, Vol. 28, December 2021, 101601.

Multiple ORCs to effectively generate power from a given pair of high- and low- temperature reservoirs



Layout of the cycles	Net power output, kW	Thermal efficiency, %	Exergy efficiency, %
3 cycles: A+B+C	7093.17	28.06	85.87
2 cycles: A+B	6674.86	26.40	80.80
Single cycle: B	5037.15	19.93	60.98

Applied Thermal Engineering, Vol. 193: 116960, 2021.

What we can do for them?

- **Electricity** + **internet** ➔ enhance **knowledge** and stimulate the civilization
- Low-cost **ORCs**, 2nd-hand **Microsoft and computers** supported from rich countries or charity groups

$$\frac{DS}{Dt} = \frac{dS}{dt} + u \cdot \nabla S \to 0^{+}$$

S: entropy

For you with tons of blessing ...