EPFL

Heat Pump Systems

Summary W2

Prof. J. Schiffmann

École
polytechnique
fédérale
de Lausanne

Heating & Cooling in Historical Context

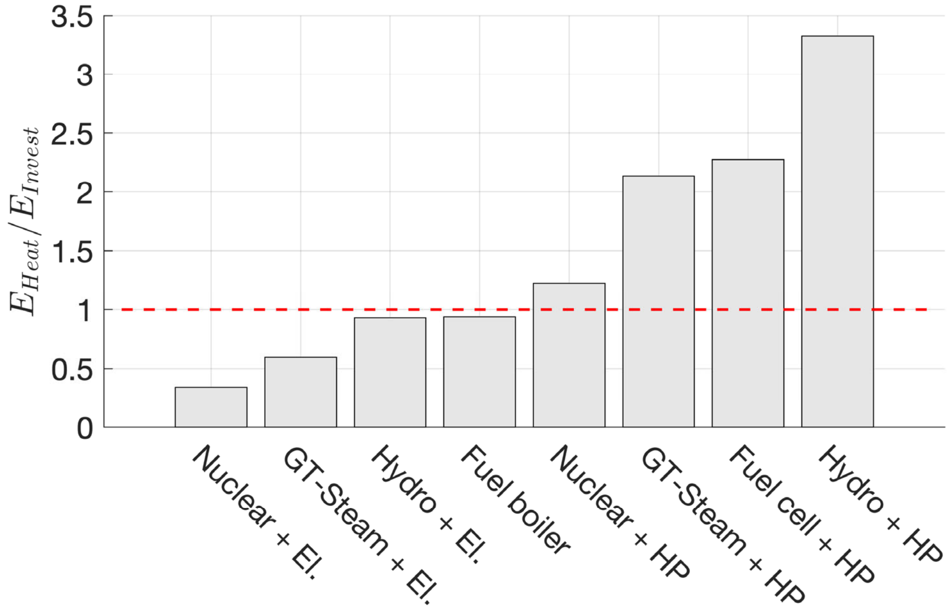
- Heat through combustion is simple and cheap
- Artificial cooling is more challenging to achieve
- Industrial vapor compression heat pump cycles only beginning of 20th century
- Today heat pumps are spread within various applications ranging from domestic to industrial applications

http://www.carel-japan.com/high-efficiency-solutions/evaporative-cooling/

americanhistory.si.edu blog ice-harvesting-electric-refrigeration

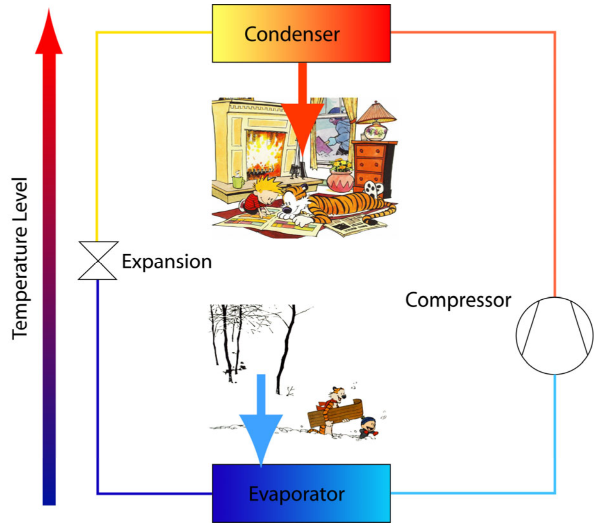
Domestic HVAC

- 27% or primary energy consumption relates to domestic HVAC
- Heat pumps play key role in reducing energy consumption and CO_2 emissions



What is a Heat Pump Thermodynamically?

- Bithermal thermodynamic cycle working in anti-clockwise direction
- Work is invested to drive the cycle, which absorbs and supplies heat at different temperatures



Heating heat pump cycle

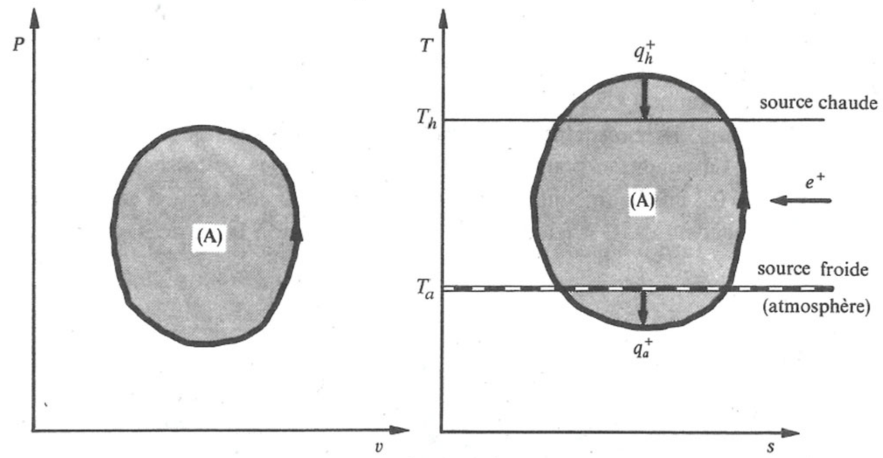
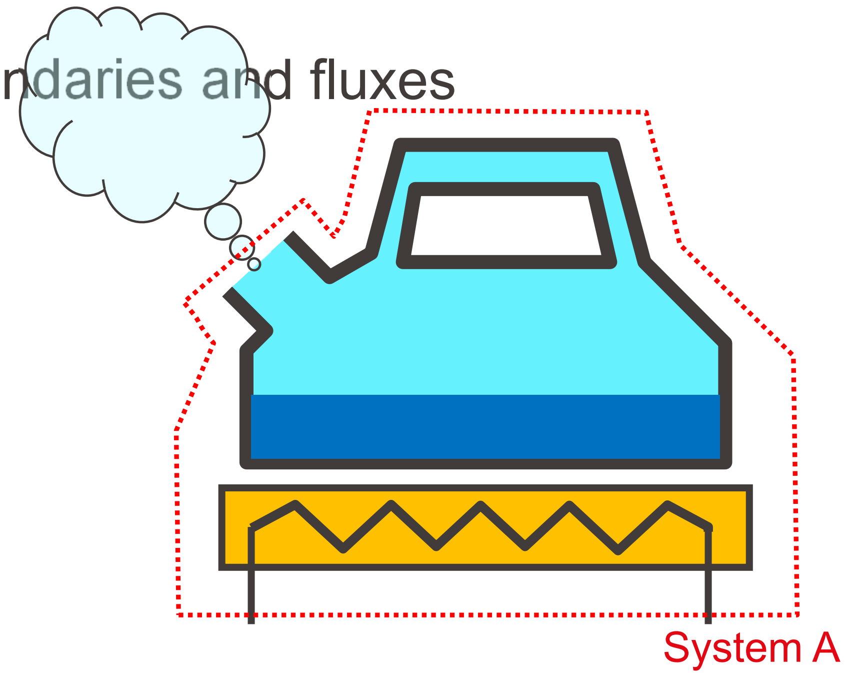


Fig 13.18 Favrat

Systematic Approach in Thermodynamics

1. What is known? → Sketch with known properties
2. What is problem? → Define objectives of analysis
3. Define the system → Identify system boundaries and fluxes



Systematic Approach in Thermodynamics (cont.)

1. What is known? → Sketch with known properties
2. What is problem? → Define objectives of analysis
3. Define the system → Identify system boundaries and fluxes
4. Define assumptions → Identify suitable simplifying assumptions
5. Thermodynamic analysis → Apply physical laws
6. Discussion → Critical analysis of results & assumptions

Heat Pump Systems

Thermodynamics Crash Course

First Law for Closed Systems

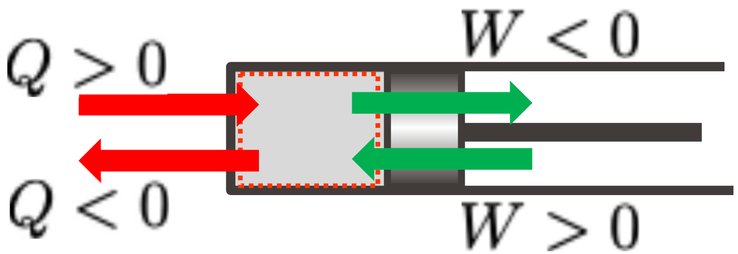
Prof. J. Schiffmann

École
polytechnique
fédérale
de Lausanne

Introduction

- Energy is fundamental quantity in thermodynamics
- Energy can only be stored, transformed, or transferred
- Energy cannot be destroyed or produced
- In closed system, energy can only be transferred through work and heat

- Reference is system
  - If work/heat is provided from surrounding to system → W > 0, Q > 0
  - If system provides work/heat to surrounding → W < 0, Q < 0



Work

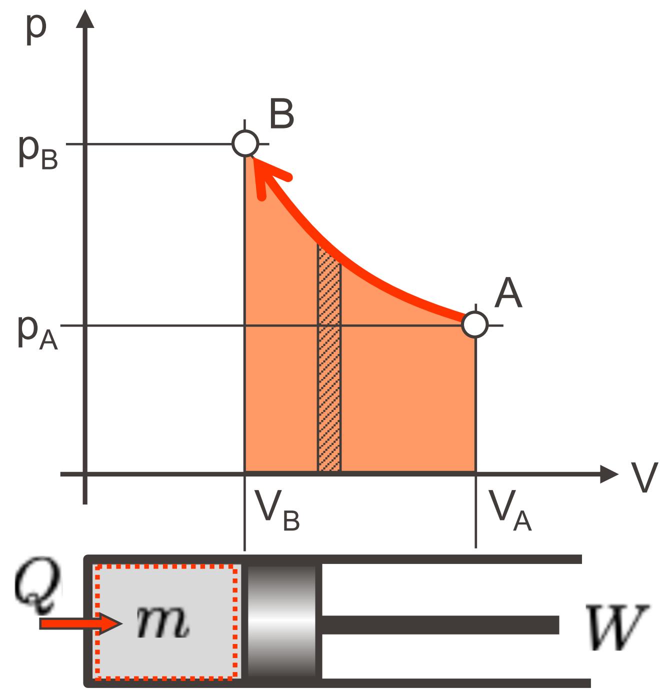
- Consider closed system where piston moves from A to B

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

- 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

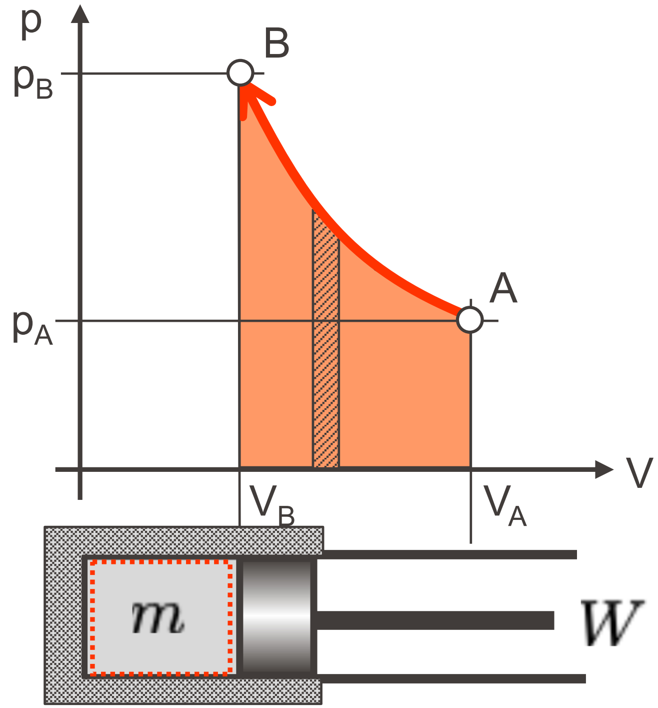


Work

- Consider closed and adiabatic system where piston moves from A to B
- Only possible energy transfer is via work
- Work on adiabatic system between fixed states depends only on start and end states

$$W = E_B - E_A$$

- Total energy E is thermodynamic state property



Total Energy E

- Total energy E includes all possible forms of energy in system
  - Kinetic energy KE
  - Potential energy PE
  - Internal energy U

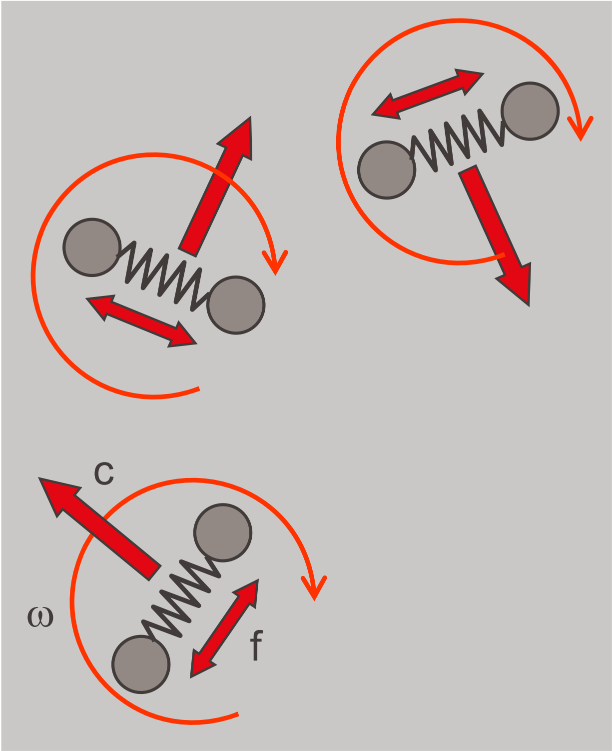
- All energy changes that are not kinetic or potential are summarized as internal energy

$$E_B - E_A = (KE_B - KE_A) + (PE_B - PE_A) + (U_B - U_A)$$

- Adiabatic work is transformed into kinetic, potential and internal energy

Internal Energy U

- Internal energy of fluid corresponds to kinetic energy related to molecular motion, chemical bonds, intramolecular forces
- Temperature plays important role
- No motion at absolute zero



Non-Adiabatic Transformation

- Consider closed system where piston moves from A to B

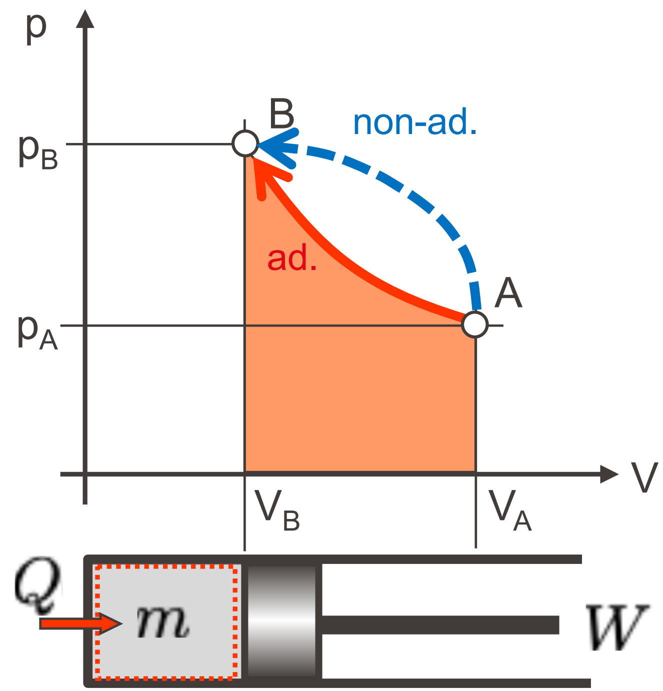
$$W_{ad.} = E_B - E_A$$

$$W_{non-ad.} \neq E_B - E_A$$

- In non-adiabatic system, change of E cannot be solely explained by work

- Total energy change result of work and heat

$$Q + W_{non-ad.} = E_B - E_A$$



First Law in Closed System

- In general process from A to B, energy is transferred to achieve $E_B - E_A$
- Energy transfer occurs across system boundary through
  - Work W
  - Heat Q

- First law becomes

$$\underbrace{E_B - E_A}_{\text{State}} = \underbrace{W_{AB} + Q_{AB}}_{\text{Process}}$$

- Change of total energy in system corresponds to net transfer of work and heat across system boundary

Equivalent Formulations of First Law in Closed System

- Balance between end and start states

$$E_B - E_A = W_{AB} + Q_{AB}$$

- Differential balance

$$dE = \delta W + \delta Q$$

- Power balance

$$\frac{dE}{dt} = \dot{W} + \dot{Q}$$

where $E = KE + PE + U = m\left(\frac{w^2}{2} + gz + u\right)$

Heat

- Like work, heat is not a thermodynamic state, depends on process

- Heat flux

$$\dot{q} = \frac{\dot{Q}}{A} \qquad \dot{Q} = \int \dot{q} dA$$

- Heat transfer mechanisms: conduction and radiation

- Energy transfer from a body to a fluid referred to as convection, i.e. combined effects of conduction and bulk motion of fluid

Conduction

- Heat transfer mechanism in solids and liquids at rest
- Heat transferred by activity at molecular scale
- Governed by Fourier's law

$$\dot{q} = \frac{\dot{Q}}{A} = -\lambda \frac{dT}{dx}$$

- Typical values for conductivity

	λ [W/mK]
Gases	0.01 – 0.2
Liquids	0.1 - 1
Solids	1 - 450

Radiation

- Radiation
  - No medium required (→ vacuum, space)
  - Governed by Boltzmann-equation

$$\dot{q} = \epsilon \sigma T^4 \qquad \sigma = 5.67 \cdot 10^{-8} \left[\frac{W}{m^2 K^4} \right]$$

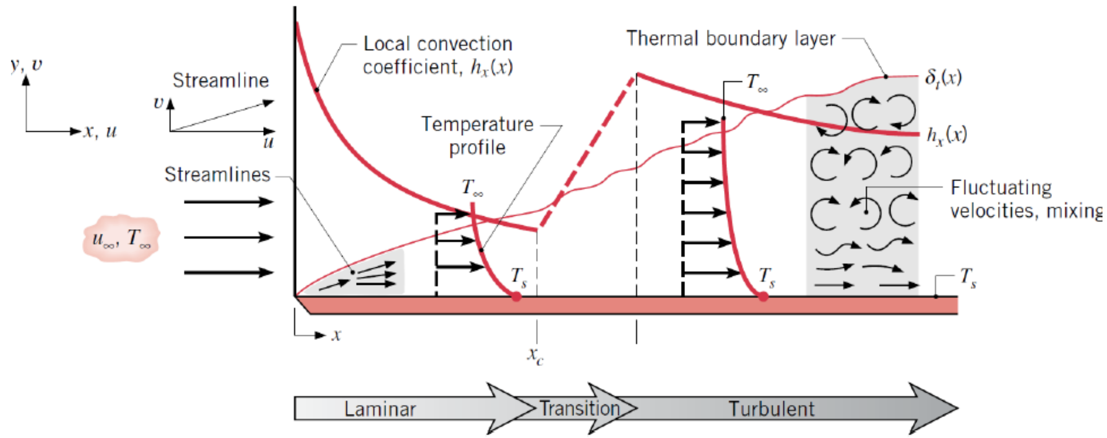
  - Emissivity $\epsilon \in [0, 1]$
  - Emissivity depends on surface shape, material properties, surface finish, orientation

Convection

- Heat transfer activated by fluid motion at interface with solid
- Coupling between fluid motion and fluid conduction
- Challenging to calculate → correlations for specific configurations
- Governed by Newton's law

$$\dot{q} = \frac{\dot{Q}}{A} = \alpha \left(T_{Wall} - T_{Fluid}\right)$$

- Laminar regime → low flux
- Turbulence enhances energy exchange between layers



Convection Correlations

- Correlations for forced convection

$$Nu = \frac{\alpha L}{\lambda} = f_{forced}\left(Re, Pr\right)$$

$$Re = \frac{vL}{\nu}$$

- Correlations for natural convection

$$Nu = \frac{\alpha L}{\lambda} = f_{nat}\left(Gr, Pr\right)$$

$$Gr = \frac{L^3 g \beta \Delta T}{\nu^2}$$

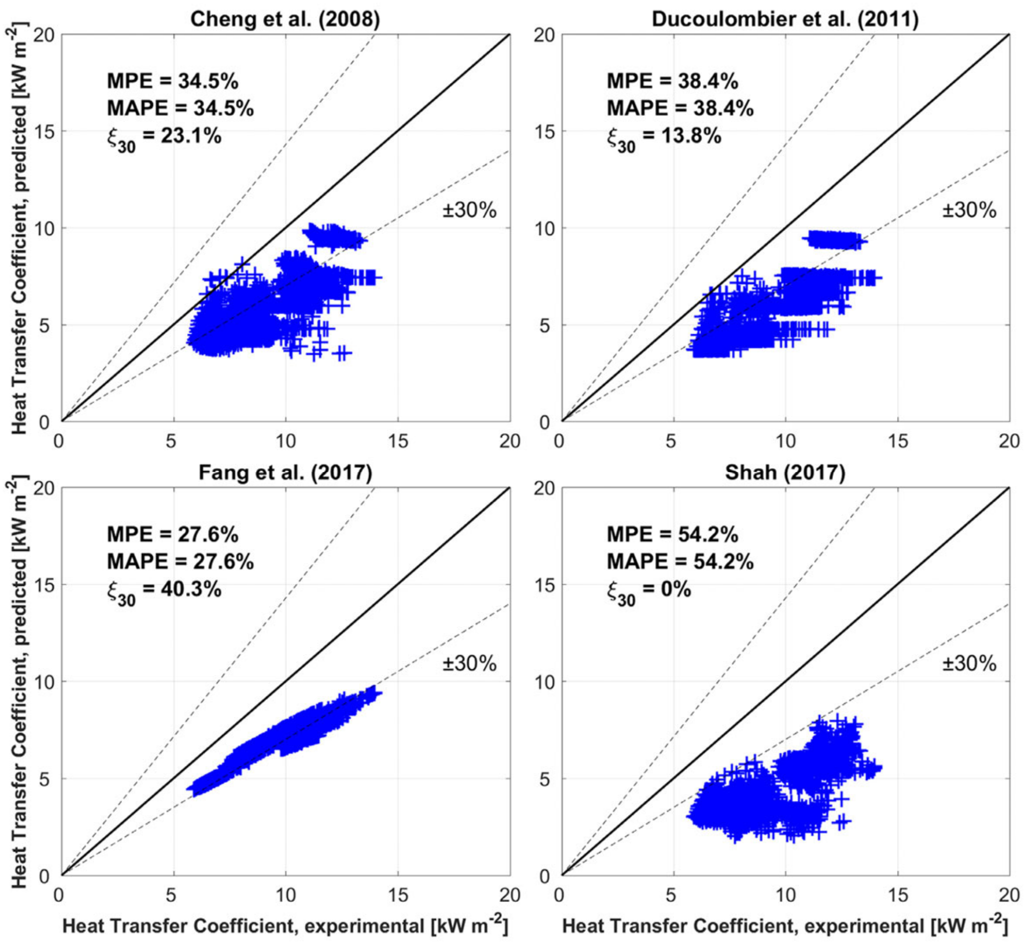
- Fluid properties condensed into Pr-number

$$Pr = \frac{\nu \rho c_p}{\lambda}$$

Performance of Typical Correlations

- Available correlations usually not very accurate

- Heat transfer coefficient highly dependent on fluid, mass-flux, geometry



D. Schmid, B. Verlaat, P. Petagna, R. Revellin, J. Schiffmann. Heat transfer of flow boiling carbon dioxide in vertical upward direction. International Journal of Heat and Mass Transfer, vol. 196, 123246, 2022.

Heat Pump Systems

Thermodynamics Crash Course

Cycles

Prof. J. Schiffmann

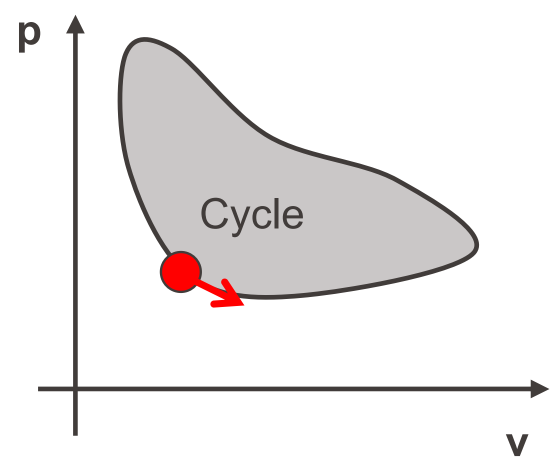
École
polytechnique
fédérale
de Lausanne

Cycle Characteristics

- Cyclic process returns to starting point periodically
- Energy balance of cycle

$$\Delta E_C = W_C + Q_C$$

Net work and net heat during one period of the cycle process

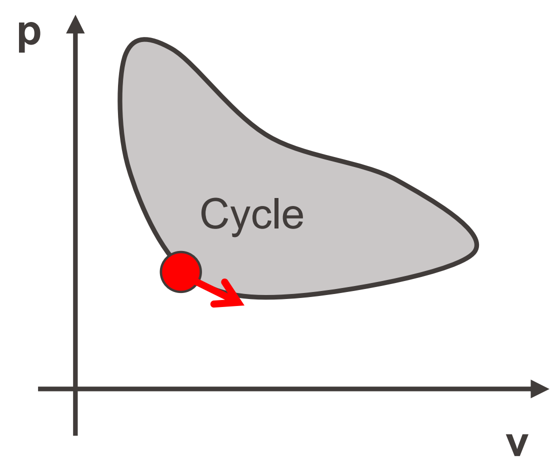


Cycle Characteristics

- Cyclic process returns to starting point periodically
- Energy balance of cycle

$$\Delta E_C = W_C + Q_C$$

Net work and net heat during one period of the cycle process



- End corresponds to starting point

$$\Delta E_C = 0$$

$$W_C = -Q_C = -\oint pdV$$

  - In cycle, net heat corresponds to net work → true for all cycles

Power Cycles

- Power cycle absorbs heat from hot source, transforms part of it into work, and delivers remaining heat to cold source

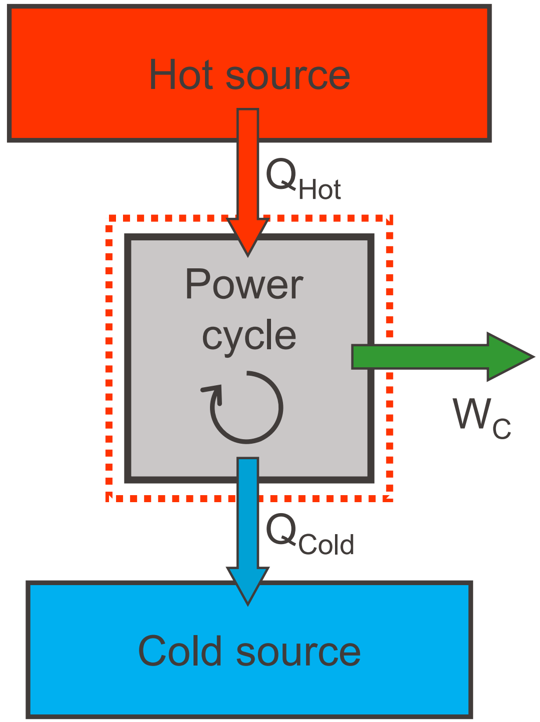
- Power cycles operate in clockwise direction

- Energy balance

$$W_C = Q_{Hot} + Q_{Cold}$$

$$W_C = Q^{+}_{Hot} - Q^{-}_{Cold}$$

Notation to get positive values for heat and work

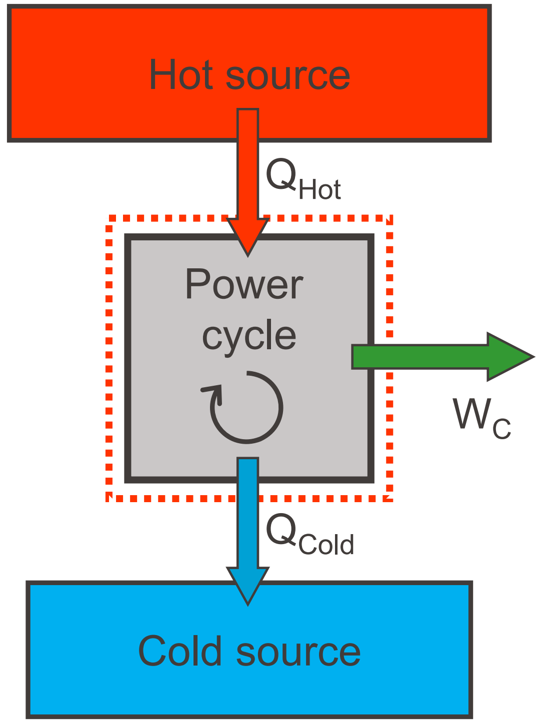


Power Cycle Efficiency

- Efficiency is ratio between yield and investment

$$\eta_{th} = \frac{W_C}{Q^+_{Hot}} = 1 - \frac{Q^-_{Cold}}{Q^+_{Hot}}$$

- Due 1st law and $Q^-_{Cold} > 0$ thermal efficiency $\eta_{th} < 1$



Typical thermal efficiencies

Steam locomotives	0.12
Nuclear power station	0.3 – 0.34
Coal plant	0.35 – 0.48
Gas turbine engines	0.3 – 0.42
Combined cycles	0.62
Internal combustion engines	0.35
Large diesel engines	0.58

EPFL

Heat Pump Systems

Thermodynamics Crash Course

First Law for Open Systems

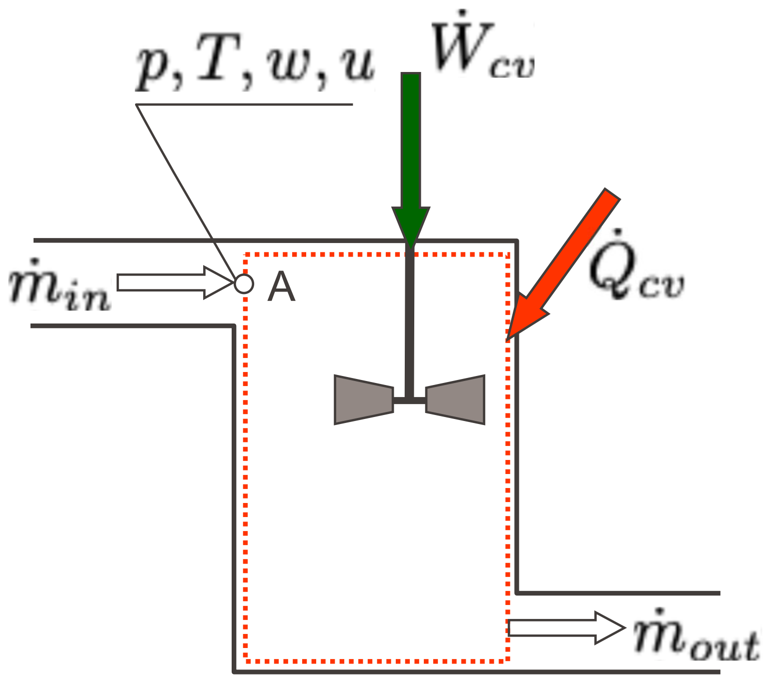
Prof. J. Schiffmann

École
polytechnique
fédérale
de Lausanne

Open Systems

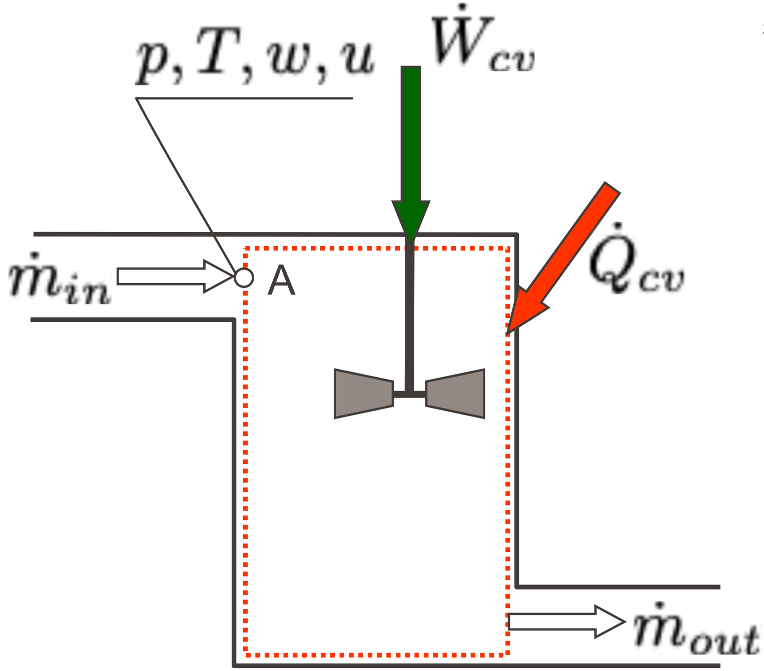
- Characterized by mass fluxes across system boundary
  - Energy balance
  - Mass balance

- Possible energy transfer
  - Work
  - Heat
  - Convective contribution through incoming and outgoing mass-flows



EPFL

Open Systems: Mass Balance



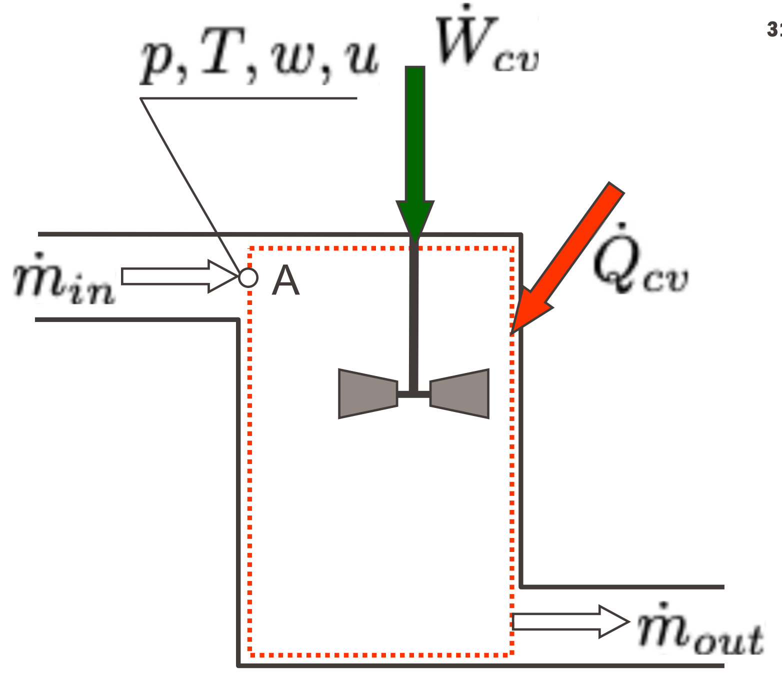
- Mass balance

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

- Mass in control volume

$$m_{cv} = \int_V \rho dV \text{ where } \rho(\vec{x}, t)$$

Open Systems: Mass Balance



- Mass balance

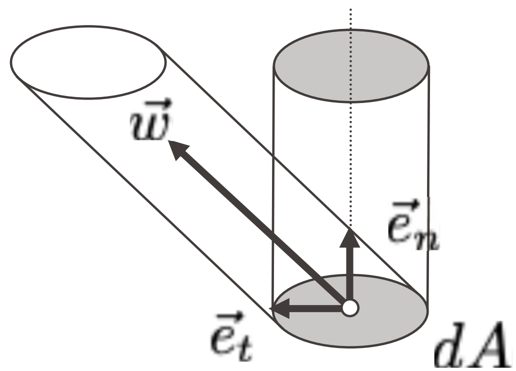
$$\frac{dm_{cv}}{dt} = \sum \dot{m}_{in} - \sum \dot{m}_{out}$$

- Mass in control volume

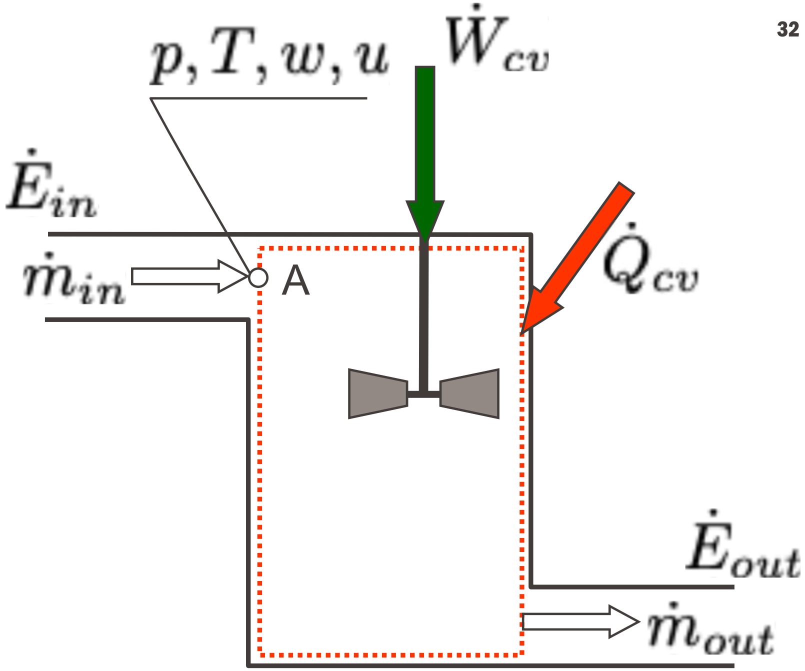
$$m_{cv} = \int_V \rho dV \text{ where } \rho\left(\vec{x}, t\right)$$

- Mass flow

$$\dot{m} = \int_A \rho \vec{w} \vec{e}_n dA$$



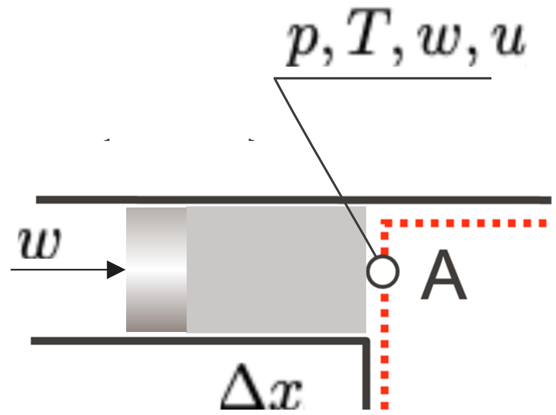
Open Systems: Energy Balance



- Incoming and outgoing mass-flows add and retrieve total energy from system
- Convective flow across system boundary composed of internal, kinetic, and potential energy

$$\frac{dE_{cv}}{dt} = \dot{W} + \dot{Q} + \underbrace{\dot{m}_{in}\left(u_{in} + \frac{w_{in}^2}{2} + gz_{in}\right)}_{\dot{E}_{in}} - \underbrace{\dot{m}_{out}\left(u_{out} + \frac{w_{out}^2}{2} + gz_{out}\right)}_{\dot{E}_{out}}$$

Open Systems: Transfer Power



- Transfer to mass across system boundary requires work that is transferred to and from system

- Transfer power: $\dot{W} = pAw$

- Expression for total work on system:

$$\dot{W} = \dot{W}_{cv} + p_{in}A_{in}w_{in} - p_{out}A_{out}w_{out}$$

$$\dot{W} = \dot{W}_{cv} + \dot{m}_{in}p_{in}v_{in} - \dot{m}_{out}p_{out}v_{out}$$

where $\dot{W}_{cv}$ corresponds to work other than transfer work delivered to system

Open Systems: Energy Balance

- Combining energy balance and expression for total work on system

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

Specific transfer work (pv)

Specific internal energy (u)

Open Systems: Energy Balance

- Combining energy balance and expression for total work on system

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

Specific transfer work (pv)

Specific internal energy (u)

- With definition of enthalpy h as a new state variable: $h = u + pv$

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

Open System Balances

- Energy balance:

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

Net convected power

Net work: $\dot{W}_{cv}$

Net heat: $\dot{Q}_{cv}$

Specific internal + transfer energy: h

Specific kinetic energy: $\frac{w^2}{2}$

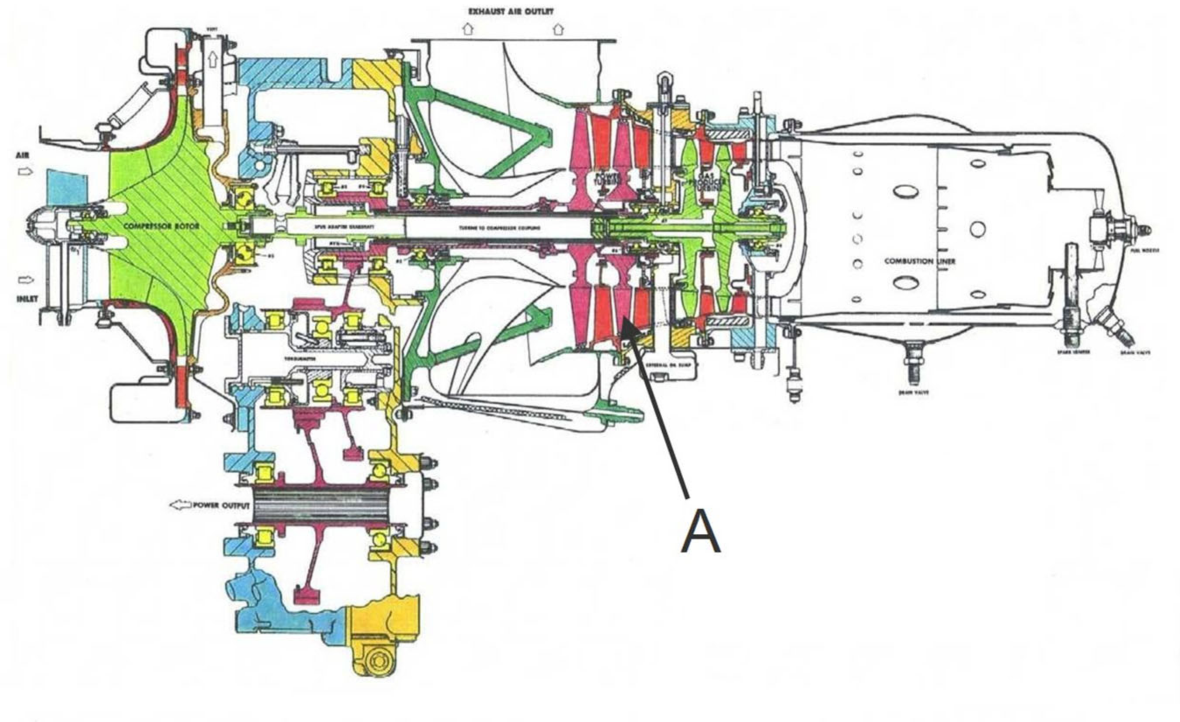
Specific potential energy: gz

- Mass balance:

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

Example: Helicopter Engine

- Mass balance
- Energy balance



Heat Pump Systems

Thermodynamics Crash Course

Second Law

Prof. J. Schiffmann

École polytechnique fédérale de Lausanne

Natural Systems: Observations

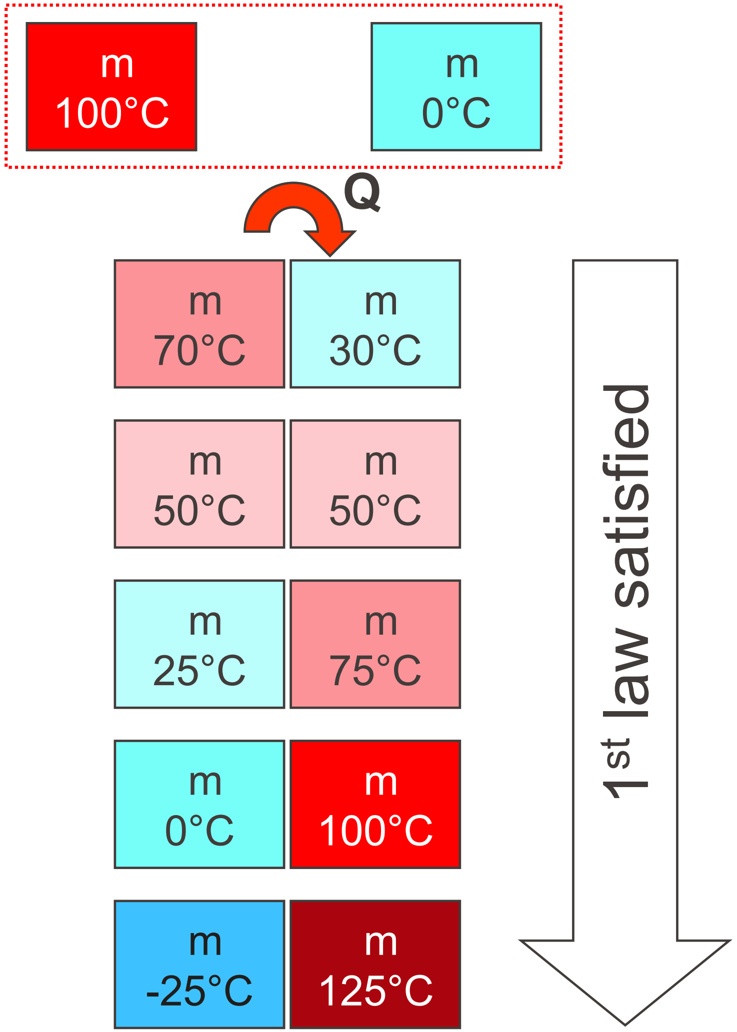
- Systems left on their own are subject to natural balancing processes until state of equilibrium is reached
- Spontaneous balancing processes only take place if there is a natural tension / imbalance / potential
- Examples of natural balancing processes
  - Body at higher temperature naturally cools down until reaching ambient temperature
  - Pressurized air bottle naturally leaks until ambient pressure is reached
  - Suspended mass naturally falls to floor

Natural Systems: Observations

- Natural balancing processes only in one direction
- Reversal is possible only by investing energy from outside system
- Problem: 1st law does not prevent reverse processes
- Description of observations requires additional law → 2nd law

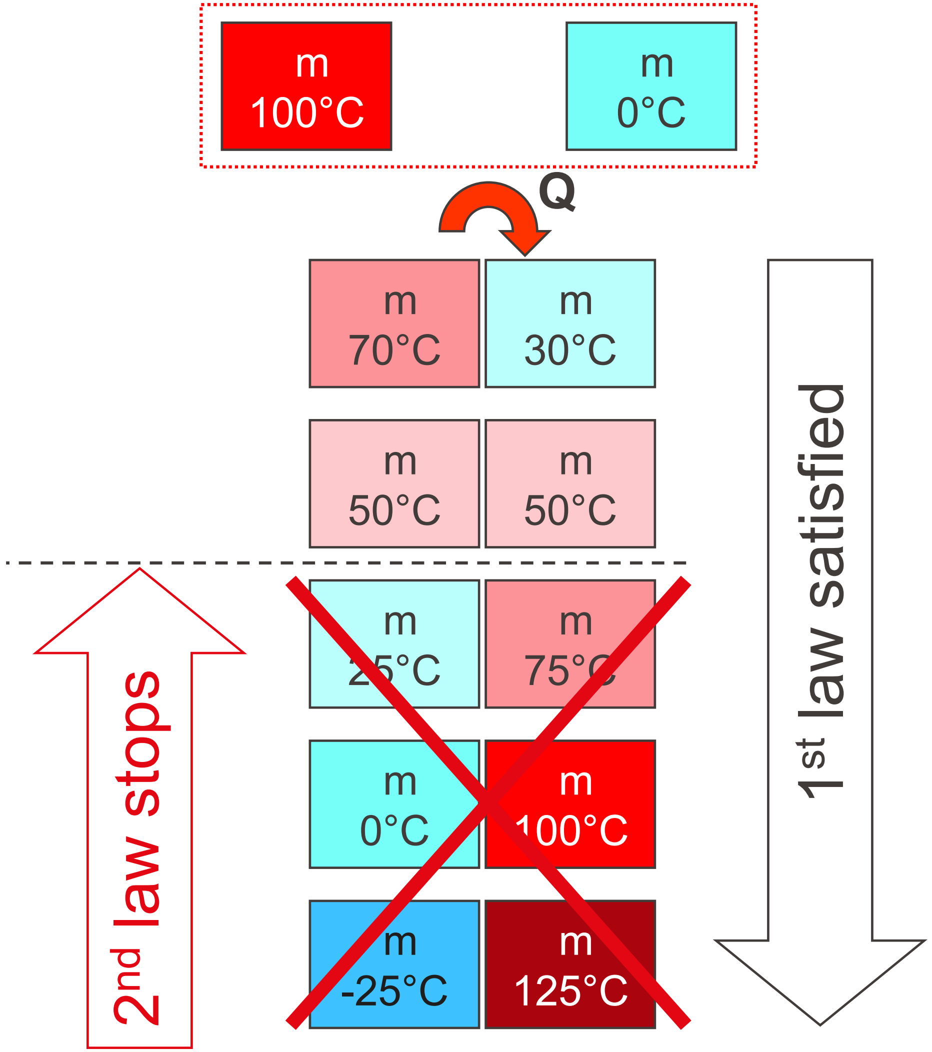
Experiment

- Closed system contains two equivalent masses, one at 0°C, one at 100°C
- 1st law violates observed natural processes



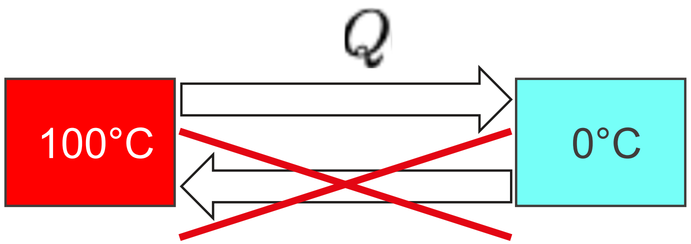
Experiment

- Closed system contains two equivalent masses, one at 0°C, one at 100°C
- 1st law violates observed natural processes
- 2nd law prevents violation



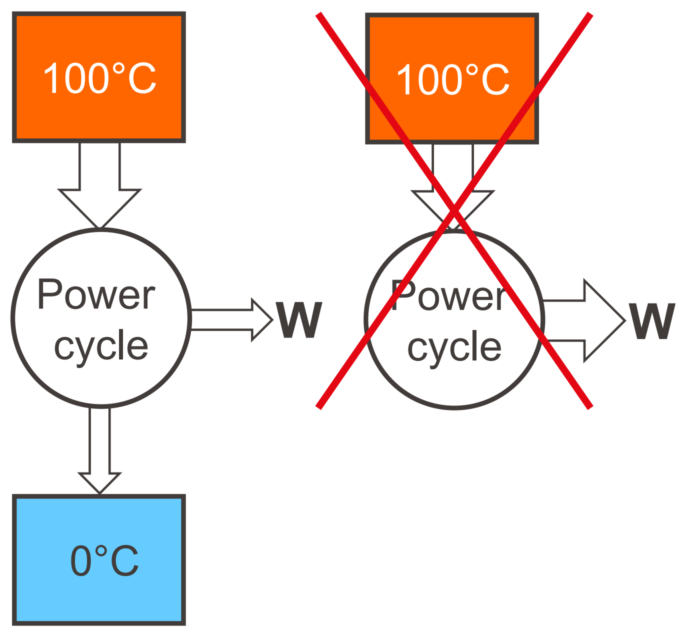
Formulations of 2nd Law

- 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
  - Heat does not flow naturally from a low-temperature reservoir to a higher one



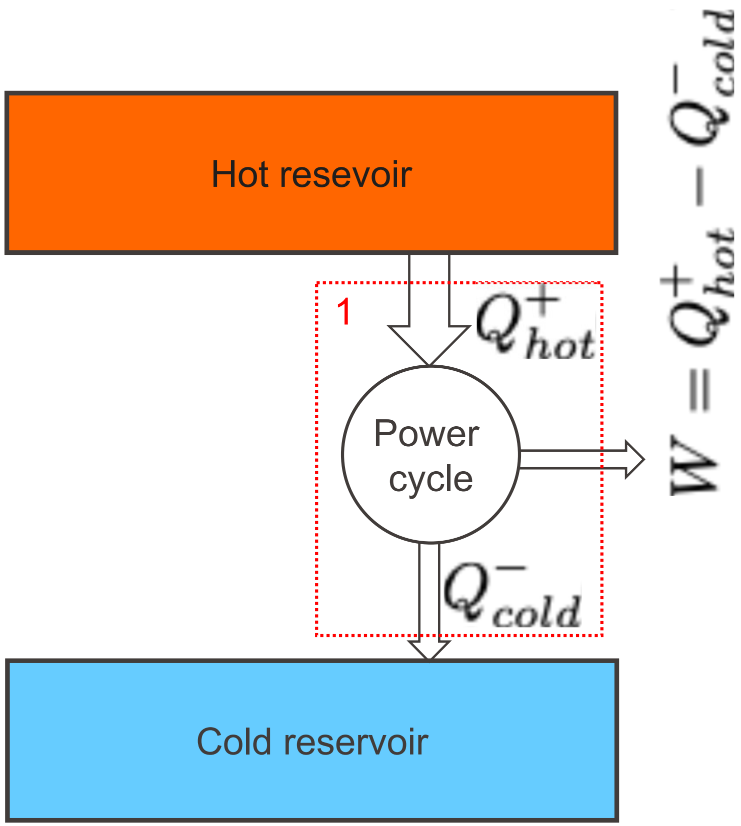
Formulations of 2nd Law

- 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
  - Power cycles requires hot and cold source
  - Thermal efficiency < 1



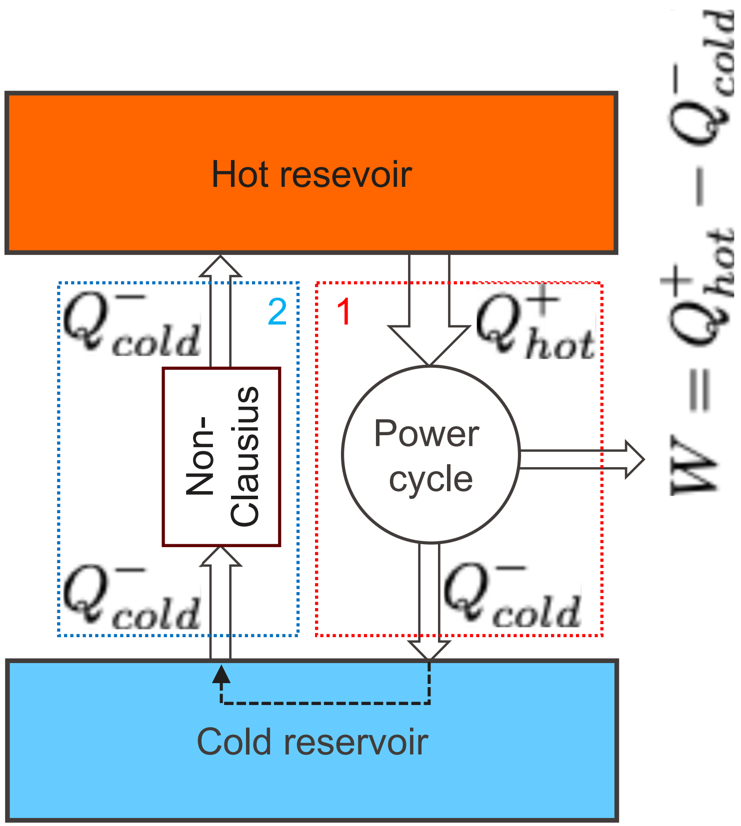
Equivalence of 2nd Law Formulations

- System 1 composed of power cycle according to Kelvin-Planck



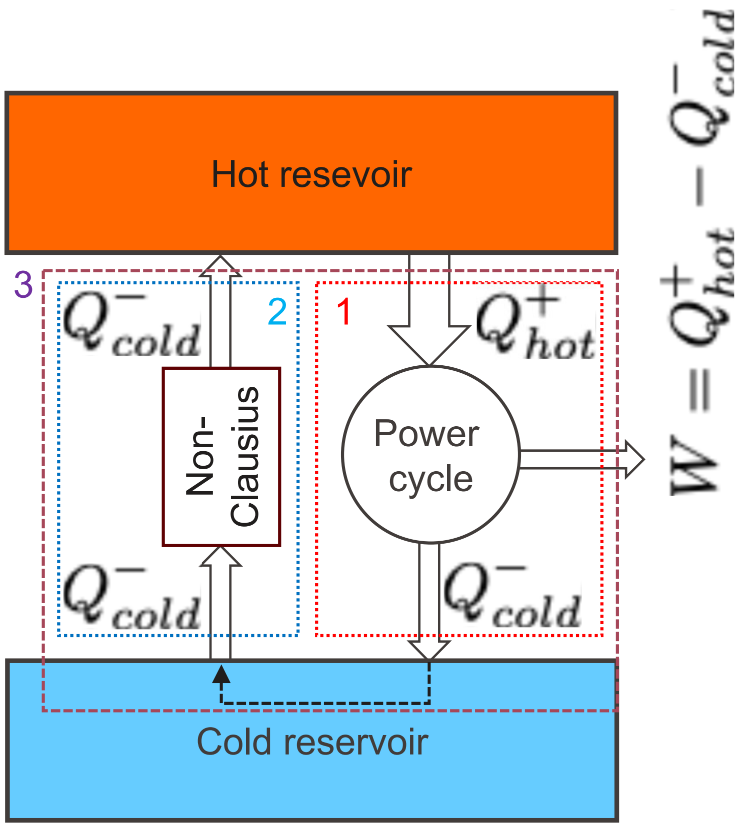
Equivalence of 2nd Law Formulations

- System 1 composed of power cycle according to Kelvin-Planck
- System 2 transferring heat opposed to Clausius
- Heat rejected by power cycle flows back to hot reservoir



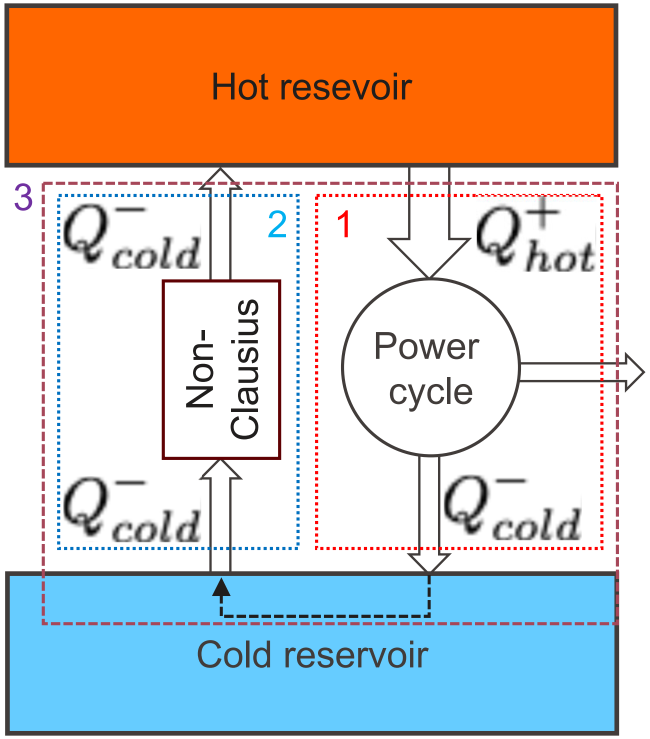
Equivalence of 2nd Law Formulations

- System 1 composed of power cycle according to Kelvin-Planck
- System 2 transferring heat opposed to Clausius
- Heat rejected by power cycle flows back to hot reservoir
- Combined system 3 draws net heat $Q^+_{hot} - Q^-_{cold}$ and transform it into W without rejecting heat to cold reservoir → violates Kelvin-Planck formulation



Equivalence of 2nd Law Formulations

- System 1 composed of power cycle according to Kelvin-Planck
- System 2 transferring heat opposed to Clausius
- Heat rejected by power cycle flows back to hot reservoir
- Combined system 3 draws net heat $Q^+_{hot} - Q^-_{cold}$ and transform it into W without rejecting heat to cold reservoir → violates Kelvin-Planck formulation
- Violation of Kelvin-Planck requires violation of Clausius → equivalence



$$W = Q^+_{hot} - Q^-_{cold}$$

Concept of Reversibility

- Knowing 1st and 2nd law that indicate what is possible, we want to know what a perfect machine looks like

- A perfect machine is reversible

- A process is called reversible if a system can be returned to its initial state without causing any changes in the environment

- Processes that take place in one direction only, are irreversible
  - Cooling of a cup of tea, emptying of a pressurized bottle, dissipation, falling mass, plastic deformation, spontaneous chemical reaction, mixing, …

Concept of Reversibility

- Irreversibility is a dissipation of energy, a loss of potential work
  → engineers want to avoid them
- Reversible processes are hypothetical and represent processes without any losses
- Reversible processes are not possible practically, but they represent the limits of what is possible while satisfying 1st and 2nd law
- Reversible processes are useful as references to measure the thermodynamic performance of real processes

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

- Reversible power cycles between same thermal reservoirs have same thermal efficiency → efficiency only function of reservoir temperatures

$$\eta_{th-rev.} = g\left(T_{hot}, T_{cold}\right)$$

- Definition of thermal efficiency $\eta_{th} = 1 - \dfrac{Q^-_{Cold}}{Q^+_{Hot}}$

- Consequently $\left[\dfrac{Q^-_{Cold}}{Q^+_{Hot}}\right]_{rev.} = f\left(T_{hot}, T_{cold}\right)$

Thermal Efficiency

- Reversible power cycles between same thermal reservoirs have same thermal efficiency → efficiency only function of reservoir temperatures

$$\eta_{th-rev.} = g\left(T_{hot}, T_{cold}\right)$$

- Definition of thermal efficiency $\eta_{th} = 1 - \frac{Q^{-}_{Cold}}{Q^{+}_{Hot}}$

- Consequently $\left[\frac{Q^{-}_{Cold}}{Q^{+}_{Hot}}\right]_{rev.} = f\left(T_{hot}, T_{cold}\right) = \frac{T_{cold}}{T_{hot}}$

Kelvins approach: ratio of reversibly transferred heats equals ratio of reservoir temperatures

Thermal Efficiency

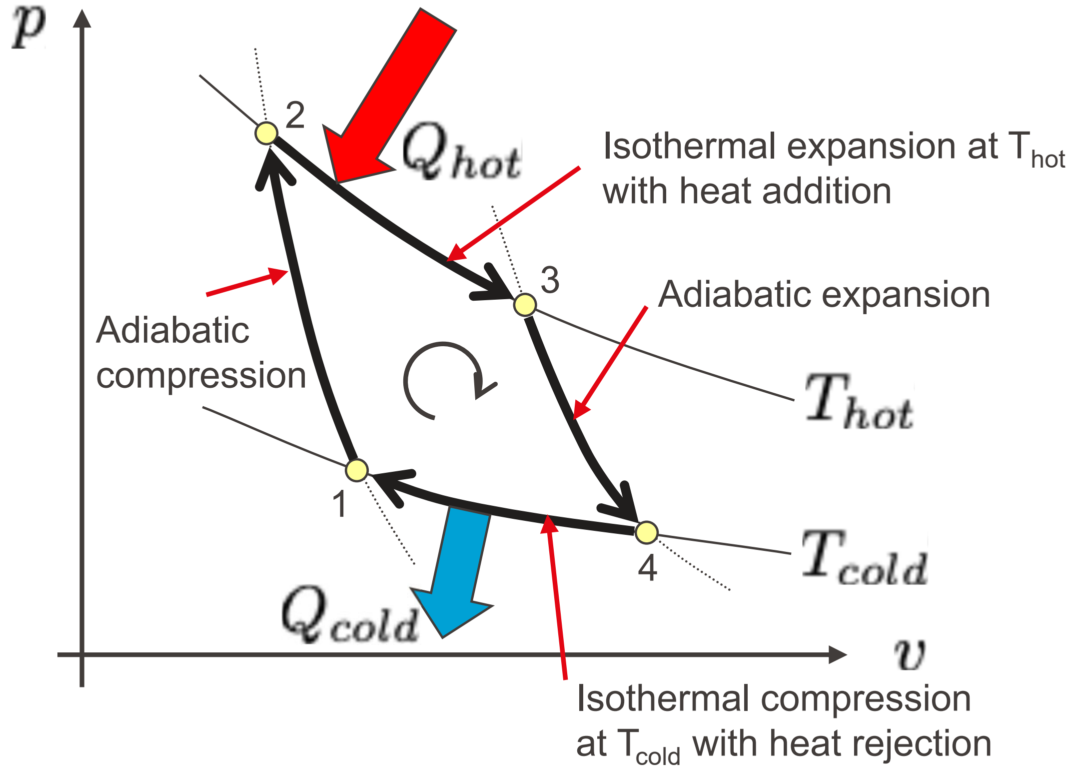
- Through Kelvins definition of the function, thermal efficiency of reversible cycle expressed as:

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

- Carnot cycle is one famous reversible power cycle
- Thermal efficiency of reversible cycle is called Carnot-efficiency
- Carnot efficiency is reference for assessing performance of power cycles

Carnot Cycle

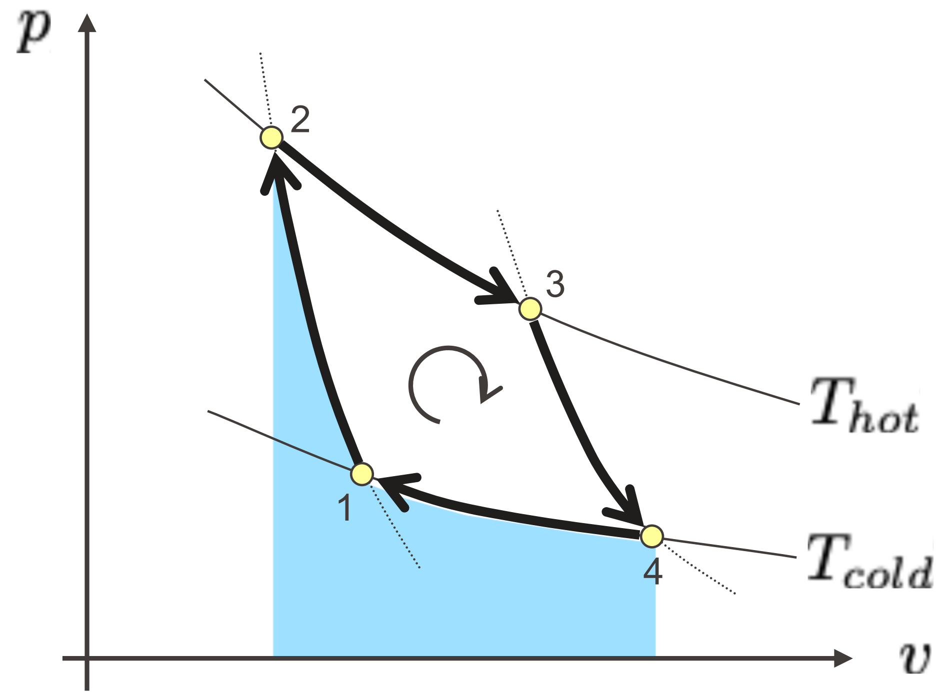
- Cycle composed of two reversible adiabatic and two reversible isothermal processes



Carnot Cycle

- Compression work

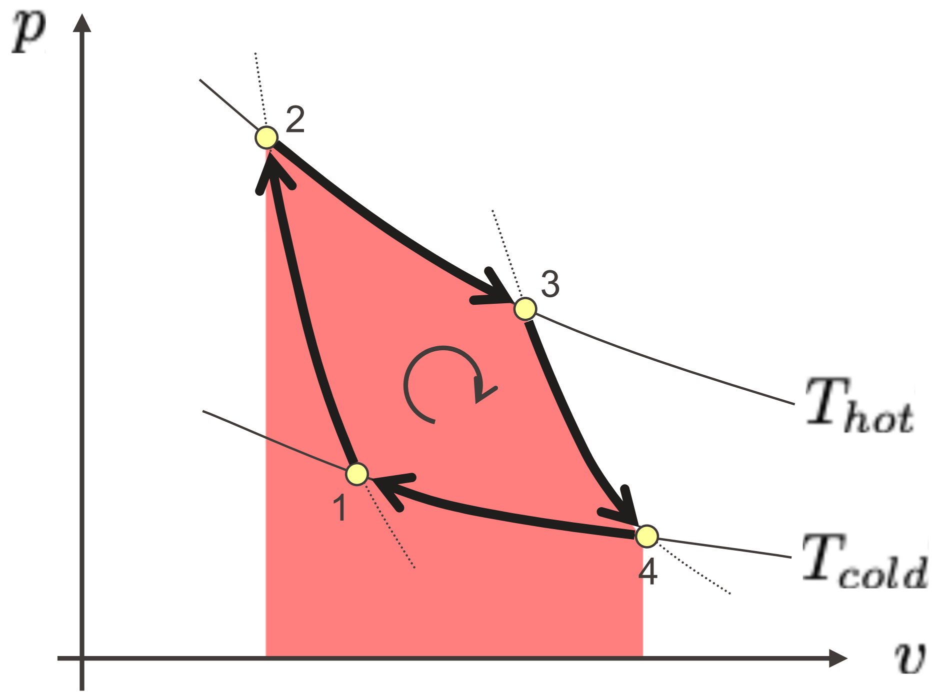
$$W_{42} = -\int_4^2 p dV > 0$$



Carnot Cycle

- Expansion work

$$W_{234} = -\int_2^4 pdV < 0$$



Carnot Cycle

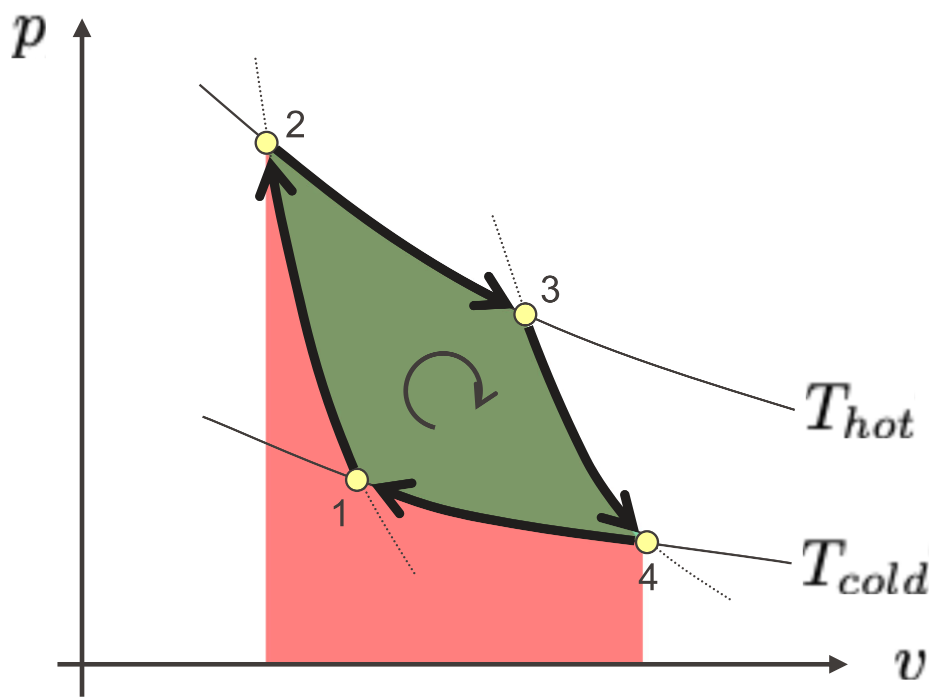
- Net work

$$W_{234} = -\int_2^4 pdV < 0$$

$$W_C = W_{234} - W_{42}$$

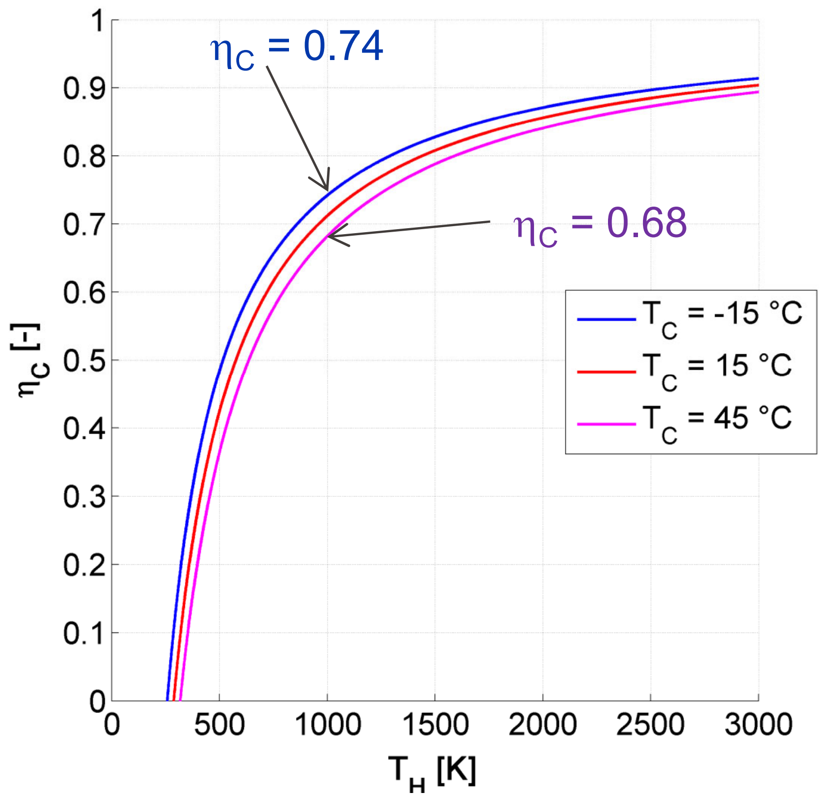
$$W_C = \eta_{th-rev.} Q_{hot}$$

$$W_C = \left[1 - \frac{T_{cold}}{T_{hot}}\right] Q_{hot}$$



Thermal Efficiency

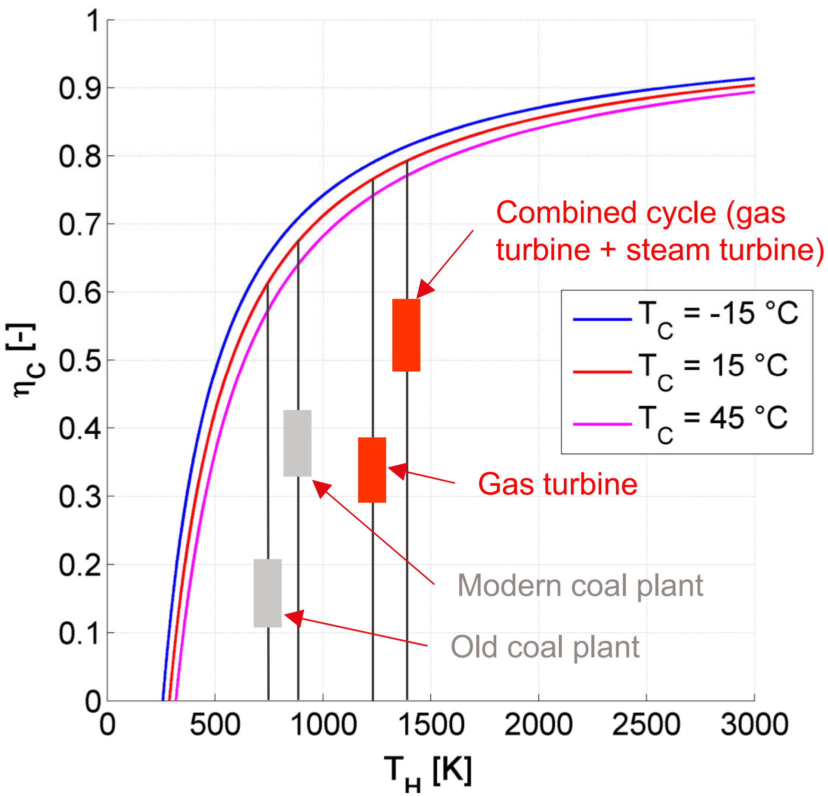
- Maximum thermal efficiency limited by Carnot efficiency
- Carnot efficiency rises with temperature different between reservoirs
- Maximizing hot source temperature is key drive to improve thermal performance



$$\eta_c = 1 - \frac{T_{cold}}{T_{hot}}$$

Typical Thermal Efficiencies

- Real life thermal efficiency always lower than Carnot efficiency

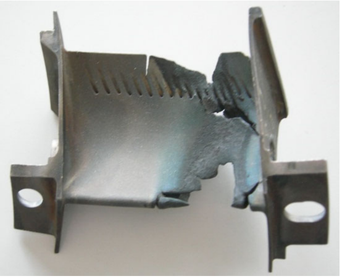


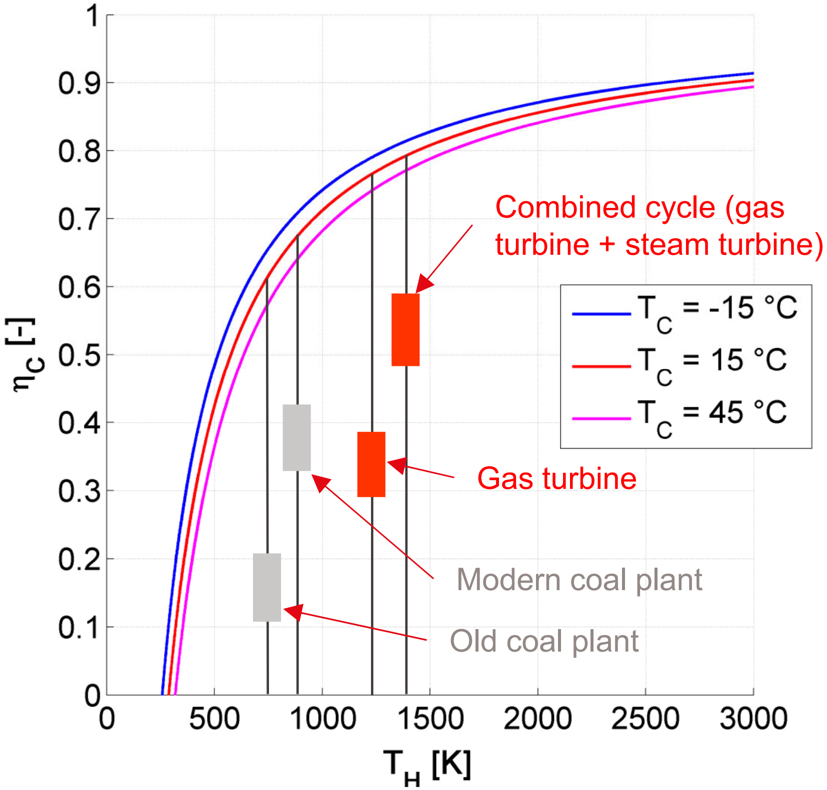
$$\eta_c = 1 - \frac{T_{cold}}{T_{hot}}$$

Typical Thermal Efficiencies

- Real life thermal efficiency always lower than Carnot efficiency

- Limitations stem from irreversibility and practical limitations
  - Temperature drop required to transfer heat
  - Friction, secondary flows
  - Pressure gradient needed to transfer mass
  - Limited temperature resistance of materials


www.siemens.de



$$\eta_c = 1 - \frac{T_{cold}}{T_{hot}}$$

Outlook for W3

- Thermodynamics crash course
  - Entropy, entropy balance in closed/open systems
  - Isentropic efficiencies
  - Concept of exergy
  - Exergy efficiency

Exercises W2

- Theory questions
- Reversible, adiabatic expansion
- Polytropic expansion
- Maximum reversible work output of a finite source
- Filling empty gas tank
- Reversible cycle efficiencies