Heat Pump Systems

Summary W2

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Open System Balances

- Energy balance:

$$\frac{dE_{cv}}{dt} = \dot{W}_{cv} + \dot{Q}_{cv} + \sum \dot{m}_{in}\left(h + \frac{w^2}{2} + gz\right)_{in} - \sum \dot{m}_{out}\left(h + \frac{w^2}{2} + gz\right)_{out}$$

Net convected power

Net work

Net heat

Specific internal + transfer energy

Specific kinetic energy

Specific potential energy

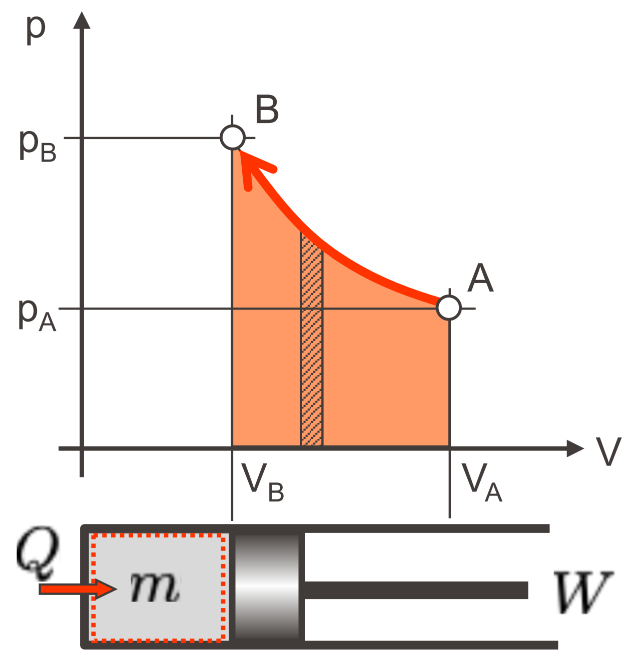
- Mass balance:

$$\frac{dm_{cv}}{dt} = \sum \dot{m}_{in} - \sum \dot{m}_{out}$$

Work

- Consider closed system where piston moves from A to B

$$W = \int_A^B \delta W = -\int_{x_A}^{x_B} pAdx = -\int_{V_A}^{V_B} pdV$$



- Work depends on evolution of p vs. V
  → work depends on process details

- Surface under transformation line in pV-diagram represents work

- Work is no thermodynamic state property

Heat

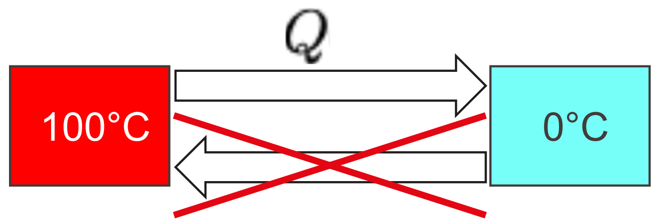
- Conduction: Fourier's law $$\dot{q} = \frac{\dot{Q}}{A} = -\lambda \frac{dT}{dx}$$

- Radiation: Boltzmann-equation $$\dot{q} = \epsilon \sigma T^4$$

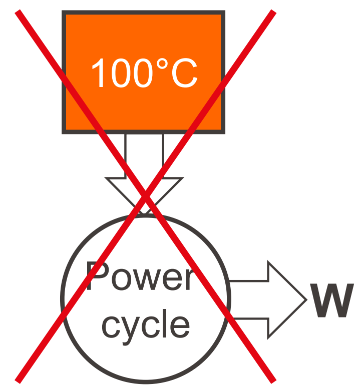
- Convection: Newton's law $$\dot{q} = \frac{\dot{Q}}{A} = \alpha \left(T_{Wall} - T_{Fluid} \right)$$

Formulations of 2nd Law

- By Clausius (1854): There is no change of state whose only result is the transfer of heat from a body at a lower temperature to a body at a higher temperature



- Kelvin-Planck (1848/1926): It is impossible to construct a device which, operating in a cycle, will produce no other effect than the extraction of heat from a reservoir and the performance of equivalent amount of work



Carnot Principles

- The thermal efficiency of an irreversible power cycle is always lower than that of a reversible cycle between the same thermal reservoirs
- All reversible power cycles between the same thermal reservoirs have the same thermal efficiency
- The efficiency of a reversible machine is independent of the process, the components, and the working fluid

Thermal Efficiency

- Through Kelvins definition, thermal efficiency of reversible cycle expressed as:

$$\eta_{th-rev.} = 1 - \frac{T_{cold}}{T_{hot}} = \eta_c$$

- Carnot cycle is one famous reversible power cycle

- Thermal efficiency of reversible cycle is called Carnot-efficiency

?

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Entropy

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Formulations of 2nd Law

- There is no change of state whose only result is the transfer of heat from a body at a lower temperature to a body at a higher temperature (Clausius)

- It is impossible to construct a device which, operating in a cycle, will produce no other effect than the extraction of heat from a reservoir and the performance of equivalent amount of work (Kelvin-Planck)

- Formulations are qualitative

Alternative Formulation of 2nd Law

- Mathematical formulation of 2nd law possible via Clausius inequality for any cycle process

$$\oint \frac{\delta Q}{T} \leq 0$$

Heat across system boundary (δQ)

Temperature of heat transfer across system boundary (T)

  - Valid for any cycle process
  - Reversible if integral = 0
  - Irreversible if integral < 0
  - 2nd law forbids processes with integral > 0

Example: Carnot Cycle

- Carnot efficiency

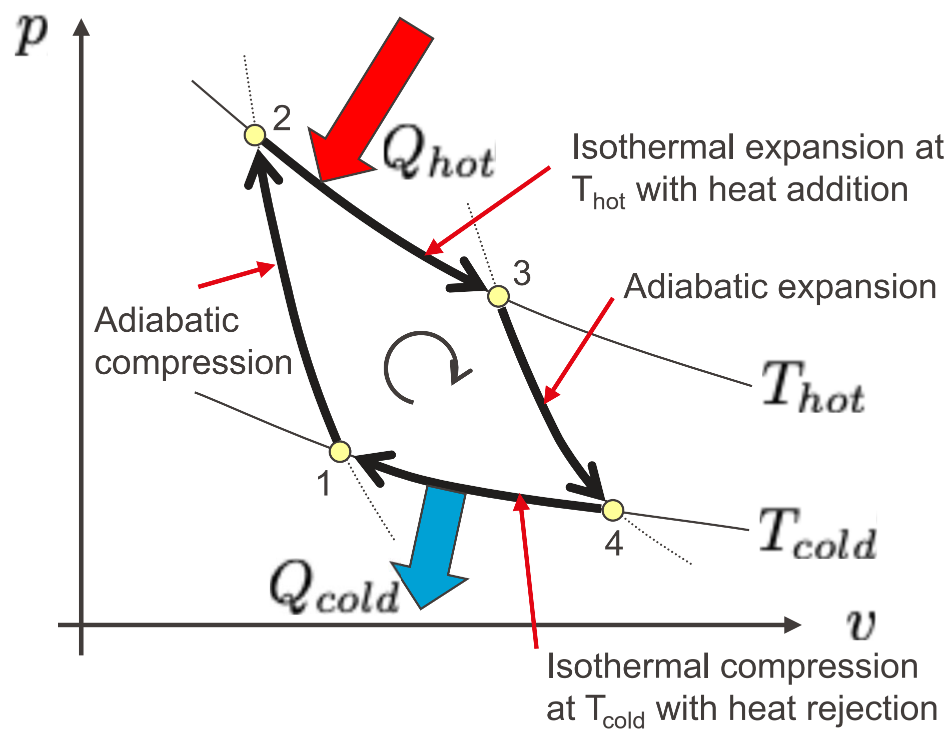
$$\eta_c = 1 - \frac{Q^-_{cold}}{Q^+_{hot}} = 1 - \frac{T_{cold}}{T_{hot}}$$

$$\frac{Q^-_{cold}}{Q^+_{hot}} = \frac{T_{cold}}{T_{hot}}$$

- Clausius inequality → equality

$$\oint \frac{\delta Q}{T} = \frac{Q^+_{hot}}{T_{hot}} - \frac{Q^-_{cold}}{T_{cold}}$$

$$\oint \frac{\delta Q}{T} = 0$$



Alternative Formulation of 2nd Law

- Writing Clausius inequality as equation

$$\oint \frac{\delta Q}{T} = -\sigma$$

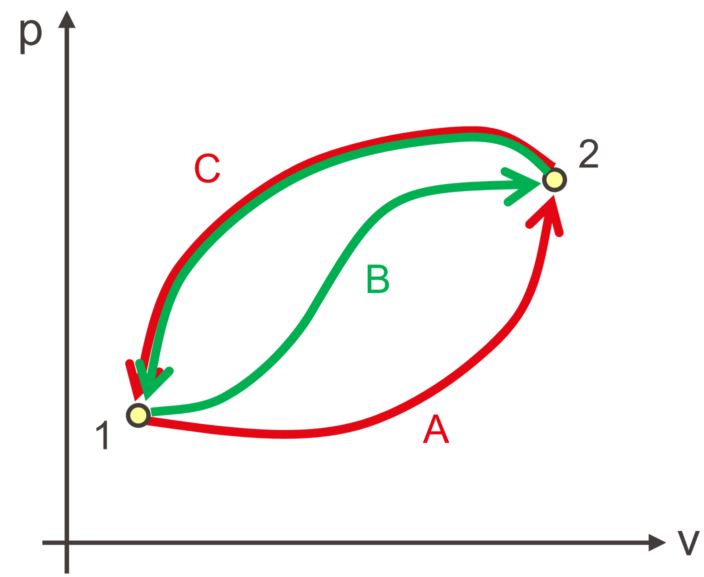
- 2nd law now contained in σ
  - $\sigma = 0$ → reversible process
  - $\sigma > 0$ → irreversible process
  - $\sigma < 0$ → Not possible (2nd law)

Entropy

- Consider two reversible cycles, AC & BC, going through states 1 & 2
- Since reversible r_{AC} and r_{BC} = 0

$$\int_1^2 \frac{\delta Q}{T}\bigg|_A + \int_2^1 \frac{\delta Q}{T}\bigg|_C = 0$$

$$\int_1^2 \frac{\delta Q}{T}\bigg|_B + \int_2^1 \frac{\delta Q}{T}\bigg|_C = 0$$



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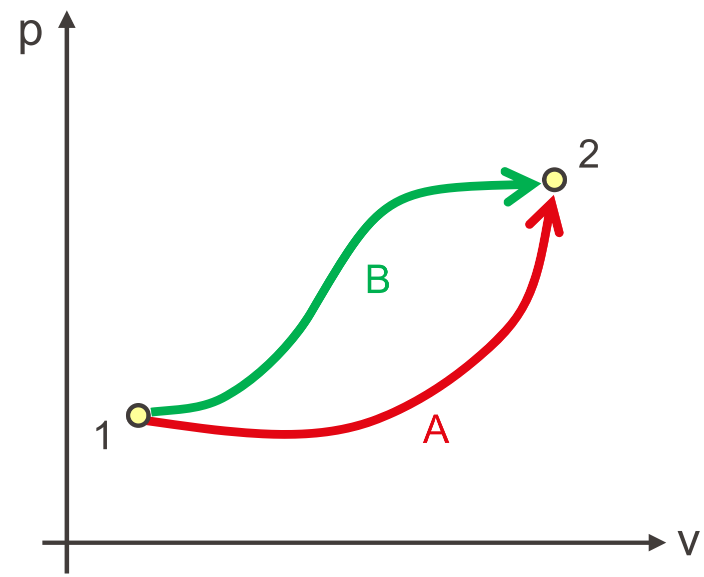


- It follows

$$\int_1^2 \frac{\delta Q}{T}\bigg|_A = \int_1^2 \frac{\delta Q}{T}\bigg|_B \Rightarrow \int_1^2 \frac{\delta Q}{T}\bigg|_{rev} = \text{const.} \Rightarrow$$

Independent on process, therefore a state variable

Entropy Definition

- New state variable entropy (S) defined through Clausius

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T}\bigg|_{rev} \Rightarrow dS = \frac{\delta Q}{T}\bigg|_{rev} \Rightarrow TdS = \delta Q|_{rev}$$

- Entropy is a state property → Knowledge of two other state properties defines also entropy of state

Entropy in Irreversible Processes?

- Consider cycle with reversible and irreversible process
  - Clausius leads to

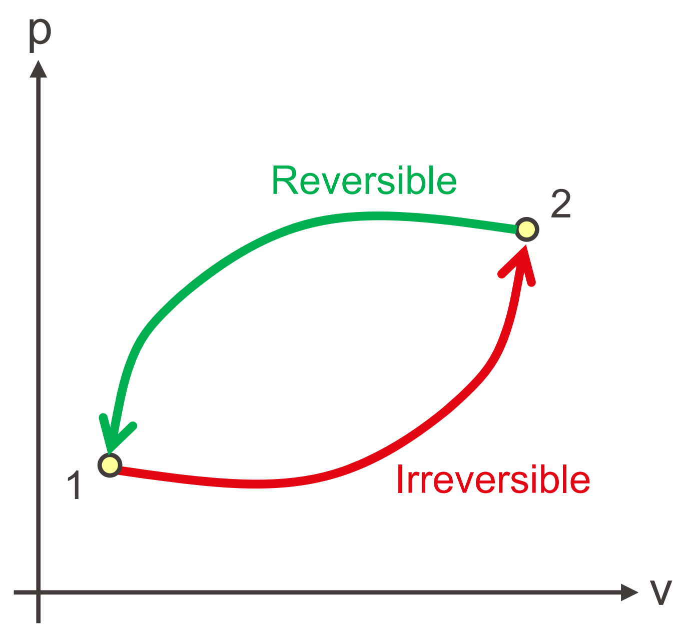
$$\int_1^2 \frac{\delta Q}{T} + \int_2^1 \frac{\delta Q}{T}\bigg|_{rev} = -\sigma$$

  - Definition of entropy change

$$S_1 - S_2 = \int_2^1 \frac{\delta Q}{T}\bigg|_{rev}$$

  - Leads to

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + \sigma$$



Entropy Balance

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + \sigma$$

- Entropy change between two states results from
  - Entropy transfer due to heat transfer → dependent on process and independent from work
  - Entropy production through irreversibility → dependent on process, always > 0 due to 2nd law!

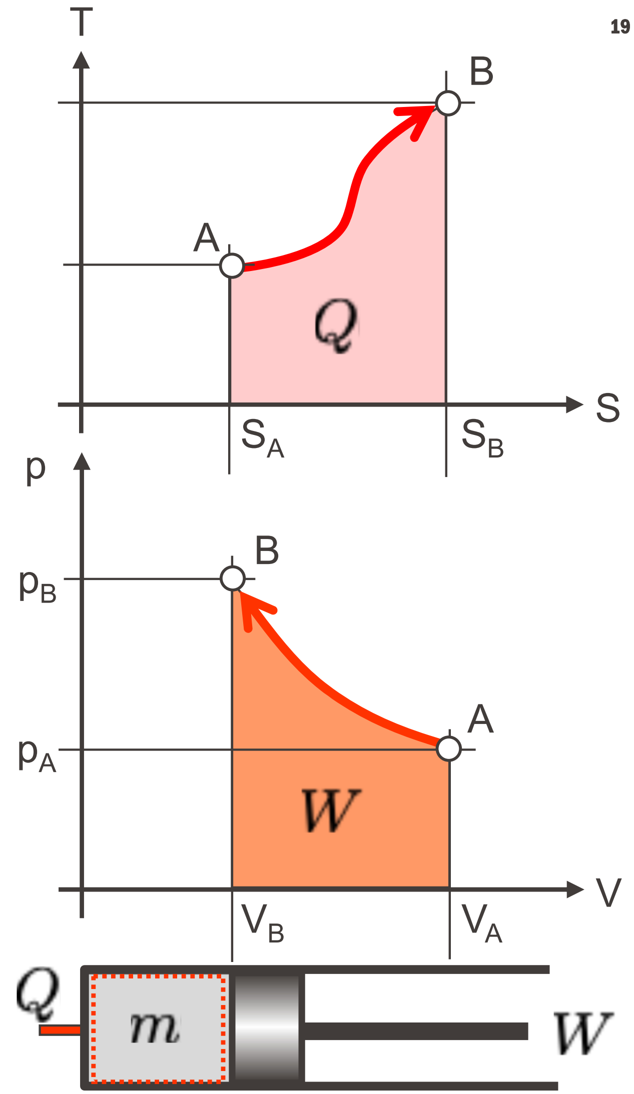
Entropy Balance in Closed Systems

- Consider reversible closed system
- Integral in PV-diagram corresponds to work

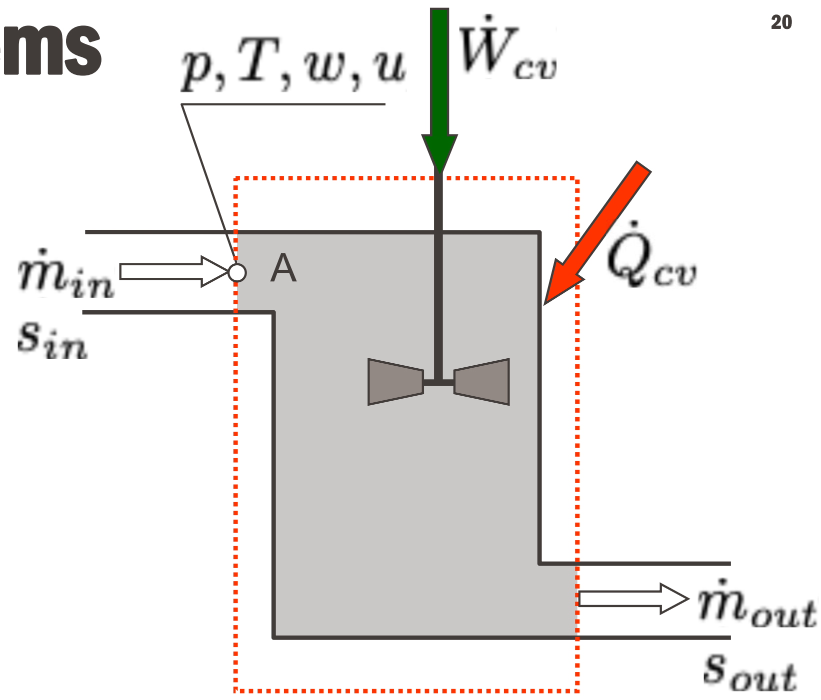
$$W = -\int_1^2 pdV$$

- Integral in TS-diagram corresponds to heat

$$Q_{rev} = \int_1^2 TdS$$



Entropy Balance in Open Systems



- Entropy can also be convected across system through mass fluxes

- Entropy balance for open system

$$\frac{dS_{cv}}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_{in} \dot{m}s|_{in} - \sum_{out} \dot{m}s|_{out} + \dot{\sigma}_{cv}$$

Comments

- 1^{st} law
  - No energy produced only transformed
  - Equivalence of work and heat

- 2^{nd} law
  - No conservation of entropy, entropy can be produced
  - Entropy transfer associated with heat transfer → can be positive or negative
  - In open systems entropy is convected across system boundary through mass fluxes
  - Irreversibility produces entropy
  - Entropy production (irreversibility) corresponds to lost work
  - Change of entropy in closed system is result of heat transfer and dissipation

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Isentropic Processes & Efficiency

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Isentropic Processes

- Definition

$$\Delta S = \int_1^2 \frac{\delta Q}{T} + \sigma = 0$$

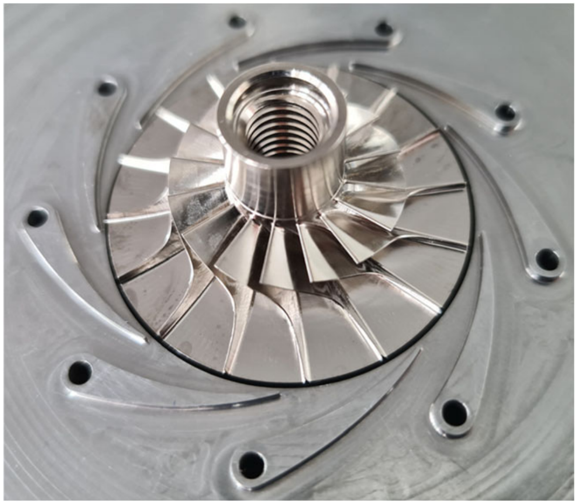
- Often system is considered adiabatic → $\delta Q = 0$ → $\sigma = 0$

- Under such assumption, isentropic transformation is perfect process

- Isentropic, adiabatic process can be used as reference to assess performance of real machines

Example: Turbine

- Machine used to expand gas to recover work
- Mass flow established through pressure difference
- Work recovered through change of momentum
- Assumptions
  - Adiabatic and stationary operation
  - Negligible change in kinetic and potential energy



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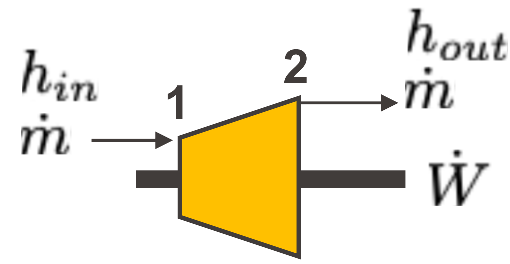
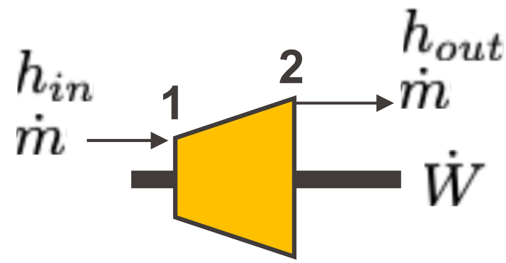
Example: Turbine (p_1 to p_2)



- Mass balance

$$\frac{dm_{cv}}{dt} = \sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \quad \Rightarrow \quad \dot{m}_{in} = \dot{m}_{out} = \dot{m}$$

Example: Turbine (p_1 to p_2)



- Mass balance

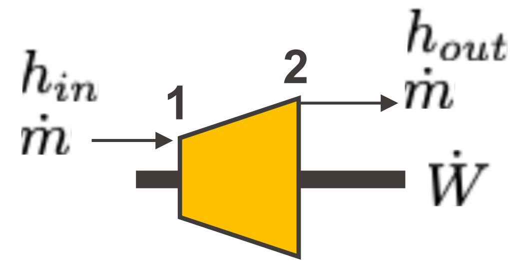
$$\frac{dm_{cv}}{dt} = \sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \quad \Rightarrow \quad \dot{m}_{in} = \dot{m}_{out} = \dot{m}$$

- Energy balance

$$\frac{dE_{cv}}{dt} = \dot{W}_{cv} + \dot{Q}_{cv} + \sum \dot{m}_{in}\left(h + \frac{w^2}{2} + gz\right)_{in} - \sum \dot{m}_{out}\left(h + \frac{w^2}{2} + gz\right)_{out}$$

$$\dot{W}_{cv}^{-} = \dot{m}\left(h_{in} - h_{out}\right)$$

Example: Turbine (p_1 to p_2)



- Mass balance

$$\frac{dm_{cv}}{dt} = \sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \quad \Rightarrow \quad \dot{m}_{in} = \dot{m}_{out} = \dot{m}$$

- Energy balance

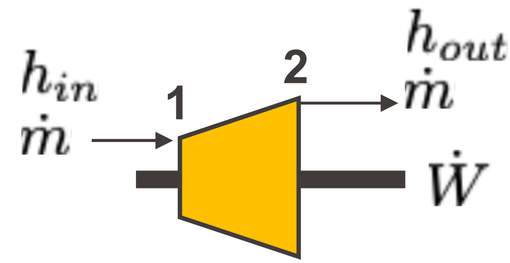
$$\frac{dE_{cv}}{dt} = \dot{W}_{cv} + \dot{Q}_{cv} + \sum \dot{m}_{in}\left(h + \frac{w^2}{2} + gz\right)_{in} - \sum \dot{m}_{out}\left(h + \frac{w^2}{2} + gz\right)_{out}$$

$$\dot{W}^{-}_{cv} = \dot{m}\left(h_{in} - h_{out}\right)$$

- Entropy balance

$$\frac{dS_{cv}}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}s|_i - \sum_o \dot{m}s|_o + \dot{\sigma}_{cv} \quad \Rightarrow \quad s_{in} - s_{out} = \frac{\dot{\sigma}_{cv}}{\dot{m}}$$

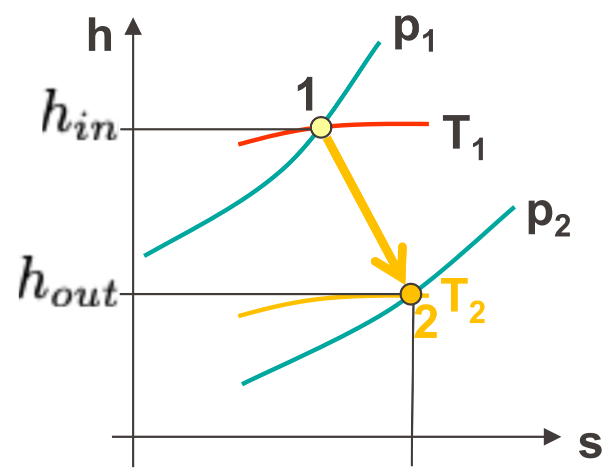
Example: Turbine (p_1 to p_2)



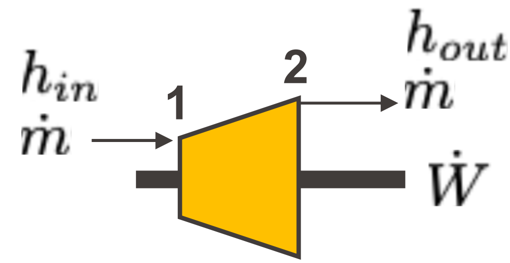
- Real process (entropy rise due to irreversibility)

$$\dot{W}_{cv}^{-} = \dot{m}\left(h_{in} - h_{out}\right)$$

$$s_{in} - s_{out} = \frac{\dot{\sigma}_{cv}}{\dot{m}}$$



Example: Turbine (p_1 to p_2)



- Real process (entropy rise due to irreversibility)

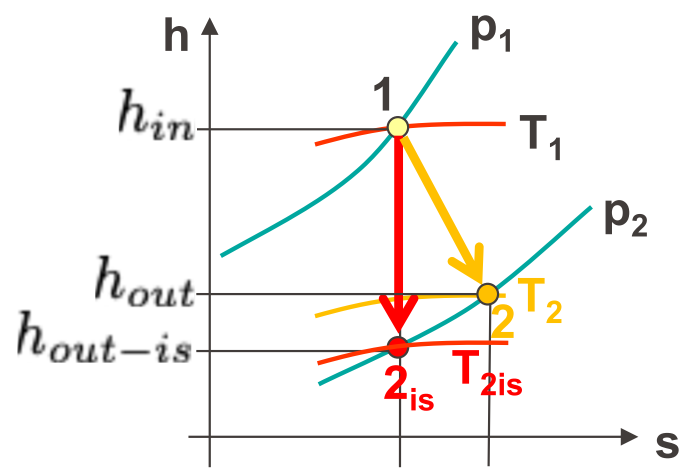
$$\dot{W}^{-}_{real} = \dot{m}\left(h_{in} - h_{out}\right)$$

$$s_{in} - s_{out} = \frac{\dot{\sigma}_{cv}}{\dot{m}}$$

- Isentropic process

$$\dot{W}^{-}_{is} = \dot{m}\left(h_{in} - h_{out-is}\right)$$

$$s_{in} - s_{out} = \frac{\dot{\sigma}_{cv}}{\dot{m}} = 0$$



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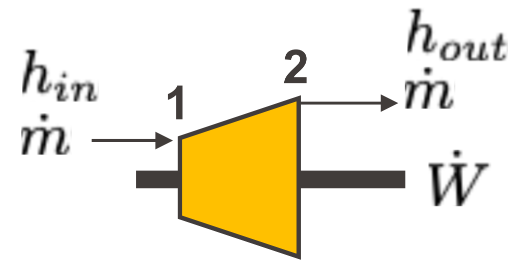
Example: Turbine (p_1 to p_2)



- Real process (entropy rise due to irreversibility)

$$\dot{W}^-_{real} = \dot{m}\,(h_{in} - h_{out})$$

$$s_{in} - s_{out} = \frac{\dot{\sigma}_{cv}}{\dot{m}}$$

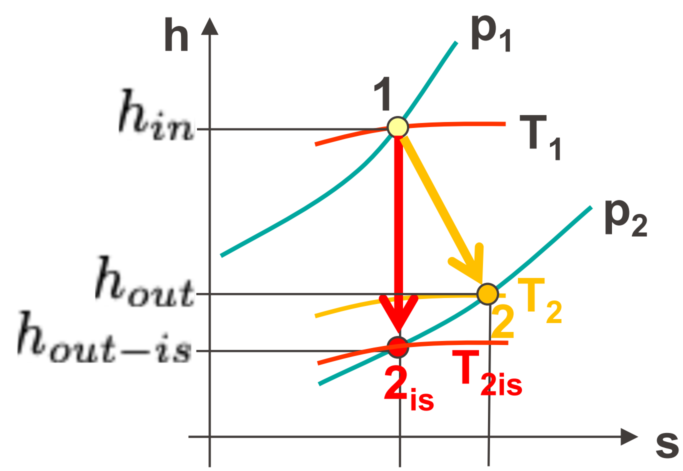
- Isentropic process

$$\dot{W}^-_{is} = \dot{m}\,(h_{in} - h_{out-is})$$

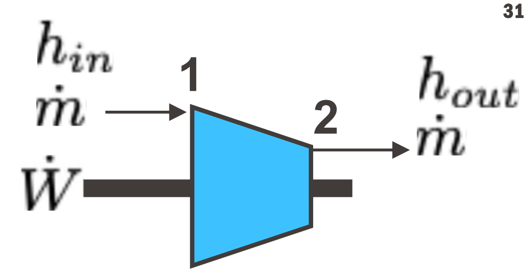
$$s_{in} - s_{out} = \frac{\dot{\sigma}_{cv}}{\dot{m}} = 0$$

- Isentropic turbine efficiency

$$\eta_{t-is} = \frac{\dot{W}^-_{real}}{\dot{W}^-_{is}} = \frac{h_{in} - h_{out}}{h_{in} - h_{out-is}}$$



Example: Compressor (p_1 to p_2)



- Real process (entropy rise due to irreversibility)

$$\dot{W}^+_{real} = \dot{m}\left(h_{out} - h_{in}\right)$$

$$s_{out} - s_{in} = \frac{\dot{\sigma}_{cv}}{\dot{m}}$$

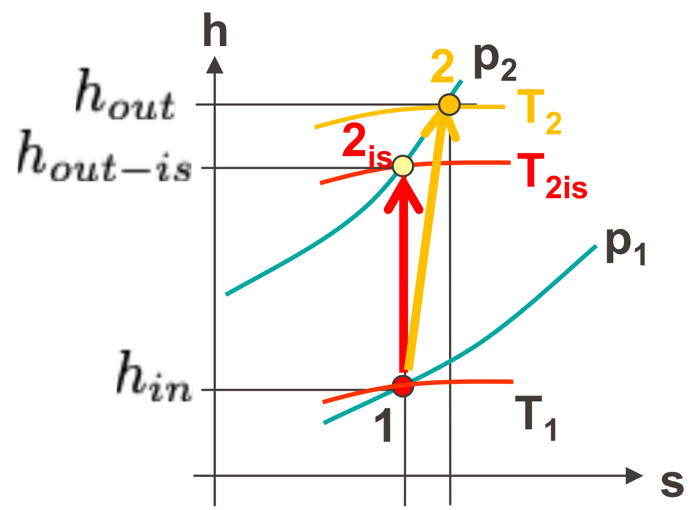
- Isentropic process

$$\dot{W}^+_{is} = \dot{m}\left(h_{out-is} - h_{in}\right)$$

$$s_{out} - s_{in} = \frac{\dot{\sigma}_{cv}}{\dot{m}} = 0$$

- Isentropic compressor efficiency

$$\eta_{k-is} = \frac{\dot{W}^+_{is}}{\dot{W}^+_{real}} = \frac{h_{out-is} - h_{in}}{h_{out} - h_{in}}$$



Heat Pump Systems

Thermodynamics Crash Course

Exergy

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Introduction

- Thermodynamic analysis governed by two laws

- First law
  - Conservation of energy
  - Energy can be transformed into different and equivalent forms

- Second law
  - Dictates direction of natural energy transfer
  - Requires cycles to work between two thermal reservoirs
  - Limits maximum efficiency of thermal machines
  - Allows distinction between perfect and real processes

Issue with 1st Law Efficiency Definition

- Classical approach to assess performance is through 1st law efficiency

$$\eta_{th} = \frac{\text{yield}}{\text{investment}} = \frac{W^-}{Q^+} = 1 - \frac{Q^-}{Q^+}$$

- For heat pump this definition leads to efficiency > 1
- In case of combined heat and power plants, yield is heat and work, efficiency close to 1
- 1st law efficiency definition makes no distinction between quality of energy → inadequate to measure degree of thermodynamic perfection

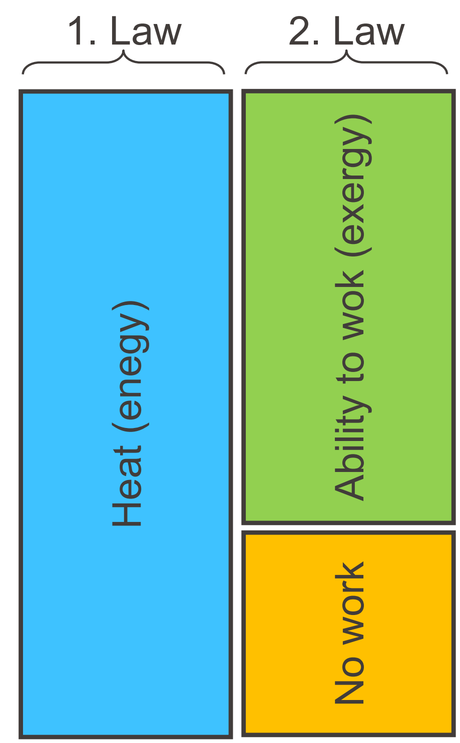
Quality of Energy

- Second law gives indication regarding quality of energy

- Heat delivered at certain temperature can only partially be transformed into work

$$\eta_c = 1 - \frac{Q^{-}_{cold}}{Q^{+}_{hot}} = 1 - \frac{T_{cold}}{T_{hot}}$$

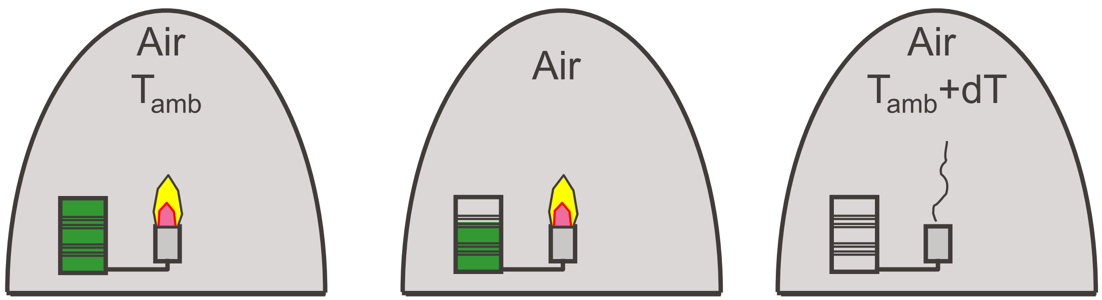
- Work has higher quality than heat, but 1st law does not differentiate



Quality of Energy: Illustration

- Consider isolated system with fuel container
- Chemical work potential of fuel initially vs. lukewarm air at end

$$E_{fuel}$$



$$E_{fuel}\left[1-\frac{T_{amb}}{T_{amb}+dT}\right]$$

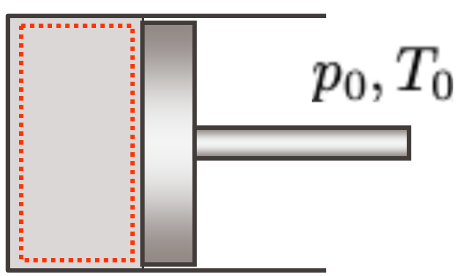
Concept of Exergy

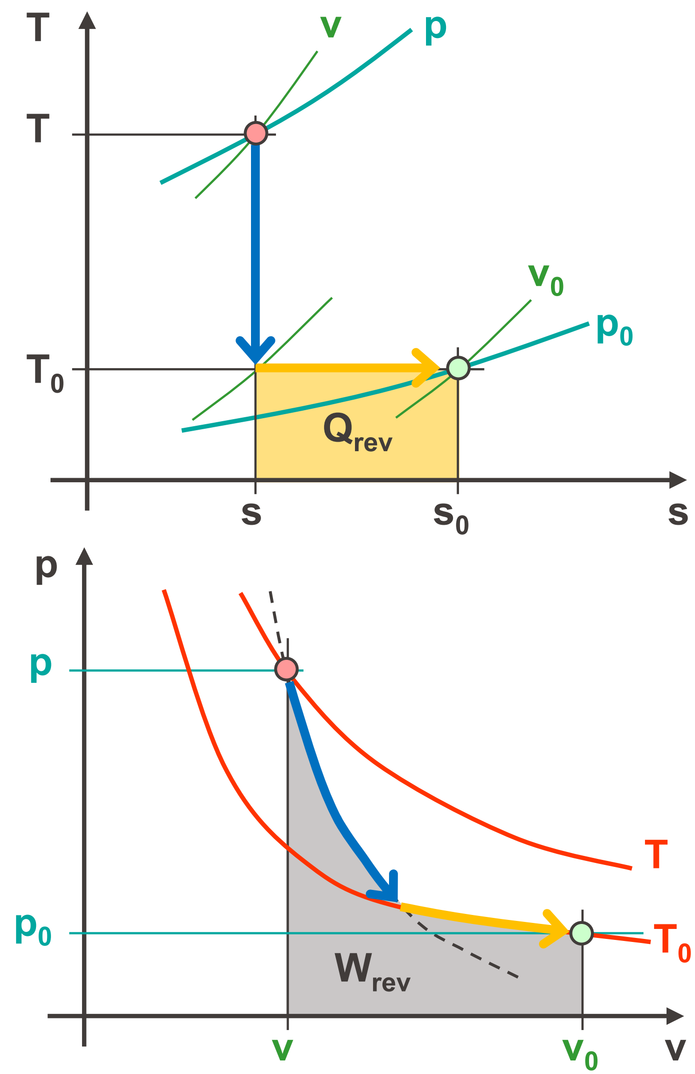
- Idea is to indicate maximum work of a system relative to ambient conditions (pressure & temperature)
- All system that has a thermodynamic “tension” relative to ambient has ability to transform it into work via reversible process → exergy
- Exergy is a thermodynamic state variable
- Such approach ensures simultaneous satisfaction of 1st & 2nd law

Concept of Exergy

- Consider pressurized vessel at rest
- Idea is to indicate maximum work relative to ambient (p_0 & T_0)
- Process involves adiabatic reversible expansion until T_0, followed by isothermal expansion until p_0

$$m, p, T, S, U, V, KE, PE$$





Concept of Exergy

- Change in energy

$$E_0 - E = Q_{rev} + W_{rev}$$

where

$$Q_{rev} = T_0 \left(S_0 - S\right)$$

$$E_0 - E = U_0 - U - KE - PE$$

- Reversible work delivered by system

$$W_{rev} = U_0 - U - T_0 \left(S_0 - S\right) - KE - PE$$

$$W_{use} = U_0 - U - T_0 \left(S_0 - S\right) - KE - PE + \underbrace{p_0 \left(V_0 - V\right)}$$

Reduction from reversible work due to ambient displacement work

Concept of Exergy

- Exergy in closed system corresponds to useful work (positive sign)

$$Ex = -W_{use}$$

$$Ex = (U - U_0) + p_0 (V - V_0) - T_0 (S - S_0) + KE + PE$$

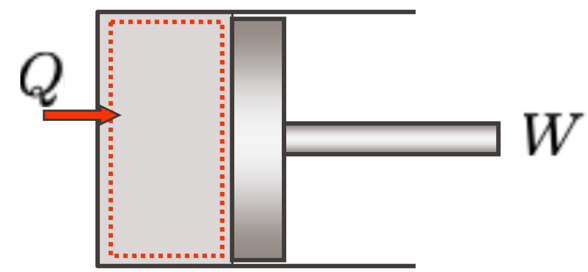
$$Ex = (E - E_0) + p_0 (V - V_0) - T_0 (S - S_0)$$

  - Exergy is thermodynamic state
  - Between two states

$$Ex_2 - Ex_1 = (E_2 - E_1) + p_0 (V_2 - V_1) - T_0 (S_2 - S_1)$$

Exergy Balance in Closed Systems

- Energy and entropy balance



$$E_2 - E_1 = \int_1^2 \delta Q + W_{12}$$

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + \sigma$$

- Change of exergy

$$Ex_2 - Ex_1 = (E_2 - E_1) + p_0 (V_2 - V_1) - T_0 (S_2 - S_1)$$

$$Ex_2 - Ex_1 = \int_1^2 \left(1 - \frac{T_0}{T}\right) \delta Q + [W_{12} + p_0 (V_2 - V_1)] - T_0 \sigma$$

Exergy Balance in Closed Systems

State variables
Process independent

Process dependent

$$\underbrace{Ex_2 - Ex_1}_{\text{State variables, Process independent}} = \underbrace{\underbrace{\int_1^2 \left(1 - \frac{T_0}{T}\right) \delta Q}_{} + \underbrace{\left[W_{12} + p_0 \left(V_2 - V_1\right)\right]}_{} - \underbrace{T_0 \sigma}_{}}_{\text{Process dependent}}$$

Exergy Balance in Closed Systems

State variables
Process independent

Process dependent

$$\underbrace{Ex_2 - Ex_1}_{\text{State variables, Process independent}} = \underbrace{\int_1^2 \left(1 - \frac{T_0}{T}\right)\delta Q + \left[W_{12} + p_0\left(V_2 - V_1\right)\right] - T_0\sigma}_{\text{Process dependent}}$$

- Exergy transfer through heat
- Heat energy reduced by Carnot efficiency
- Best process to transform heat into useful work

Exergy Balance in Closed Systems

State variables
Process independent

Process dependent

$$\underbrace{Ex_2 - Ex_1}_{\text{State variables, Process independent}} = \underbrace{\int_1^2 \left(1 - \frac{T_0}{T}\right) \delta Q}_{} + \underbrace{\left[W_{12} + p_0 \left(V_2 - V_1\right)\right]}_{} - \underbrace{T_0 \sigma}_{}$$

- Exergy transfer through heat
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- Best process to transform heat into useful work

- Exergy transfer through work
- Reduced by ambient displacement work

Exergy Balance in Closed Systems

State variables
Process independent

Process dependent

$$Ex_2 - Ex_1 = \underbrace{\int_1^2 \left(1 - \frac{T_0}{T}\right) \delta Q}_{} + \underbrace{\left[W_{12} + p_0 \left(V_2 - V_1\right)\right]}_{} - \underbrace{T_0 \sigma}_{}$$

- Exergy transfer through heat
- Heat energy reduced by Carnot efficiency
- Best process to transform heat into useful work

- Exergy transfer through work
- Reduced by ambient displacement work

- Exergy losses due to process irreversibiliy

Exergy Balance in Open Systems

- Transfer of exergy through convection across system boundary
- Definition of co-enthalpy in analogous way as for closed system and with definition of enthalpy

$$K = (H - H_0) - T_0 (S - S_0) + KE + PE$$

  - Co-enthalpy is thermodynamic state
  - Between two states

$$k_2 - k_1 = (h_2 - h_1) - T_0 (s_2 - s_1) + \frac{w_2^2 - w_1^2}{2} + g (z_2 - z_1)$$

Exergy Balance in Open Systems

- Transfer of exergy through convection across system boundary
- Definition of co-enthalpy in analogous way as for closed system and with definition of enthalpy

$$\frac{dEx_{cv}}{dt} = \underbrace{\sum_j \int \left(1 - \frac{T_0}{T_j}\right) \delta\dot{Q}}_{\text{Balance of heat exergy}} + \underbrace{\dot{W}_{cv} + p_0 \frac{dV_{cv}}{dt}}_{\text{Balance of work}} + \underbrace{\sum_i \dot{m}_i k_i - + \sum_o \dot{m}_o k_o}_{\text{Balance of co-ethalpy}} - \underbrace{T_0 \dot{\sigma}_{cv}}_{\text{Exergy losses } \dot{L}}$$

Balance of heat exergy

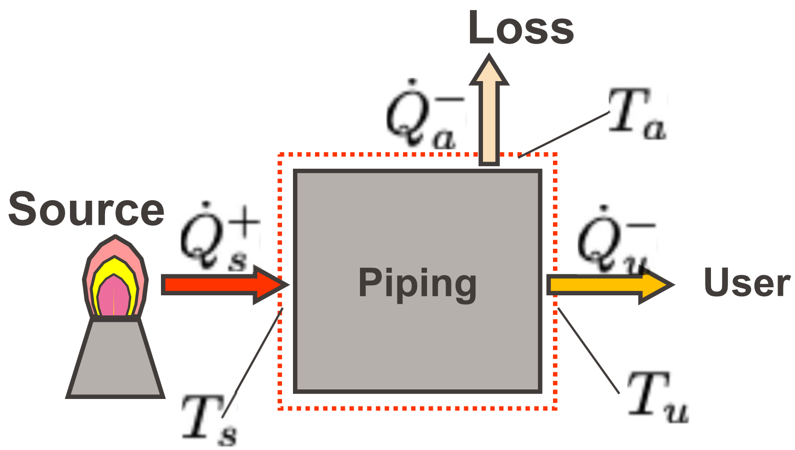
Balance of work

Balance of co-ethalpy

Exergy losses $\dot{L}$

Example: Piping System in Fuel Boiler

- Consider fuel boiler system
- Stationary system, no work

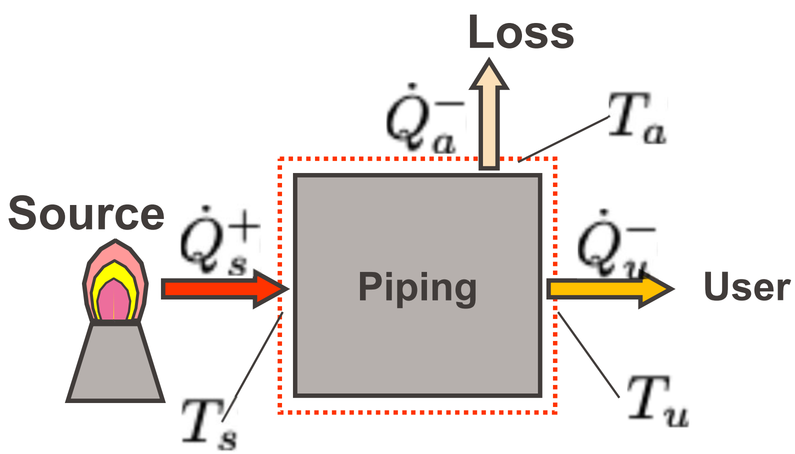


- Energy balance

$$\frac{dE_{cv}}{dt} = \dot{W}_{cv} + \dot{Q}_{cv} + \sum \dot{m}_{in}\left(h + \frac{w^2}{2} + gz\right)_{in} - \sum \dot{m}_{out}\left(h + \frac{w^2}{2} + gz\right)_{out}$$

$$\dot{Q}_s^+ - \dot{Q}_u^- - \dot{Q}_a^- = 0$$

Example: Piping System in Fuel Boiler



- Consider fuel boiler system
- Stationary system, no work

- Energy balance

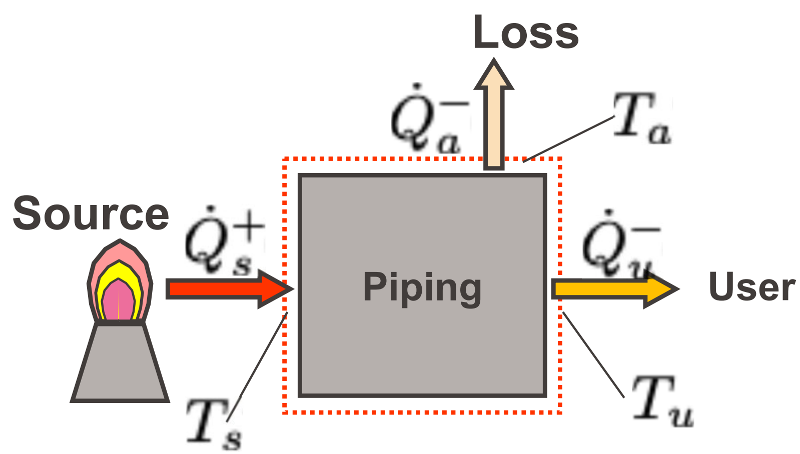
$$\frac{dE_{cv}}{dt} = \dot{W}_{cv} + \dot{Q}_{cv} + \sum \dot{m}_{in}\left(h + \frac{w^2}{2} + gz\right)_{in} - \sum \dot{m}_{out}\left(h + \frac{w^2}{2} + gz\right)_{out}$$

$$\dot{Q}_s^+ - \dot{Q}_u^- - \dot{Q}_a^- = 0$$

- Energy efficiency

$$\eta = \frac{\dot{Q}_u^-}{\dot{Q}_s +} \approx 1$$

Example: Piping System in Fuel Boiler



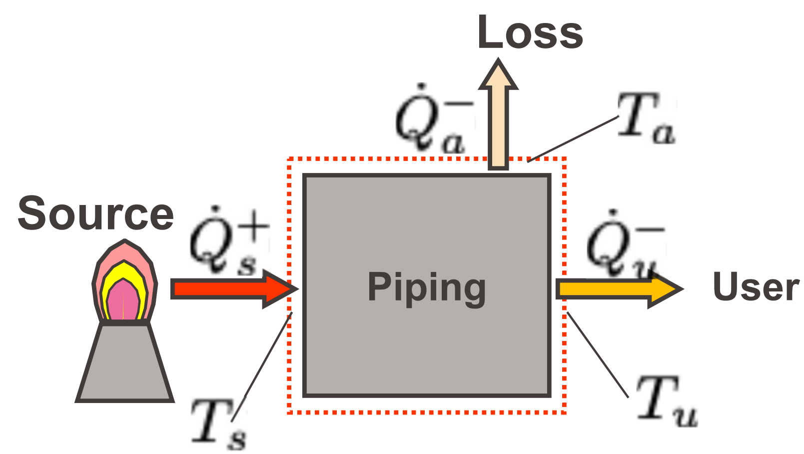
- Consider fuel boiler system
- Stationary system, no work

- Exergy balance

$$\frac{dEx_{cv}}{dt} = \sum_j \int \left(1 - \frac{T_0}{T_j}\right) \delta\dot{Q} + \dot{W}_{cv} + p_0 \frac{dV_{cv}}{dt} + \sum_i \dot{m}_i k_i - + \sum_o \dot{m}_o k_o - T_0 \dot{\sigma}_{cv}$$

$$\left(1 - \frac{T_0}{T_s}\right) \dot{Q}_s^+ - \left(1 - \frac{T_0}{T_u}\right) \dot{Q}_u^- - \left(1 - \frac{T_0}{T_a}\right) \dot{Q}_a^- = \dot{L}$$

Example: Piping System in Fuel Boiler



- Consider fuel boiler system
- Stationary system, no work

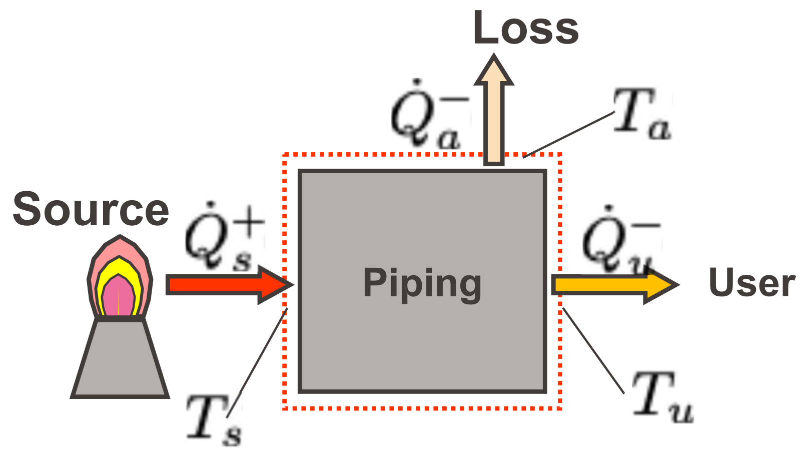
- Exergy balance

$$\left(1-\frac{T_0}{T_s}\right)\dot{Q}_s^+ - \left(1-\frac{T_0}{T_u}\right)\dot{Q}_u^- - \left(1-\frac{T_0}{T_a}\right)\dot{Q}_a^- = \dot{L}$$

- Exergy efficiency

$$\eta_{ex} = \frac{\left(1-\frac{T_0}{T_u}\right)\dot{Q}_u^-}{\left(1-\frac{T_0}{T_s}\right)\dot{Q}_s^+}$$

Example: Piping System in Fuel Boiler



- Consider fuel boiler system
- Stationary system, no work

- Exergy balance

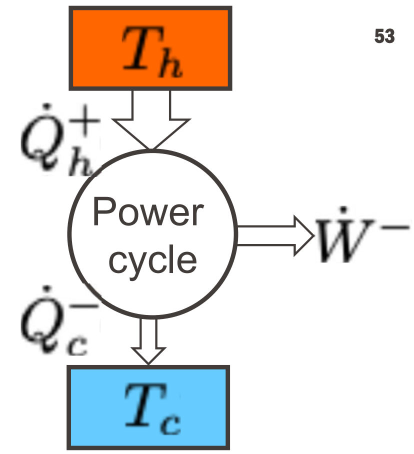
$$\left(1-\frac{T_0}{T_s}\right)\dot{Q}_s^+ - \left(1-\frac{T_0}{T_u}\right)\dot{Q}_u^- - \left(1-\frac{T_0}{T_a}\right)\dot{Q}_a^- = \dot{L}$$

- Exergy efficiency

$$\eta_{ex} = \frac{\left(1-\frac{T_0}{T_u}\right)\dot{Q}_u^-}{\left(1-\frac{T_0}{T_s}\right)\dot{Q}_s^+} = \frac{\left(1-\frac{T_0}{T_u}\right)}{\left(1-\frac{T_0}{T_s}\right)}\eta \ll 1$$

- 90% of heat exergy received by source is lost
- Due primarily to the temperature de-evaluation of high temperature source to low temperature in piping system

Example: Power Cycle



- Consider power cycle
- Stationary system

- Energy balance

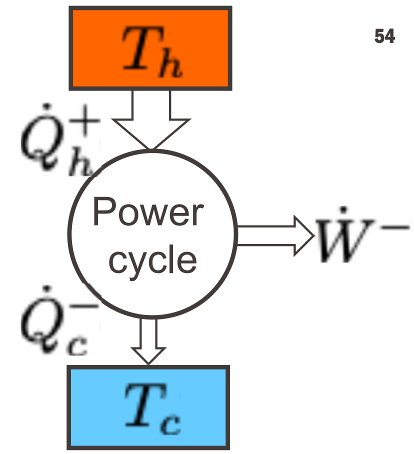
$$\frac{dE_{cv}}{dt} = \dot{W}_{cv} + \dot{Q}_{cv} + \sum \dot{m}_{in}\left(h + \frac{w^2}{2} + gz\right)_{in} - \sum \dot{m}_{out}\left(h + \frac{w^2}{2} + gz\right)_{out}$$

$$\dot{Q}_h^+ - \dot{Q}_c^- - \dot{W}^- = 0$$

- Energy efficiency

$$\eta_{th} = \frac{\dot{W}^-}{\dot{Q}_h^+}$$

Example: Power Cycle



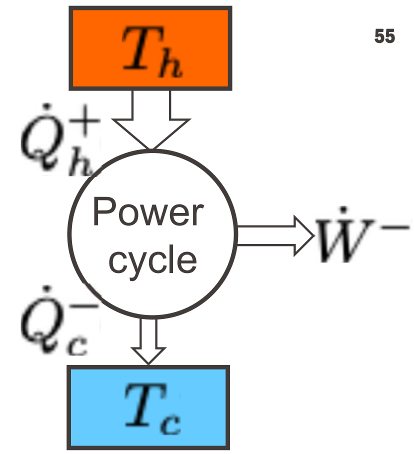
- Consider power cycle
- Stationary system, no work

- Exergy balance

$$\frac{dEx_{cv}}{dt} = \sum_j \int \left(1 - \frac{T_0}{T_j}\right) \delta\dot{Q} + \dot{W}_{cv} + p_0 \frac{dV_{cv}}{dt} + \sum_i \dot{m}_i k_i - + \sum_o \dot{m}_o k_o - T_0 \dot{\sigma}_{cv}$$

$$\left(1 - \frac{T_0}{T_h}\right) \dot{Q}_h^+ - \left(1 - \frac{T_0}{T_c}\right) \dot{Q}_c^- - \dot{W}^- = \dot{L}$$

Example: Power Cycle



- Consider power cycle
- Stationary system, no work

- Exergy balance

$$\left(1-\frac{T_0}{T_h}\right)\dot{Q}_h^+ - \left(1-\frac{T_0}{T_c}\right)\dot{Q}_c^- - \dot{W}^- = \dot{L}$$

- Exergy efficiency

$$\eta_{ex} = \frac{\dot{W}^-}{\left(1-\frac{T_0}{T_h}\right)\dot{Q}_h^+} = \frac{\eta_{th}}{\left(1-\frac{T_0}{T_h}\right)} = \frac{\eta_{th}}{\eta_c}$$

Conclusion

- Opposed to energy balance, exergy analysis combines 1st and 2nd law into a new thermodynamic state
- Exergy analysis automatically merges energy balance with feasibility limits imposed by 2nd law
- Energy efficiency does not consider quality of energy → may lead to spurious values
- Exergy efficiency suggested to be more sound approach to assess quality of thermodynamic system

Outlook for W4

- Introduction to heat pumps
- Thermodynamic analysis of heat pumps (energy & exergy)
- Technical challenges and limitations
- Main components of heat pumps

Exercises W3

- Theory questions
- Entropy and exergy analysis of a power plant
- Entropy and exergy analysis of a turbine
- Entropy and exergy analysis of a compressor
- Cold room of a refrigeration plant