Application of Finite-time Thermodynamics for Evaluation Method of Heat Engines

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Institute of Ocean Energy, Saga University

- Established in 2003
- Over 40 years of experience of OTEC*
  (*Ocean Thermal Energy Conversion)

<OTEC team:>

- System optimization
  (Experimental, Computational)
- Heat exchanger development
  (Performance test benches, visualization, CFD)

30kW / 15kW OTEC experimental facilities

HE test facilities

Ocean Thermal Energy Conversion System in Japan

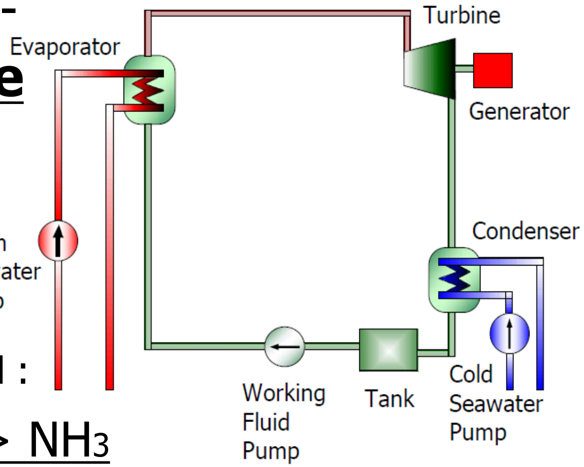
- 100kW
- HFC134a
- Rankine cycle (2-stages)

In 2013, launched NEW STAGE to connect the grid for the first time in the 21st century.

1. Motivation & lessons

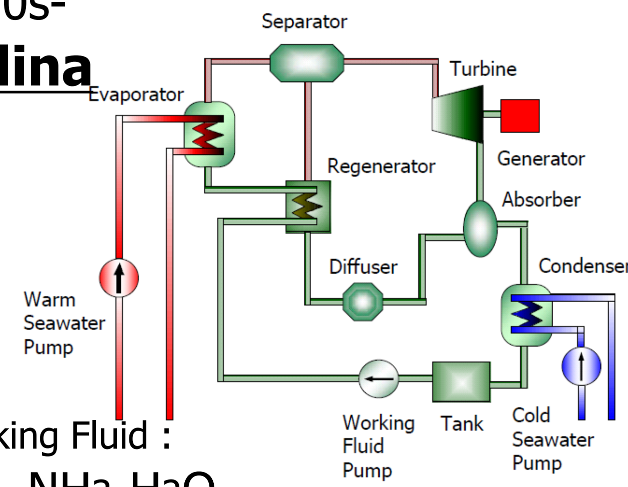
Development of High Efficiency Thermo-Cycle

1970s,80s-
Rankine



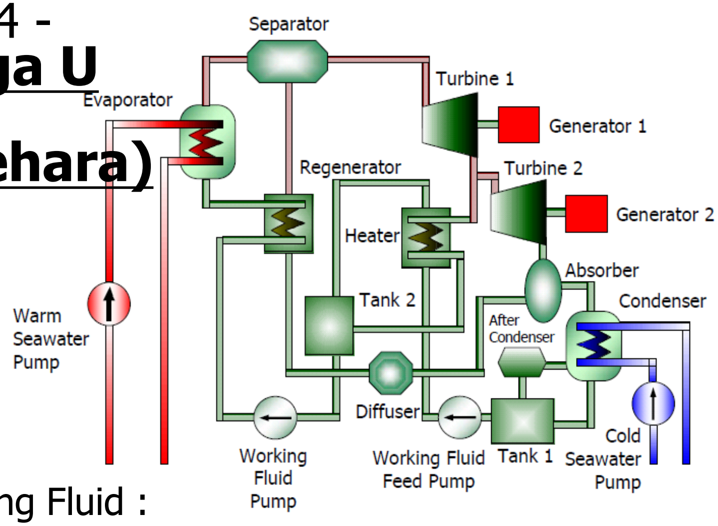
Working Fluid :
HFC22 -> NH_3

1990s-
Kalina



Working Fluid :
NH_3-H_2O

1994 -
Saga U
(Uehara)



Working Fluid :
NH_3-H_2O

2011 – **Double Rankine**
NH_3
HFC134a

Increase Net power
NOT
Thermal efficiency

Thermal efficiency

Avery, H. W. and Wu, C., Renewable Energy from the Ocean - A guide to OTEC - (1994)

- Upper bound of thermal efficiency:
Warm seawater temp T_W and
Cold seawater temp T_C

$$\eta_{th,m} = 1 - \frac{T_C}{T_W}$$

- At the maximum work condition the thermal efficiency:
(Finite-time thermodynamics)

The half of Upper

$$\eta_{th,CA} = 1 - \sqrt{\frac{T_C}{T_W}}$$

Condition at maximum efficiency and maximum work is different.
That is the contradiction of the performance.

Propose the normalized thermal efficiency for low-grade thermal energy conversion
– An application of ORC -

[2] I. I. Novikov, The efficiency of atomic power stations, Nucl. Energy II-7 1958;125-128; Translated from At. Energ. 3; 1957. p. 409
[3] F. L. Curzon and B. Ahlborn, Efficiency of a Carnot engine at maximum power output, Am. J. Phys., Vol. 43; 1975. p.22-24

Applicable heat sources

Low-grade Thermal Energy Conversion (LTEC)

Series of small scale ORC package units commercialized or semi-commercialized in Japan

ULVAC

3 kW

ANEST IWATA

11 kW

IHI

20 kW

KOBELCO

72 kW

ELECTRA THERMO

110 kW

ACCESS ENERGY

135 kW

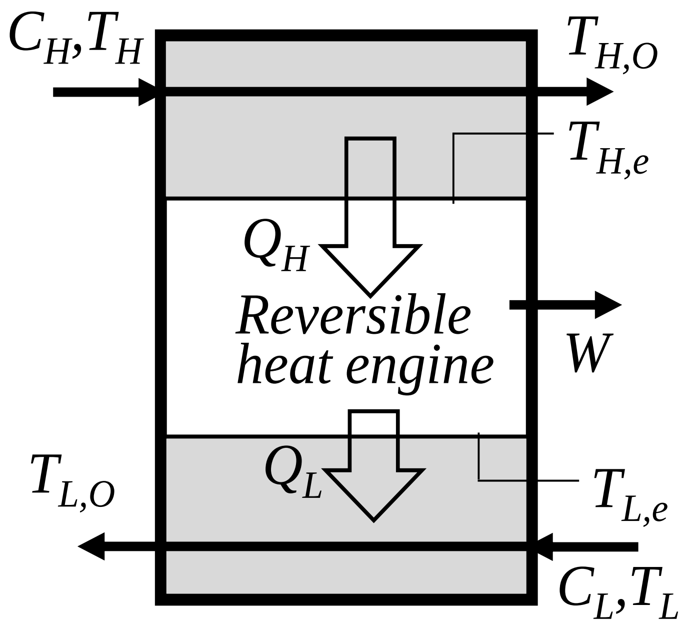
Performance Spec. is only Capacity of Products. Why ?

On the other hand, many researches uses the achievement of increase of the thermal efficiency in their system.

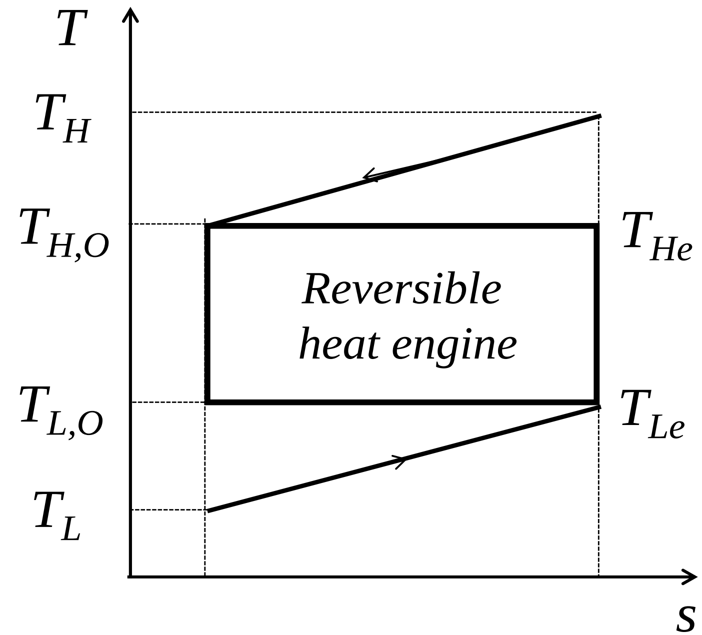
Definition of the effective thermal efficiency is required.

2. Concept

Thermodynamic model of ideal condition



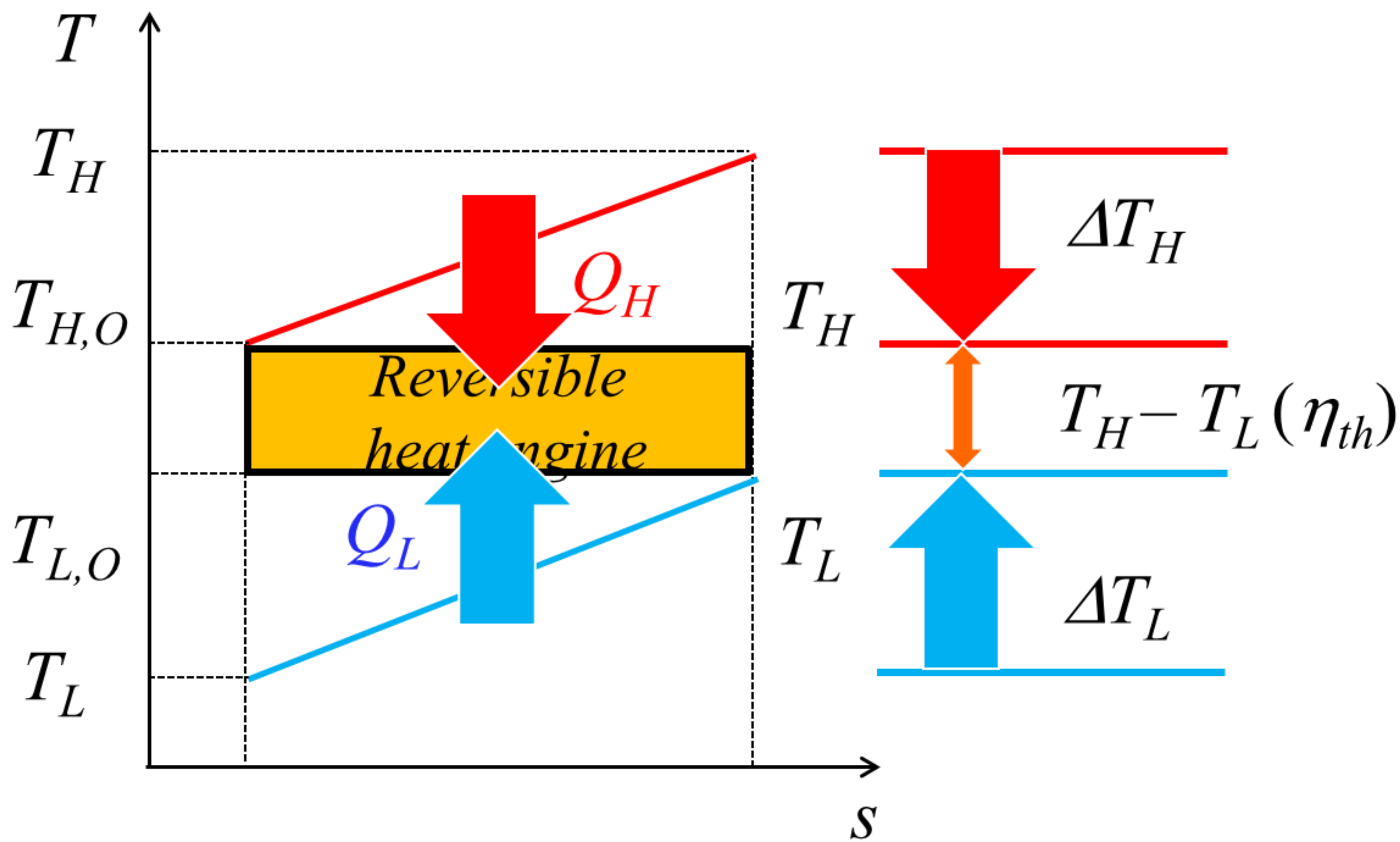
Conceptual model



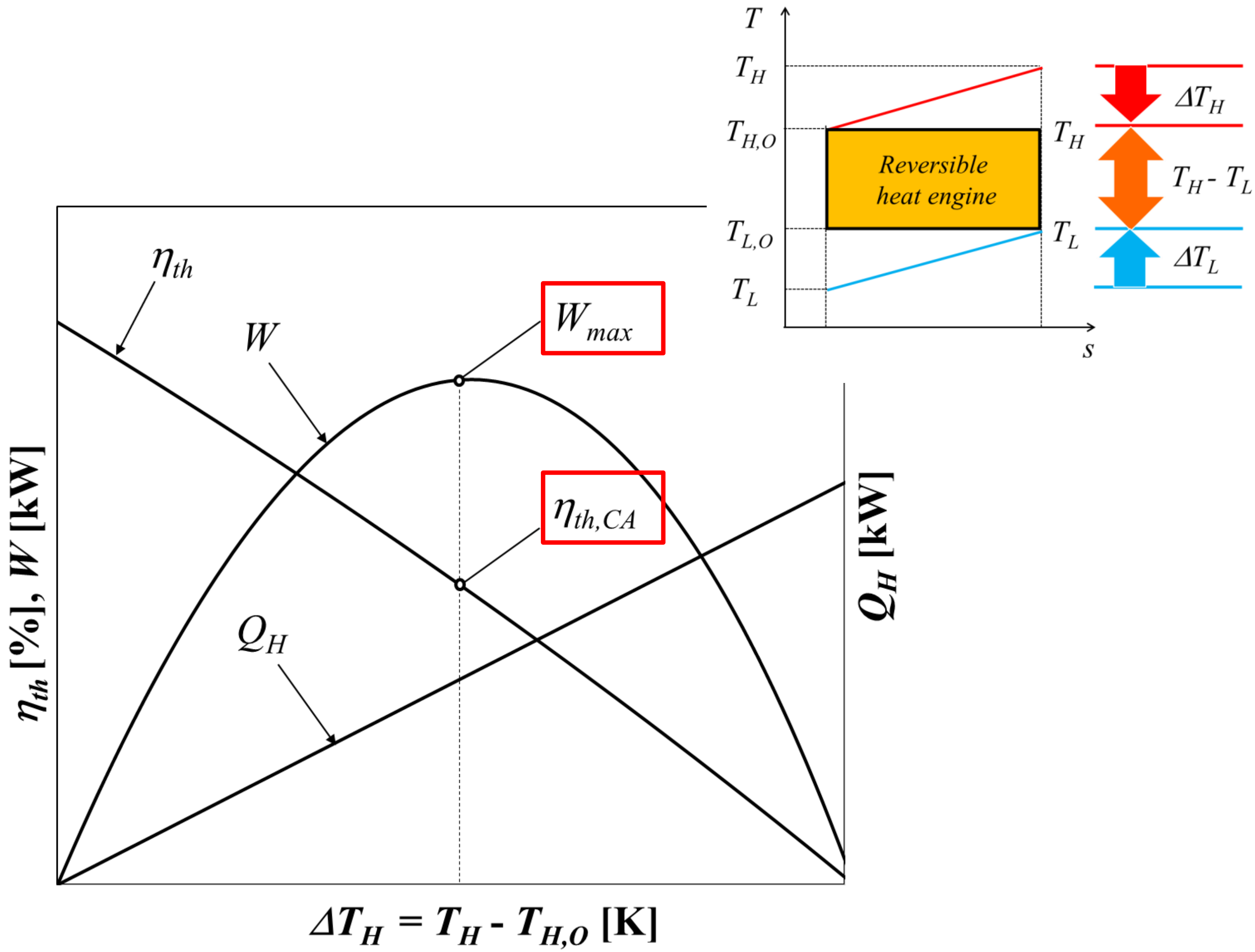
Conceptual T-s diagram

- *Thermal energy is stored in liquid as sensible heat*
- *Specific heat is constant*
- *Ideal heat exchanger (zero pinch temperature)*
- *Reversible heat engine (Carnot cycle)*

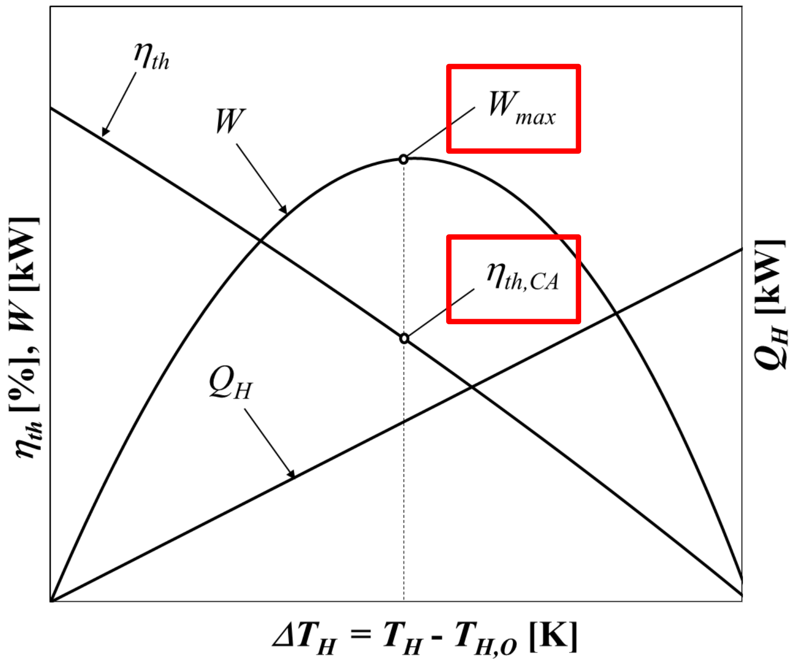
Contradiction of the perk of work and thermal efficiency



Contradiction of the perk of work and thermal efficiency



Maximum work condition



$$Q_H = rC_{HS}(T_H - T_{H,O})$$

$$\eta_{th} = 1 - \frac{T_{L,O}}{T_{H,O}}$$

$$\Delta s = \frac{Q_H}{T_{H,O}} - \frac{Q_L}{T_{L,O}} = 0$$

$$W = \eta_{th} Q_H = f(T_{H,O})$$

W will be the one degree of freedom

$$\frac{\partial W}{\partial T_{H,O}} = 0 \Rightarrow W_{max}$$

$$C_{HS} = C_H + C_L \quad , r = C_H / C_{HS}$$

C is the heat capacity flow rate [W/K]
(mass flow rate [kg/s] times specific heat [kJ/kgK])

$$W_{max} = r(1-r)C_{HS}\left(\sqrt{T_H} - \sqrt{T_L}\right)^2$$

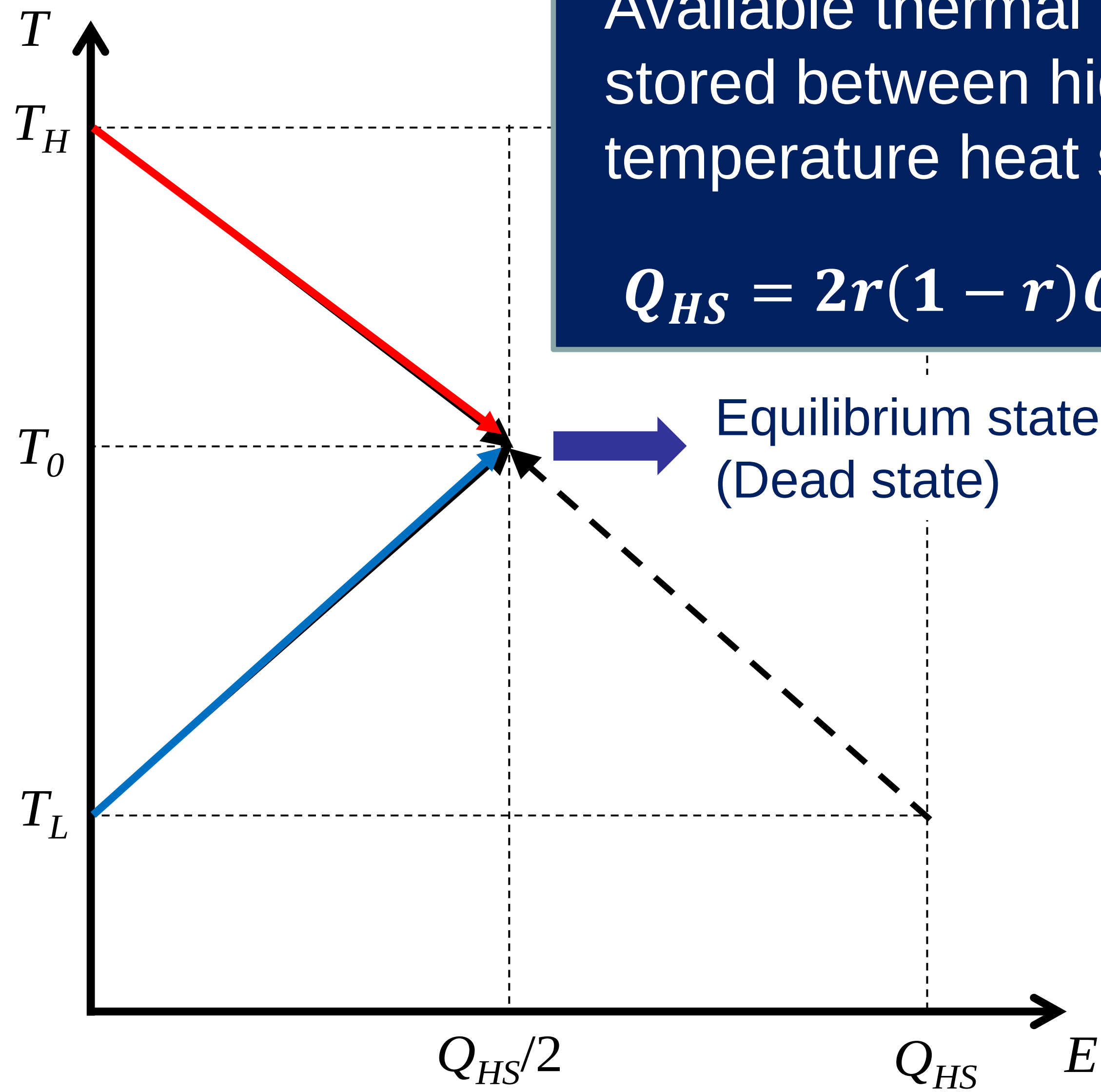
$$\eta_{th,CA} = 1 - \sqrt{\frac{T_L}{T_H}}$$

3. Normalization of Thermal Efficiency

Thermal energy in heat source

Available thermal energy stored between high and low temperature heat source

$$Q_{HS} = 2r(1-r)C_{HS}(T_H - T_L)$$



Conventional thermal efficiency

$$\eta_{th} = \frac{W}{Q_H} = \frac{W}{rC_{HS}\left(T_H - T_{H,O}\right)}$$

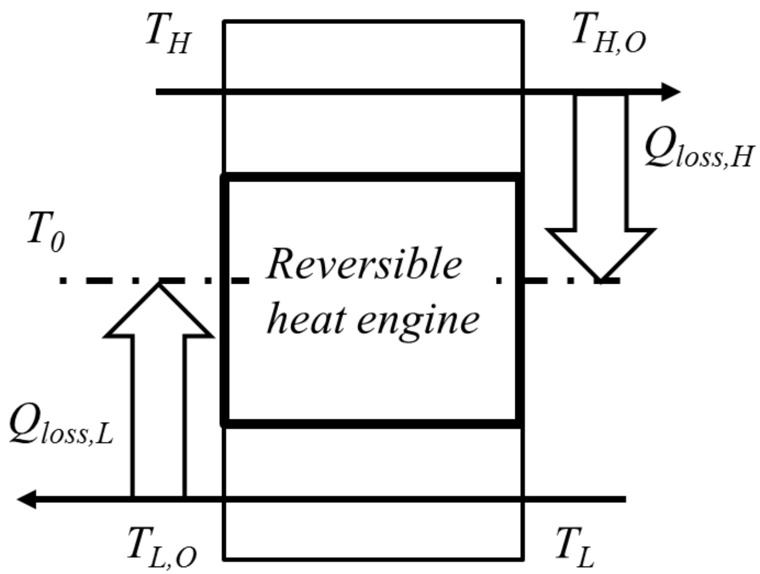
Change the denominator to available thermal energy

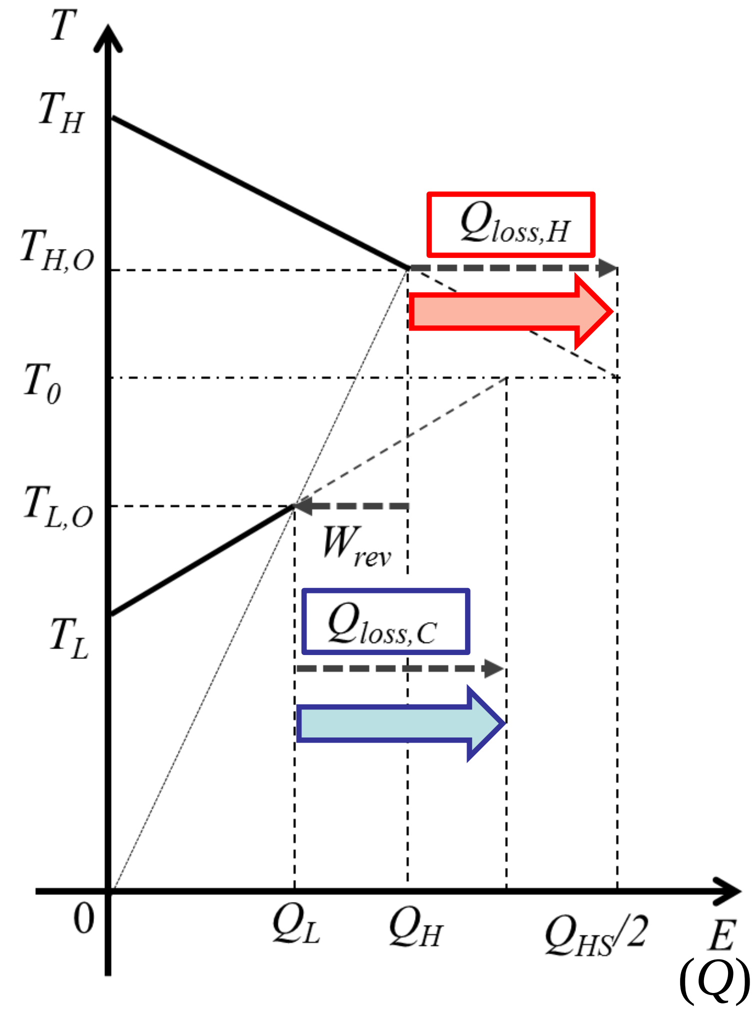
$$\eta_{th,Nor} = \frac{W}{Q_{HS}} = \frac{W}{2r(1-r)C_{HS}(T_H - T_L)}$$

Normalized thermal efficiency

Normalized thermal efficiency only depends on the heat source condition and independent from the heat transfer rate to heat engine

Normalized thermal efficiency takes into account the external irreversibility

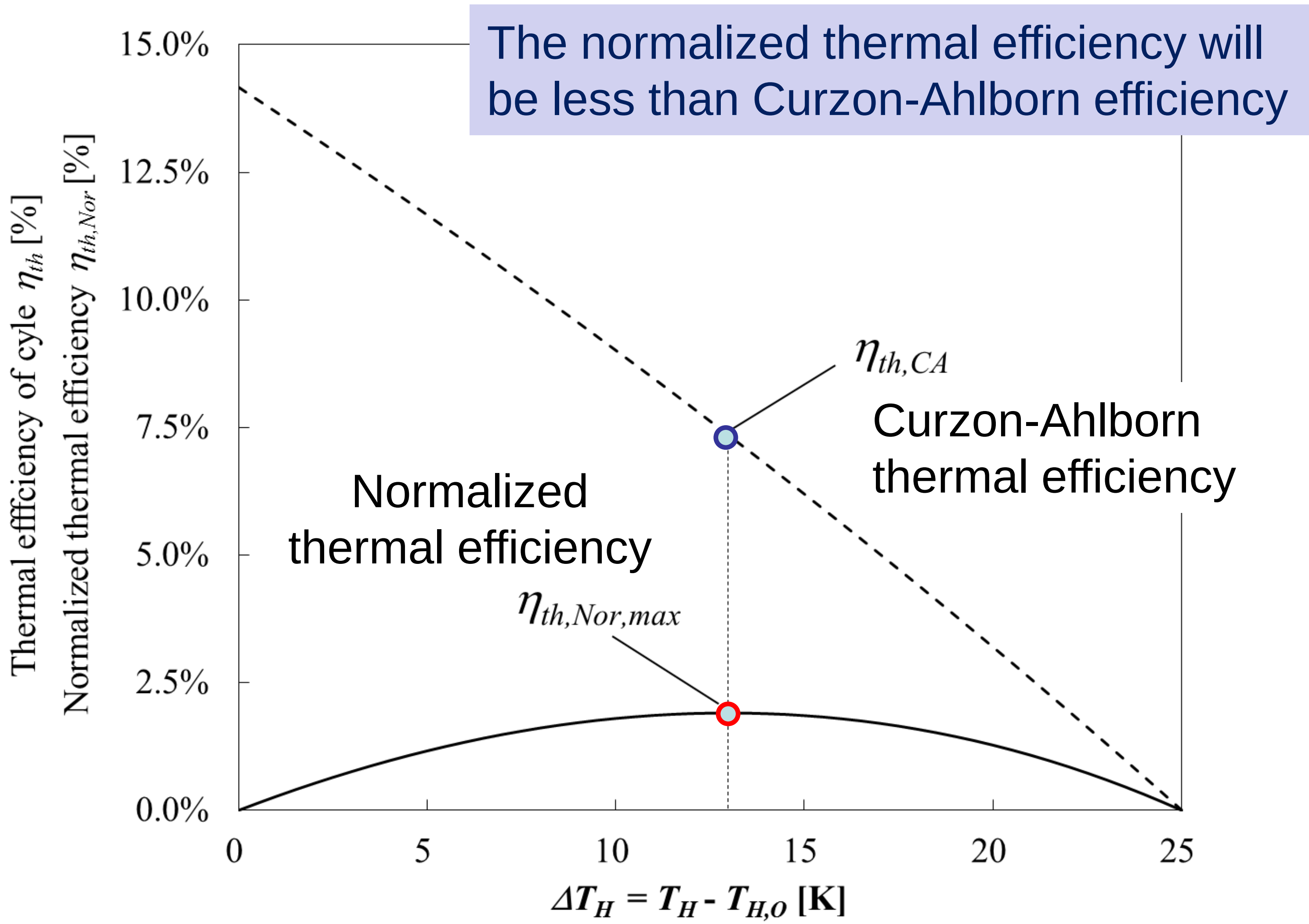




To apply the heat source thermal energy based on the equilibrium state to thermal efficiency is equivalent to take into account the external irreversibility

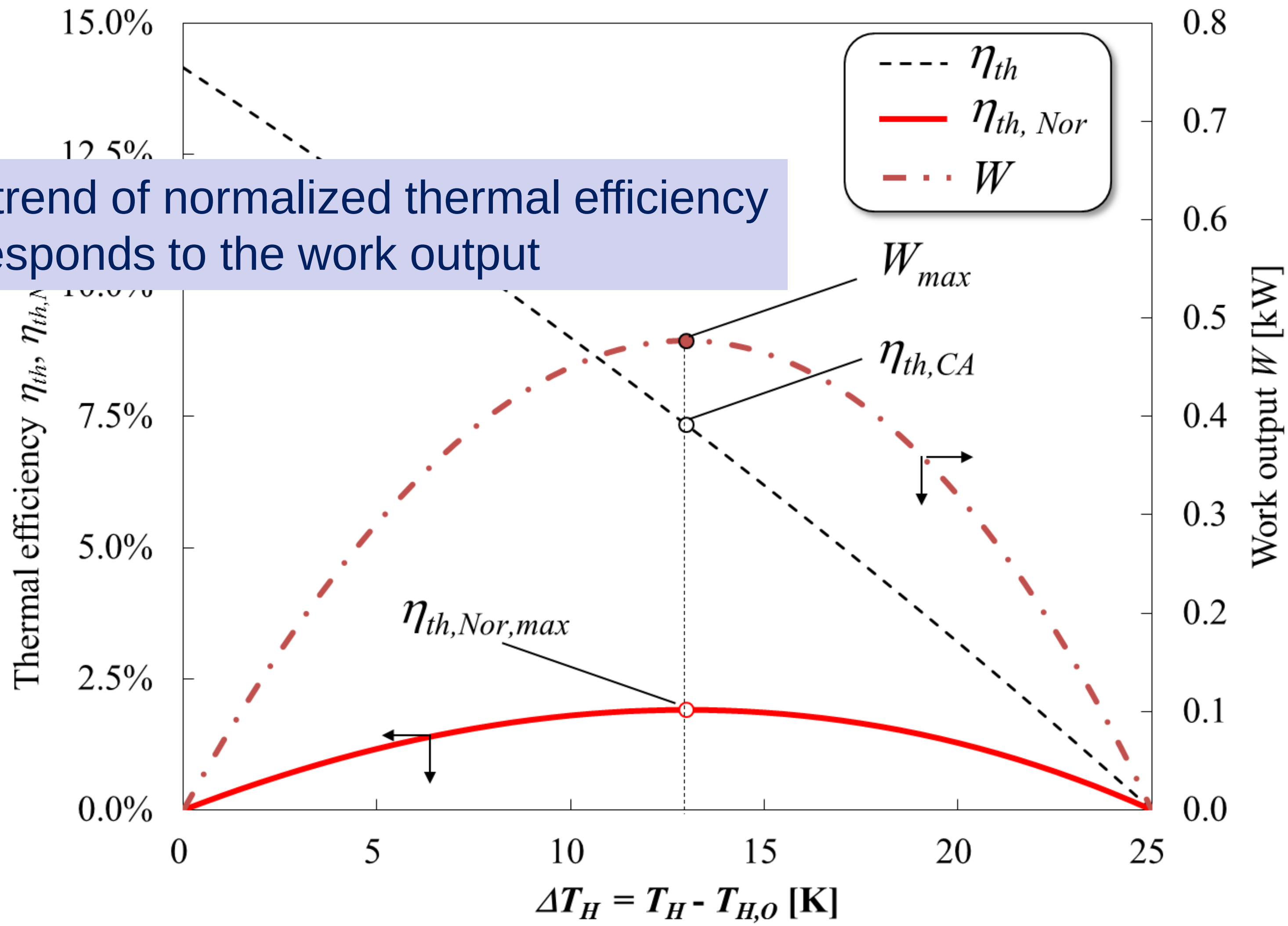
[11] A.Bejan, Graphic Techniques for Teaching Engineering Thermodynamics, *Mechanical Engineering News*, (1997), pp.26-28
[12] P. Salamon, K. H. Hoffmann, S. Schubert, R. S. Berry, B. Anderson, What conditions make minimum entropy production equivalent to maximum power production, *J. Non-Equilibrium Thermodynamics*, Vol. 26, (2001), pp.73-83

Comparison between normalized thermal efficiency and conventional thermal efficiency



In case T_H=80^{o}C, T_L=30^{o}C, r=0.5, C_{HS}=1 kW/K.

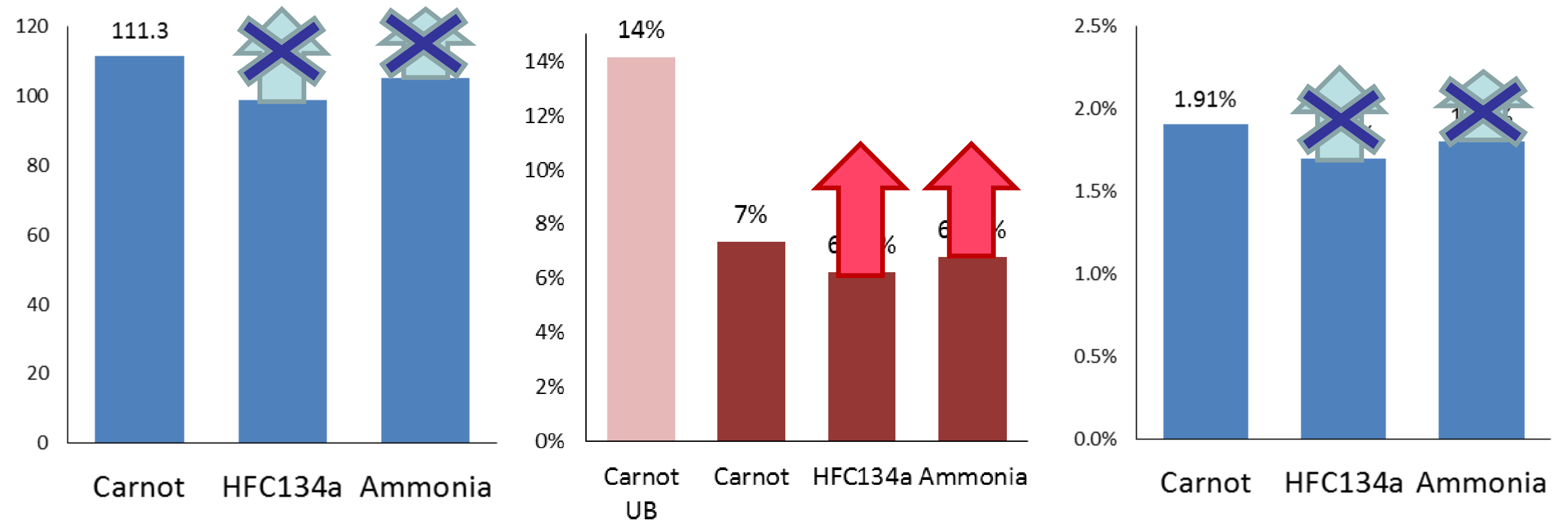
Comparison between normalized thermal efficiency and conventional thermal efficiency



The trend of normalized thermal efficiency corresponds to the work output

In case T_H=80^{o}C, T_L=30^{o}C, r=0.5, C_{HS}=1 kW/K.

Application of normalized thermal efficiency to Rankine cycles



Maximum power output | Thermal efficiency | Normalized thermal efficiency

In the design stage of ORC on LTEC, the maximization of normalized thermal efficiency will lead to the maximization of work output from a heat engine, instead of the conventional thermal efficiency.

The heat source condition corresponds to Ref. [15] that T_H=80 °C, T_L=30 °C, C_{HS}=233 kW/K.

[15] T. Morisaki and Y. Ikegami, Maximum power of a multistage Rankine cycle in low-grade thermal energy conversion, *Applied Thermal Engineering*, Vol.69, (2014), pp.78-85

4. Summary and future work

Summary

Still the field of Low-grade thermal energy conversion (LTEC) system uses the thermal efficiency as the performance evaluation and try to achieve higher thermal efficiency.

The effective thermal efficiency is required for the effective evaluation of the system.

In the field of the LTEC, the normalized thermal efficiency is proposed and the maximization of normalized thermal efficiency will maximize the power output of the system.

$$\eta_{th,Nor} = \frac{W}{Q_{HS}} = \frac{W}{2r(1-r)C_{HS}(T_H - T_L)}$$

Future work

- To extend the concept to exergy efficiency for Low-grade thermal (Not to misread the normalized thermal efficiency)

- To apply the normalized thermal and exergy efficiencies to the design optimization for Low-grade thermal energy conversion

- To extend the idea to the other heat source systems

Thank you so much for your attention.

Grazie mille

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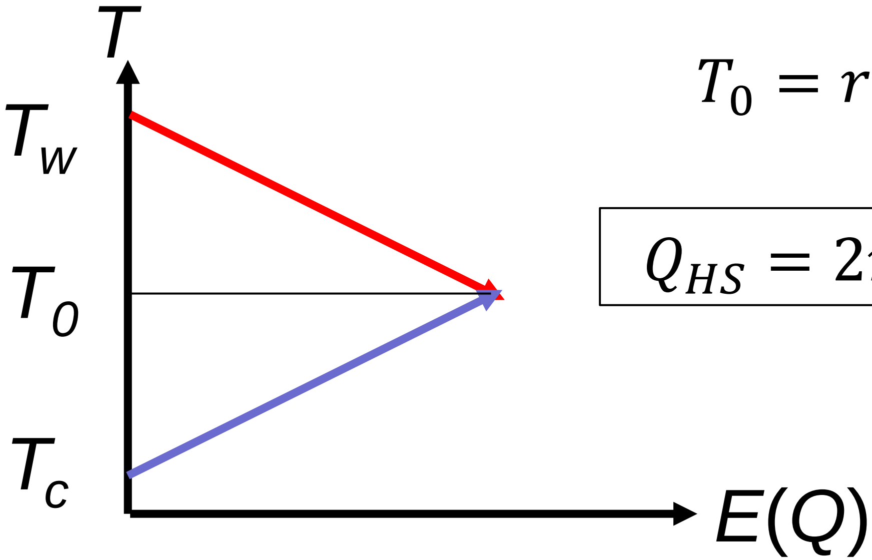
$$Q_{HS} = \underline{(mc_p)_H\left(T_H - T_{H,O}\right)} + \underline{(mc_p)_L\left(T_{L,O} - T_L\right)}$$

$$= \underline{C_H}\left(T_H - T_{H,O}\right) + \underline{C_L}\left(T_{L,O} - T_L\right)$$

$$Q_{HS} = C_H(T_H - \underline{T_0}) + C_L(\underline{T_0} - T_L)$$

T_0: dead state (Equilibrium state)



$$T_0 = rT_H + (1 - r)T_L$$

$$Q_{HS} = 2r(1 - r)C_{HS}(T_H - T_L)$$