Heat Pumps Systems

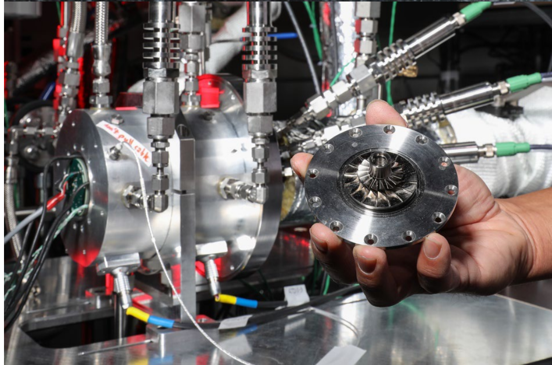
Course Introduction

Prof. J. Schiffmann

École
polytechnique
fédérale
de Lausanne

Presentation

- Laboratory for Applied Mechanical Design (MechE)
- Small scale turbomachinery
  - Heat pumps
  - Power cycles
  - Fuel cell blowers
- Gas lubricated bearings
- Automated design methodologies



Course Contents

- W1: Societal drive, history of heat pumps, thermodynamic basis
- W2-3: Thermodynamics crash course
- W4: Thermodynamics of heat pump cycles
- W5: Performance analysis, single-stage & two-stage cycles
- W6: Cycle improvements
- W7: Working fluids, introduction to compressors
- W8: Positive displacement compressor performance, screws, scroll
- W9-10: Turbocompressors
- W11: Heat exchangers
- W12: Absorption, supercritical, humid air + air-conditioning, acr
- W13: Absorption, supercritical, humid air + air-conditioning, acr

Course Organization

- Organization
  - Course at 9.15h followed by exercises
  - Course, exercices and corrections on moodle
  - Teaching assistants
    - A. Jena, K. Jacoby, I. Soukhmane, A. Zervent

EPFL

Heat Pumps Systems

Historical Background of Heat Pumps

Prof. J. Schiffmann

École polytechnique fédérale de Lausanne

Social Needs

- Heating and cooling are basic requirements to make living more comfortable

- Heat pumps are technical systems to provide heating and / or cooling by driving them with electrical / mechanical power

Heating in Historical Context

- Artificial and controlled use of fire was major step towards improved comfort, food preparation and defense
- Heat through combustion is simple and cheap → little motivation to do better
- Today we put a box around the fire and call it modern heating system

manashsubhaditya.blogspot.com/2012/06/stone-age-people-discovery-of-haunting.html

Cooling in Historical Context

- Cooling is important for comfort in hot climate
- Goes back to 2’500 BC with Egyptians using evaporative cooling
- Used in middle east through “wind catchers”
- Used today for terrace cooling

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

https://quilohome.com/evaporative-cooling-ancient-world/

https://theplumber.com/the-pros-cons-of-outdoor-misting-systems/

Cooling in Historical Context

- Cooling is important for storing perishable food
- Ice harvesting and trade was important business branch until ~1900
- Natural ice was traded and distributed at intercontinental scale
- Strong demand for cooling called for more efficient alternative

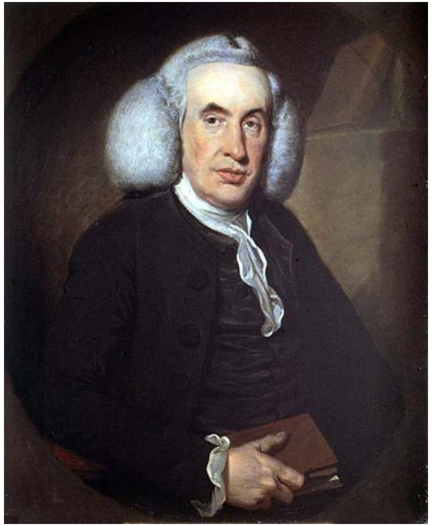
welt.de geschichte article145039745 Die-unerhoerte-Ladung-des-Eiskoenigs-aus-Boston.html#cs-lazy-picture-placeholder-01c4eedaca.png

teachingwiththemes.com index.php 2018 07 11 how-did-humans-survive-without-refrigerators ice-wagon

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

First Steps in Artificial Cooling

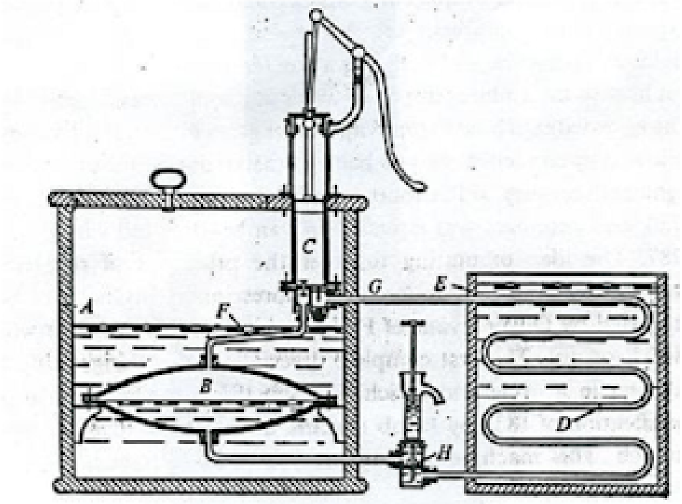
- Artificial cooling was much more difficult to achieve
- Experiment by W. Cullen in 1755 (Edinburgh)
  - Decrease pressure in vessel containing diethyl ether
  - Pressure reduction leads to boiling, which absorbs heat from surroundings
  - Water in thermal contact with vessel cooled down and turned into ice
- Experiment highlights two thermodynamic concepts
  - Vapor pressure → liquid with own vapor at equilibrium is at saturation pressure → $P_{SAT} = f(T)$
  - Latent heat is absorbed from surrounding required to boil



https://en.wikipedia.org/wiki/William_Cullen

First Steps in Artificial Cooling

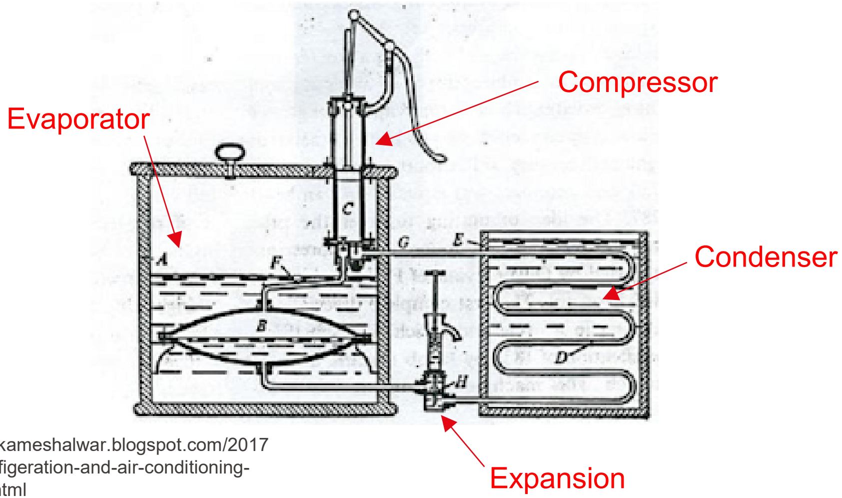
- To make Cullen's experiment continuous, boiled vapor would have to be condensed and brougth back to original vessel
- Condensation requires rejection of latent heat at higher temperature
- J. Perkins patented such a system in 1835
- J. Hague realized Perkins' idea using ether as a working fluid
  - Machine has all components of modern refrigeration cycle: compressor, condenser, expansion valve, evaporator
- First commercial ice-making plant in Australia in 1855



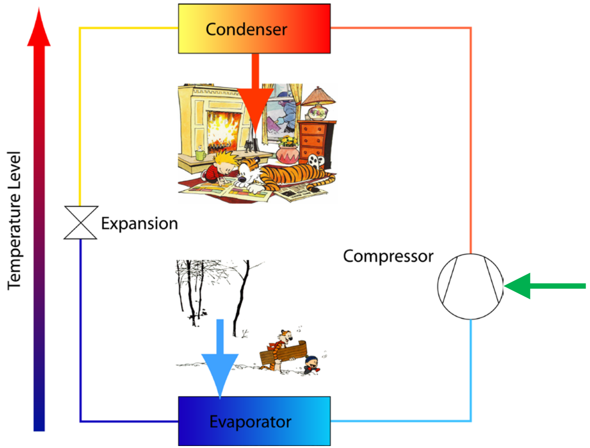
http://kameshalwar.blogspot.com/2017/03/refigeration-and-air-conditioning-brief.html

Heat Pump Operation

- Heat pump allows to gather heat at low temperature (cooling) and to reject it at higher temperature (heating)
- Can be used to provide cooling and/or heating
- Composed of compressor, condenser, expansion valve & evaporator

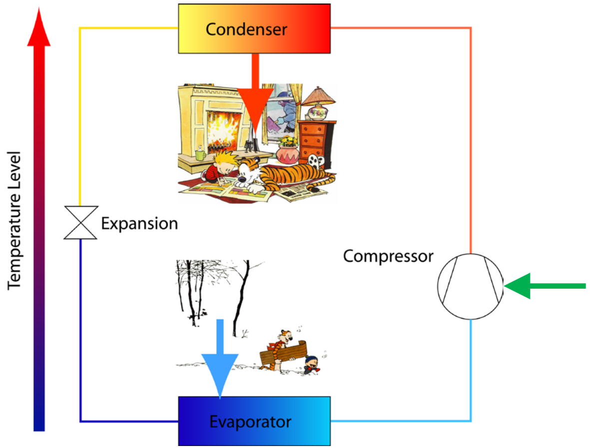


http://kameshalwar.blogspot.com/2017/03/refigeration-and-air-conditioning-brief.html



Typical Heat Pump Components

- Evaporator absorbs heat from low temperature reservoir
- Condenser rejects heat to high temperature reservoir
- Compressor increases working fluid pressure by absorbing energy
- Expander decreases working fluid pressure



Typical Heat Pump Settings

- Typical cases of bi-thermal heat pump cycles
- Bi-thermal → transfer occurs with two different thermal sources → involves pressure change within cycle

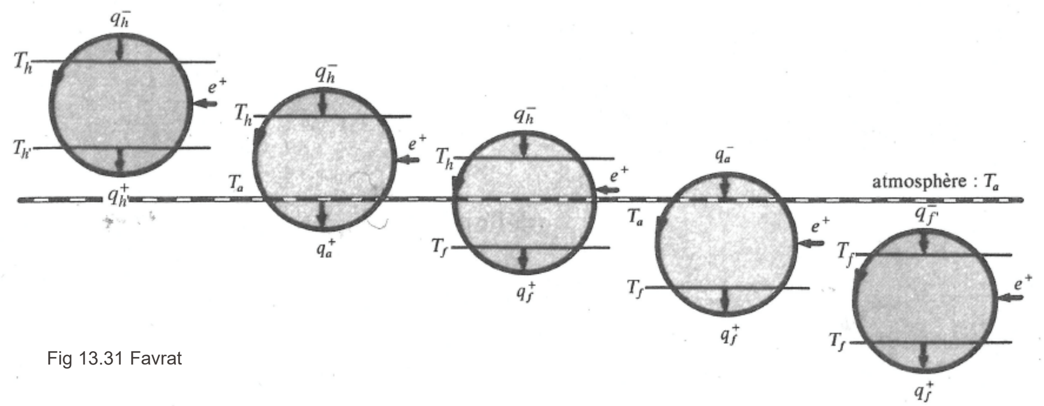
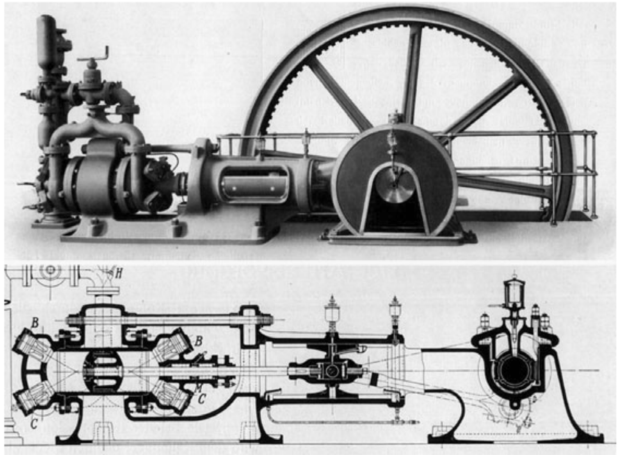


Fig 13.31 Favrat

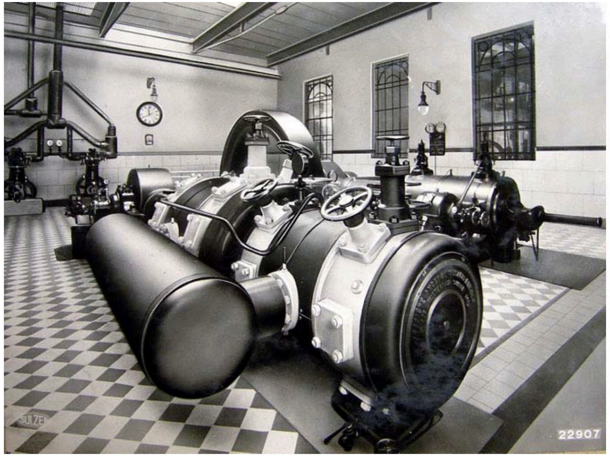
- Most common are cases b and d → one if thermal source is atmosphere

Developments of Artificial Cooling

- Industrialization of refrigeration driven by C. von Linde after 1875
- Most fundamental inventions made by 1900
- Raising business for compressor manufacturers in US and Europe



Sulzer piston compressor ~1905

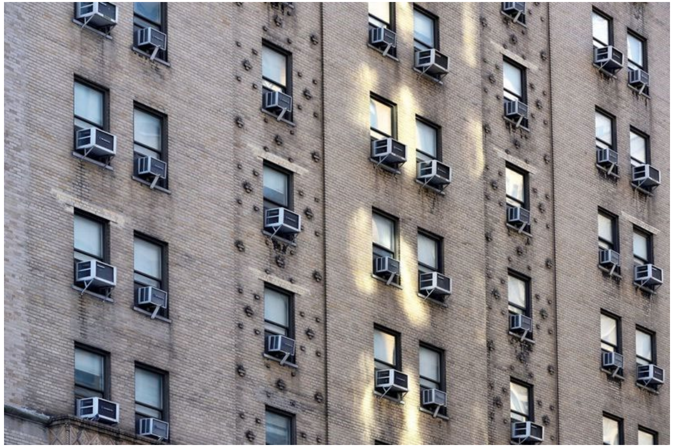


Steam engine driven piston compressor ~1925

Typical Applications Today: Cooling

- Air-conditioning units extract heat from apartment and reject to ambient

www.servicechampions.net blog the-basics-of-air-conditioner-preparation-and-maintenance



www.nydailynews.com news world ny-news-climate-change-air-conditioners-20180704-story.jpg

Typical Applications Today: Cooling

- Fridges and freezers for food conservation or medical drug storage
- Heat is extracted from fridge and rejected to room

www.danby.com/blog/fridge-cleaning-tips-give-fridge-spring-purge/

bcfocus.com/global-commercial-refrigerators-freezer-market-2020-industry-status-carrier-commercial-refrigeration-frigoglass-haier-panasonic-dover-corporation/

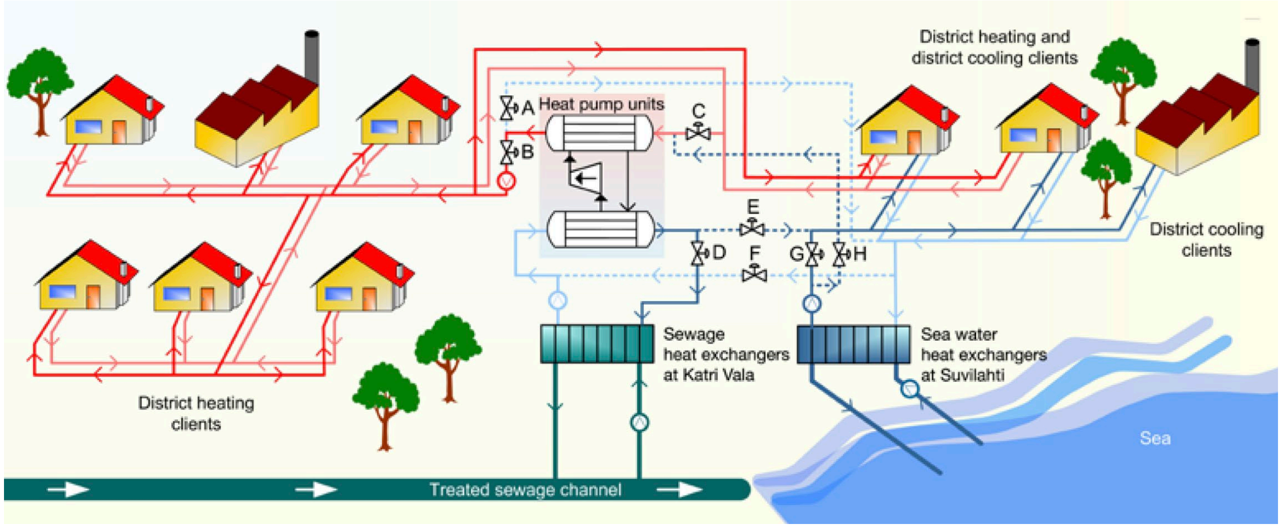
Typical Applications Today: Cooling

- Cooling for food storage

suisse.zero-c.com/fr/references/

Typical Applications Today: Heating & Cooling

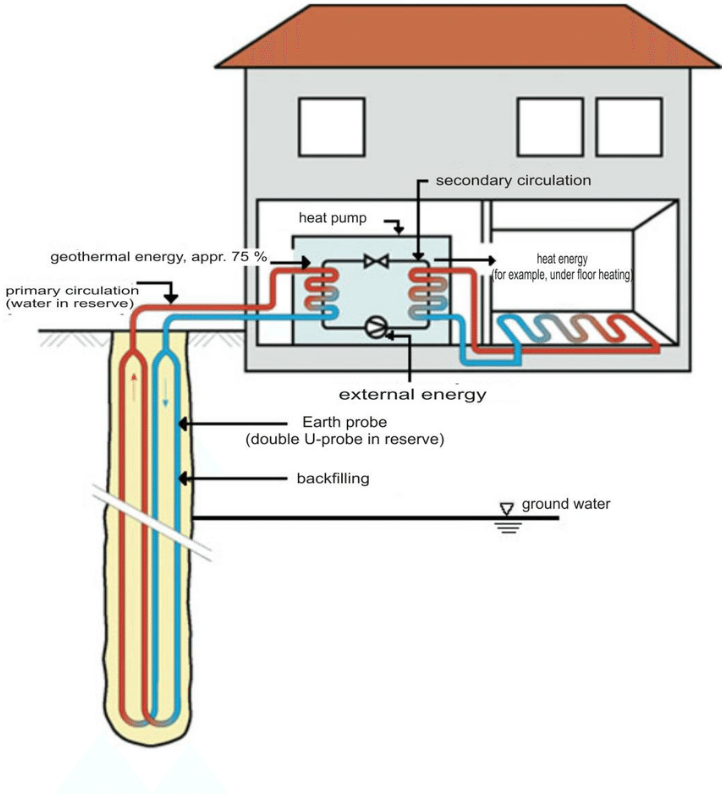
- Providing heating and cooling services in distric networks



www.friotherm.com/wp-content/uploads/2017/11/katri_vala_e012_uk.pdf

Typical Applications Today: Domestic Heating

- Heat is extracted from ground at low temperature and rejected to house at higher temperature
- Alternatively, low temperature heat can be extracted from lake / river or from external air



www.researchgate.net/figure/Brine-water-heat-pump_fig2_309027046

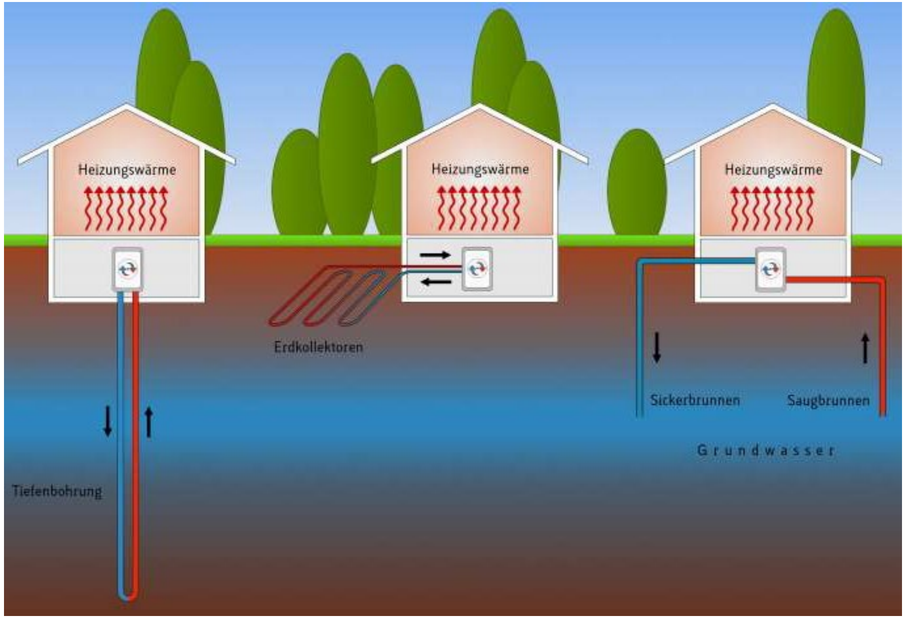
Typical Applications Today: Air-Water Heat Pumps

- Low-temperature heat is extracted from from external air

https://www.waermepumpen.info/luftwaermepumpe/luft-wasser

Typical Applications Today: Water-Water Heat Pumps

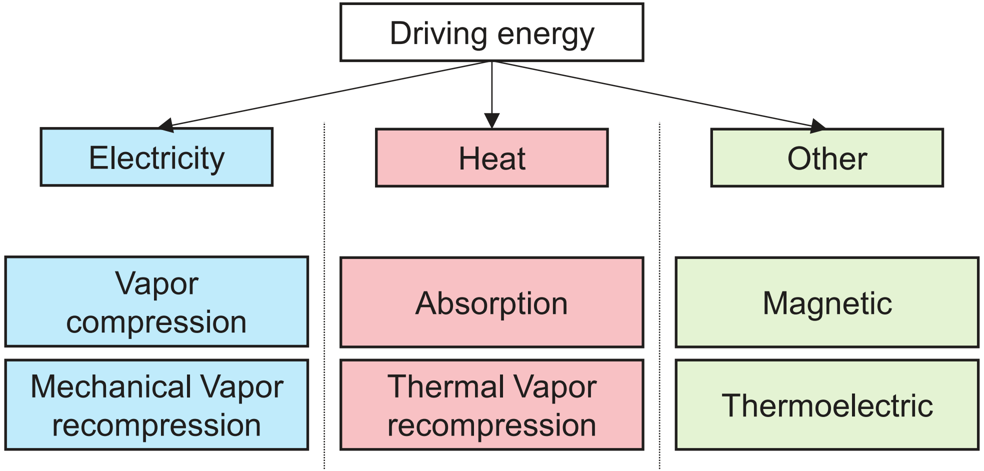
- Low-temperature heat is extracted from ground



https://solarwissen.selfmade-energy.com

Artificial Cooling Technologies Overview

- Production of cold for comfort, preserving perishable goods and hygiene was key driver for vapor compression heat pumps
- Alternative technologies have been developed for cooling
- Vapor compression and mechanical vapor recompression type represent 95% of market



Heat Pumps Systems

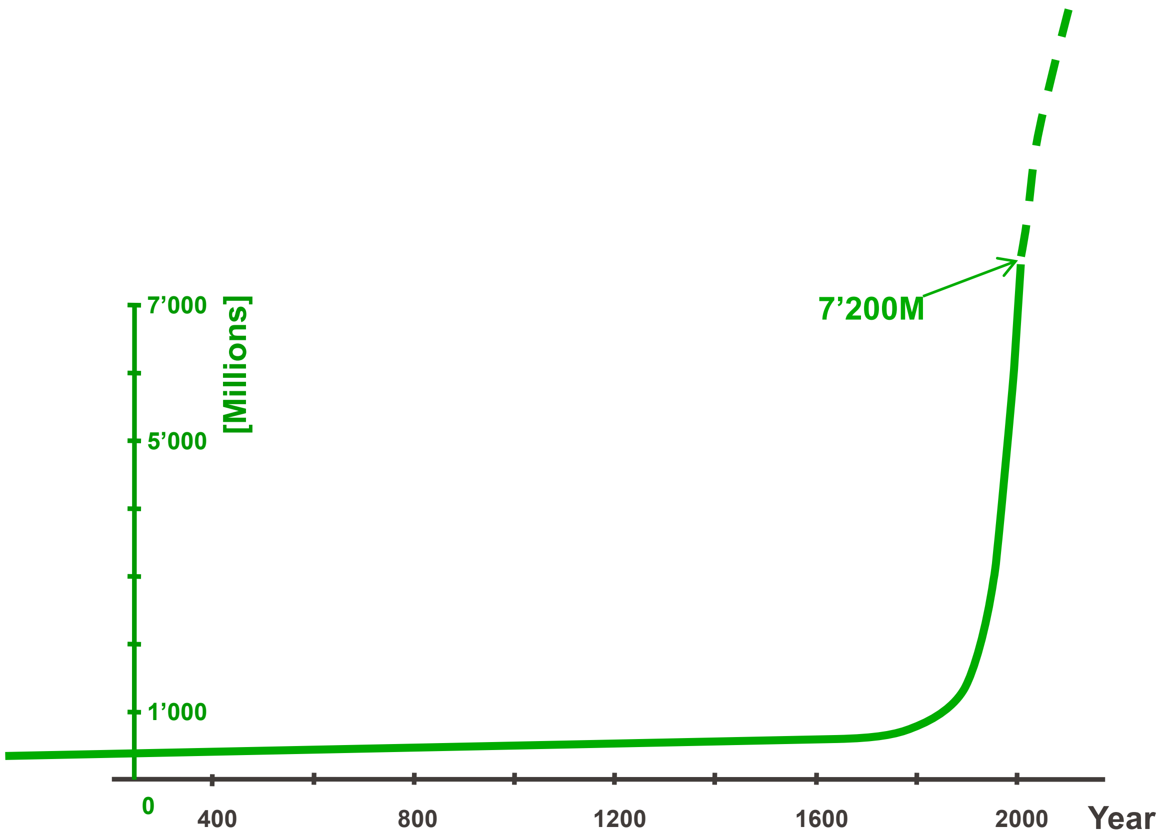
Considerations on Energy for Domestic Heating

Prof. J. Schiffmann

École polytechnique fédérale de Lausanne

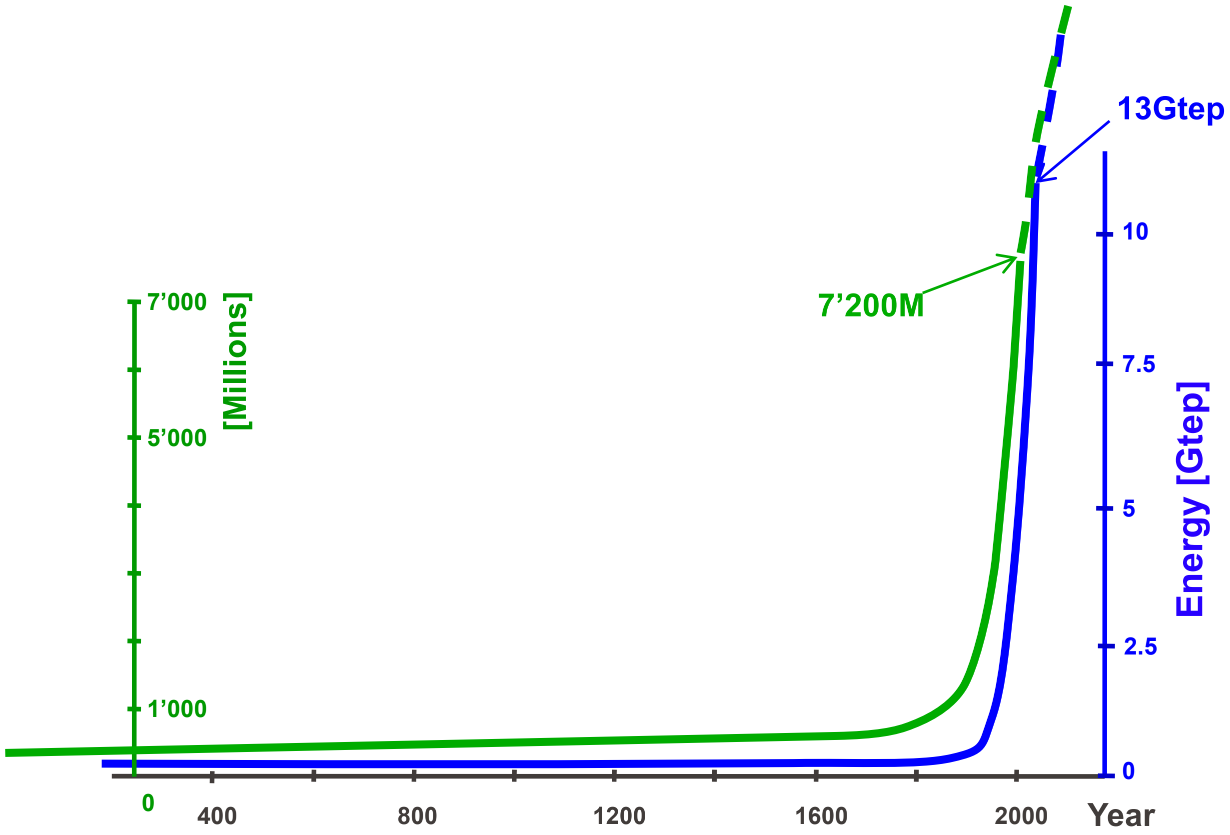
Population, Energy Consumption, CO_2 concentration

- Population



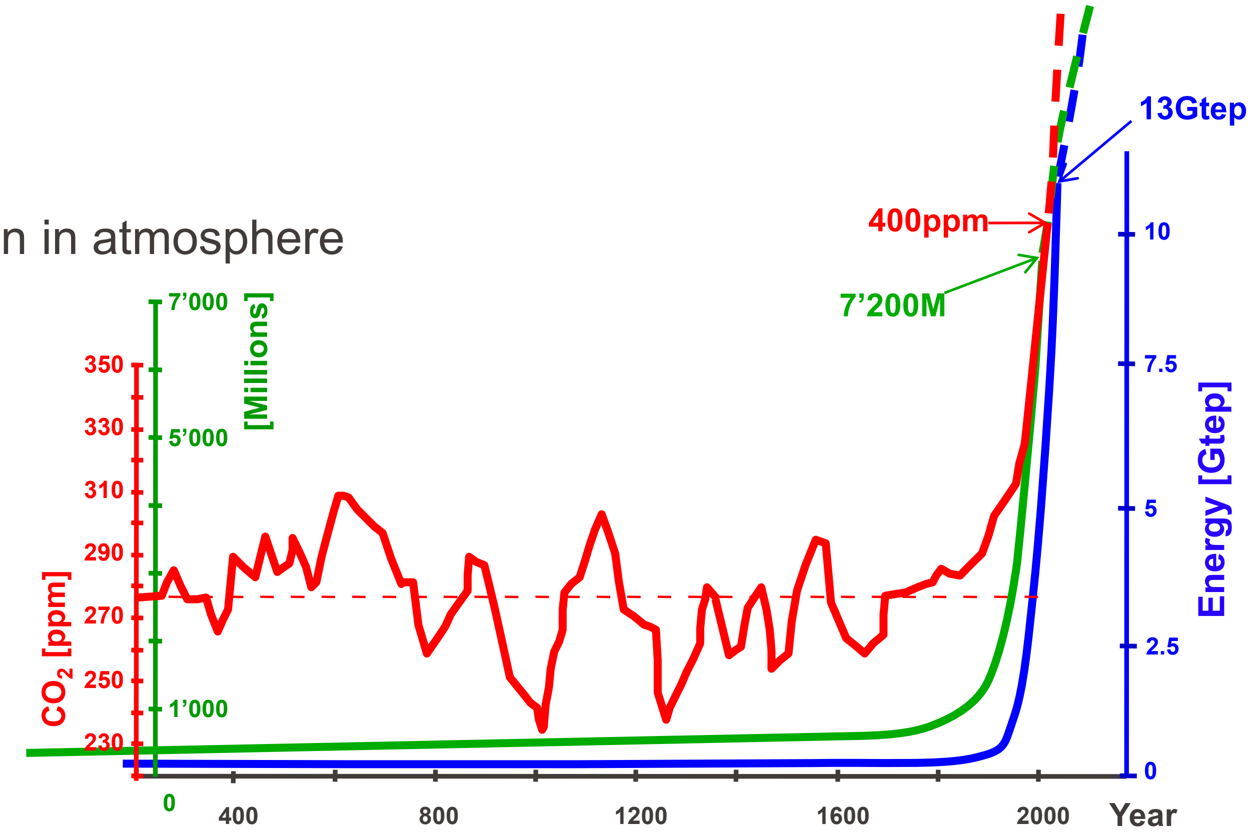
Population, Energy Consumption, CO_2 concentration

- Population
- Energy

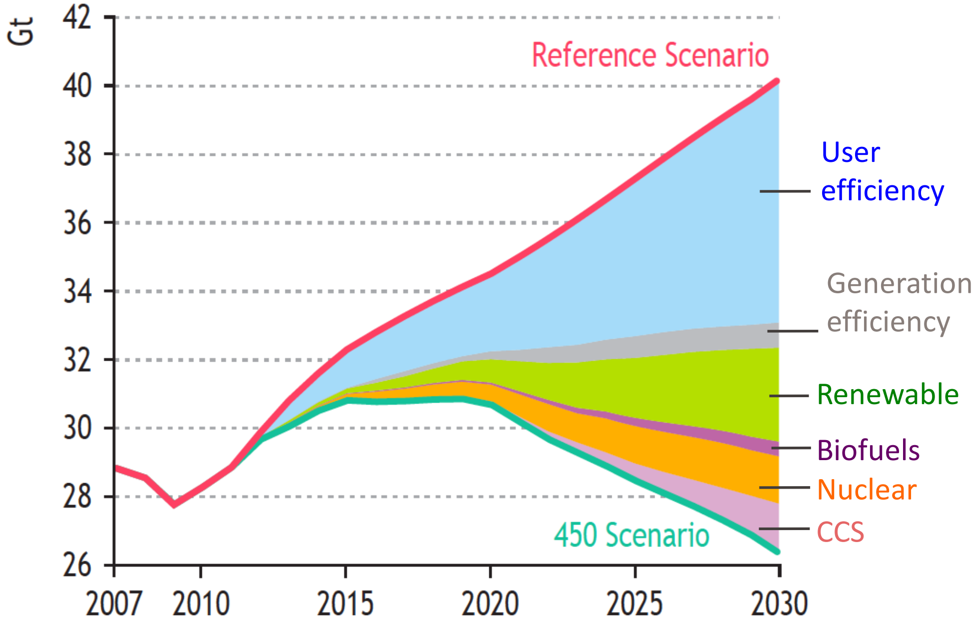


Population, Energy Consumption, CO_2 concentration

- Population
- Energy
- CO_2 concentration in atmosphere



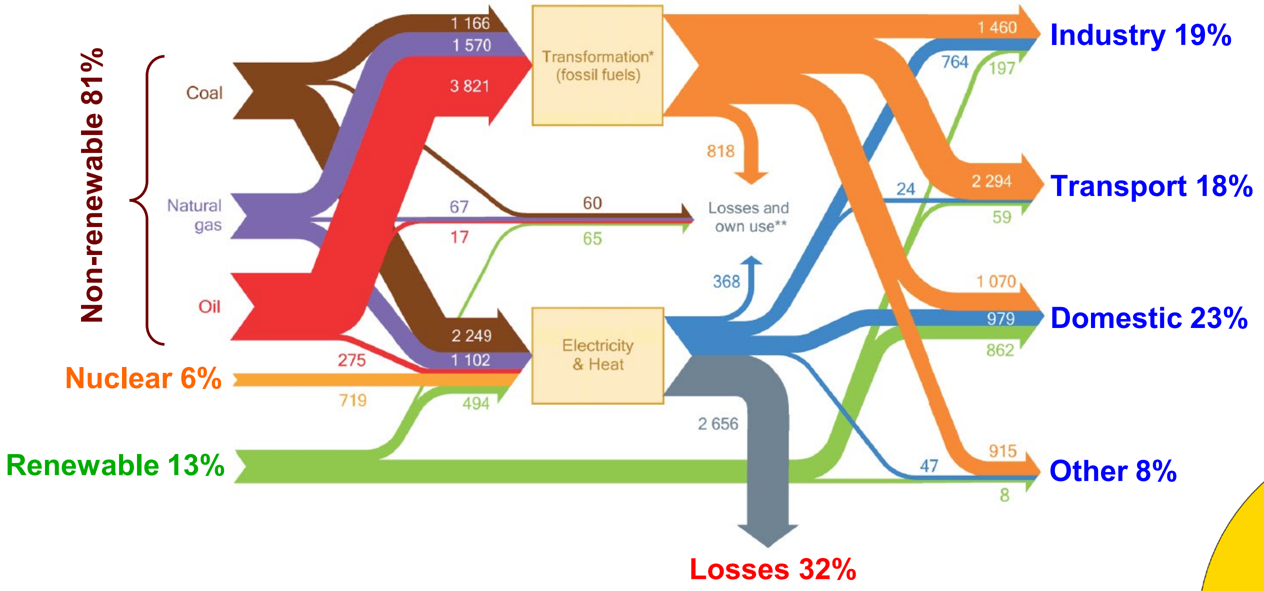
Steps Towards Sustainable Energy Landscape

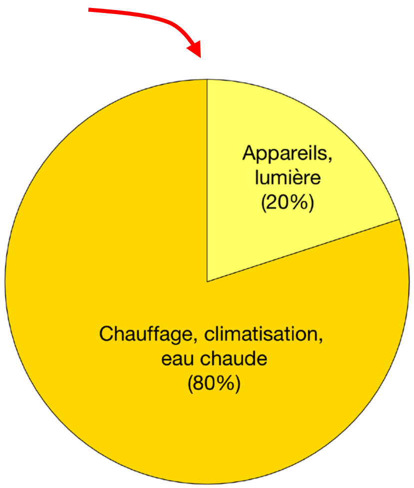


Source: IEA outlook

- 50% of required cuts achieved by increasing conversion efficiency

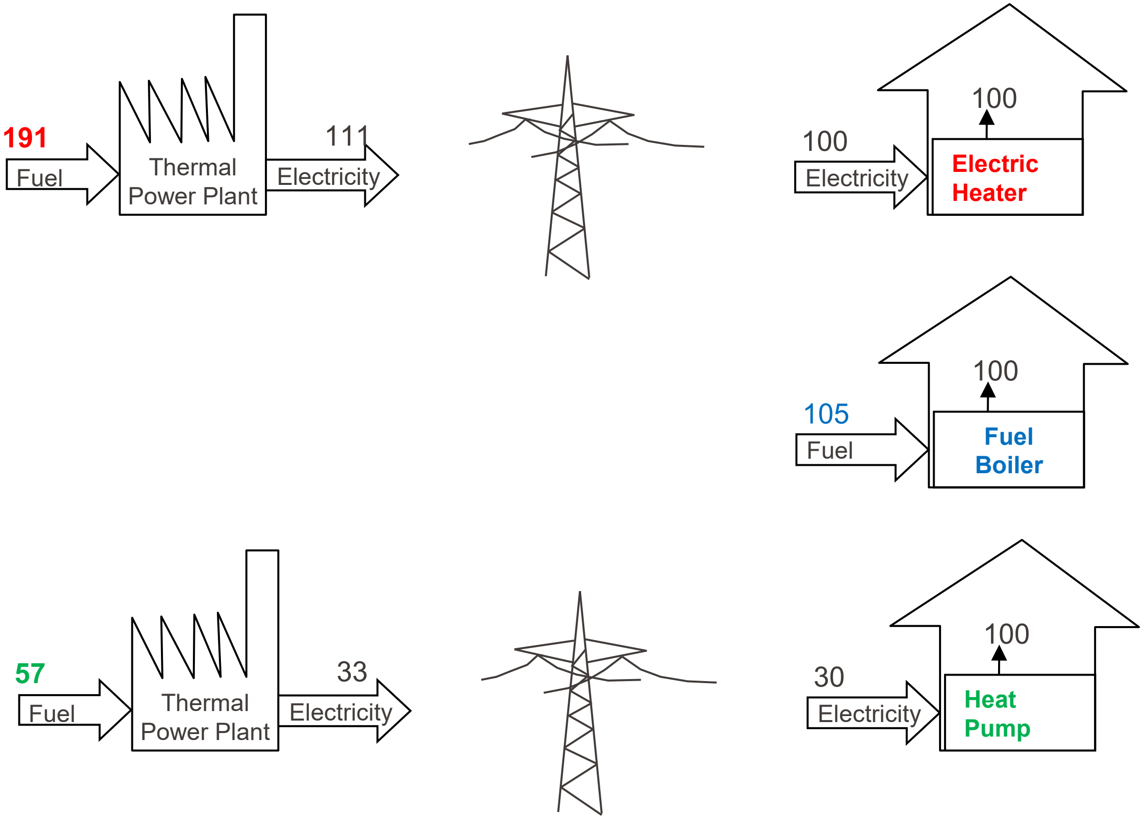
Worldwide Energy Fluxes





- 80% non-renewables
- 32% lost
- 27% for domestic heating ventilation and air-con (HVAC)

Domestic Heating: Comparison of Technology Combinations



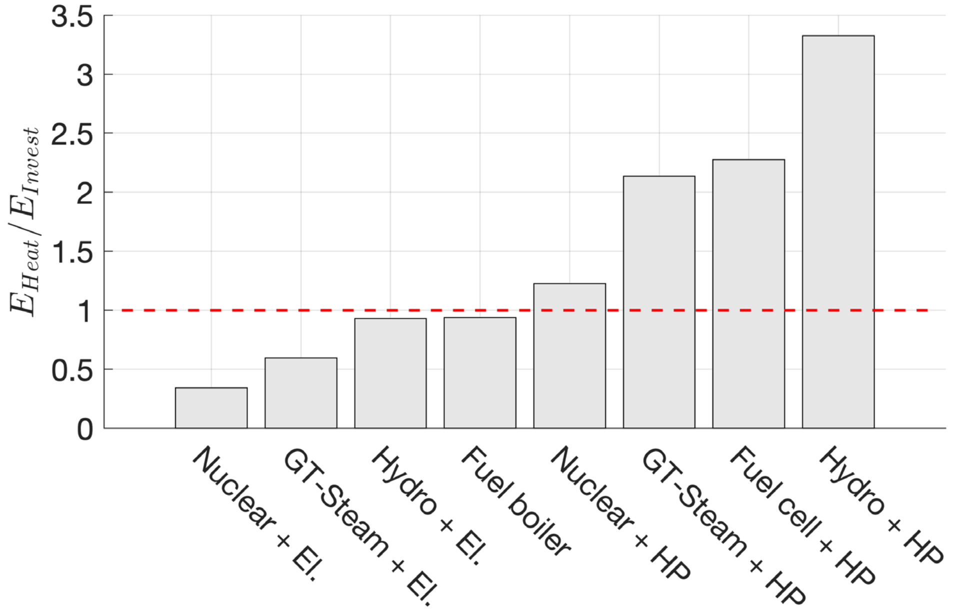
$$\text{Efficiency} = \frac{100}{191} = 52\%$$

$$\text{Efficiency} = \frac{100}{105} = 95\%$$

$$\text{Efficiency} = \frac{100}{57} = 176\%$$

Domestic Heating: Comparison of Technology Combinations

- Heat pumps play key role in reducing energy consumption and CO_2 emissions



Heat Pump Systems

Thermodynamics Crash Course

Introduction

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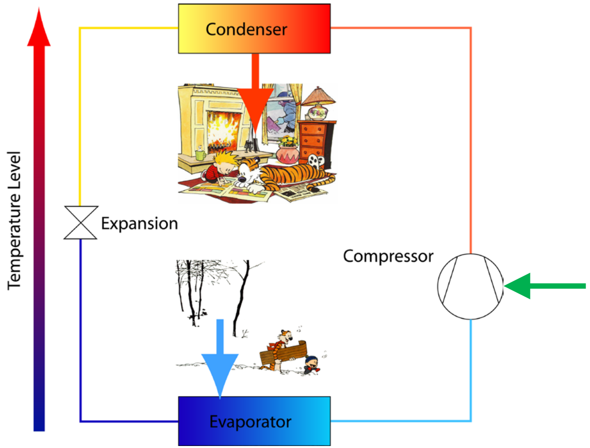
Typical Heat Pump Components

- Evaporator absorbs heat from low temperature reservoir
- Condenser rejects heat to high temperature reservoir
- Compressor increases working fluid pressure by absorbing energy
- Expander decreases working fluid pressure

- Tool needed to describe these processes



Thermodynamics

- Deals with transformation of energy from one form into another, transformation of fluid properties, systems to transform energy

- Thermodynamics is a tool that joins physics with mechanical engineering

- Thermodynamics is useful tool to assess achievement of efficiency, power, cost, and environmental objectives

Thermodynamics at Home

- Cooling and heating of rooms
- Humidity control
- Cooling of perishable goods

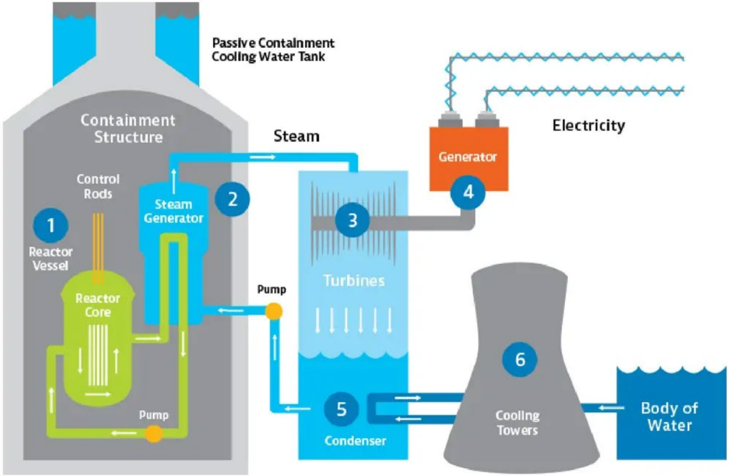
Thermodynamics in Transport

GE90 (B-777)
- Fan diameter: 3.26 m
- Weight: 8.3 t
- Thrust: 569 kN

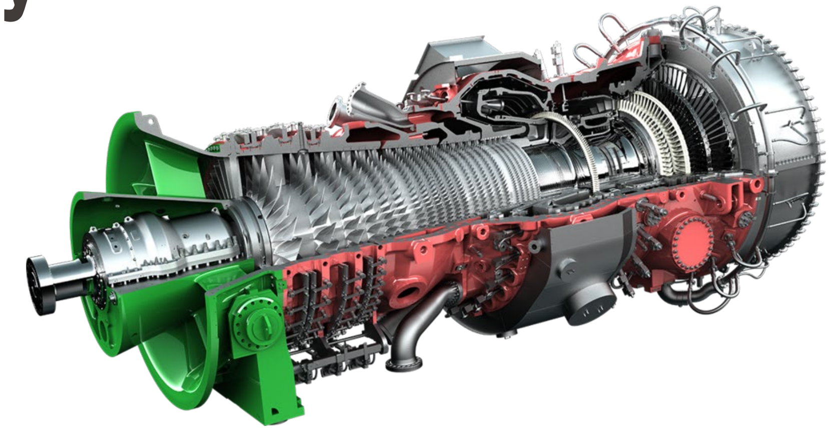
Raptor 3 (Space X)
- Diameter: 1.3 m
- Weight: 1.53 t
- Thrust: 2750 kN

Wärtsilä RT-flex96C
- Height: 13.5 m
- Weight: 2300 t
- 14 cylinders
- Power: 81.3 MW

Thermodynamics in Industry



Nuclear power plant
- Pressurized water reactor
- Several cycles



Gas turbine engine power station

Industry
- Processes
- Pinch analysis

Thermodynamic System Approach

- Define system boundary
- Identify interactions across boundary
  - Work
  - Heat
  - Fluid fluxes
- Apply energy conservation and mass conservation for system

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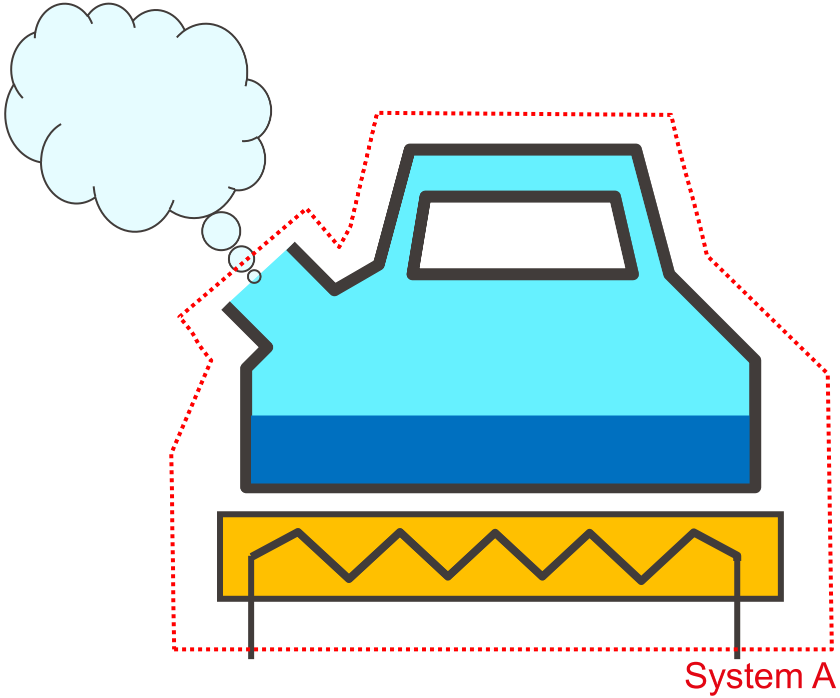

Thermodynamic System

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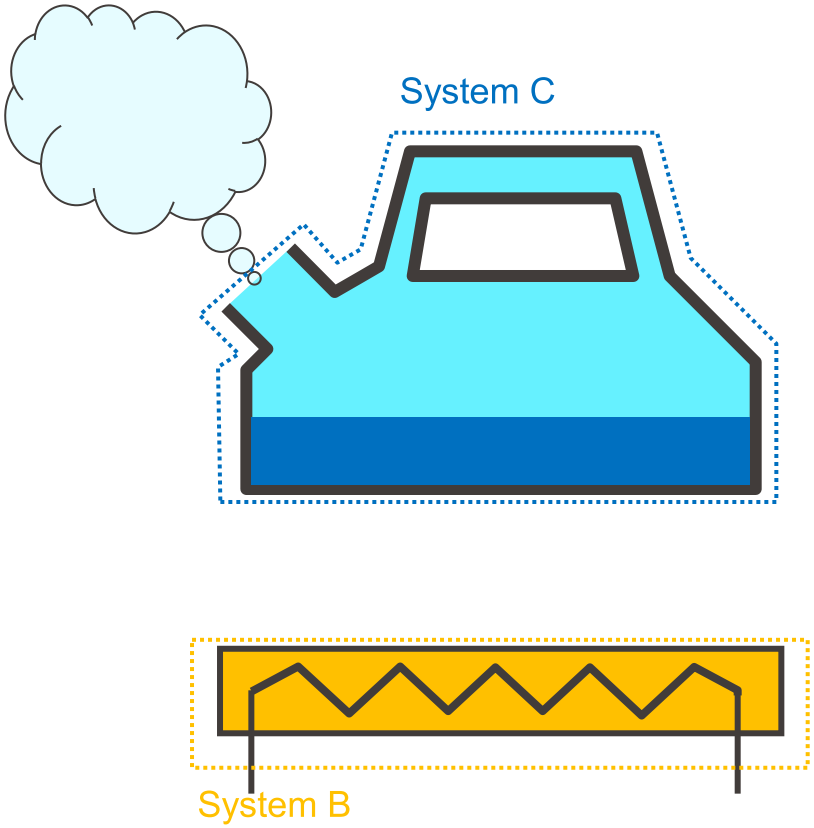
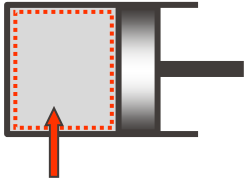
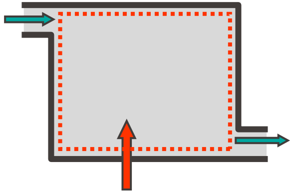


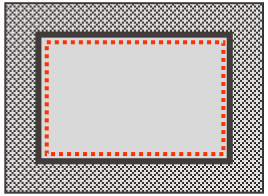
Characterization of Thermodynamic Systems

- Closed & open systems
  - Closed: constant mass
  - Open: mass fluxes across boundary

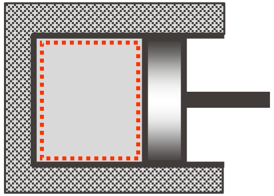




- Isolated systems
  - No work, heat, or fluxes

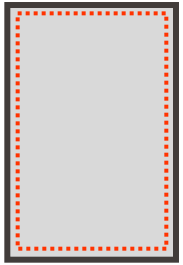


- Adiabatic systems
  - No heat transfer

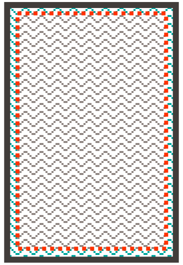


Characterization of Thermodynamic Systems

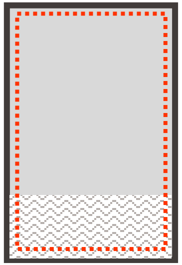
- Homogeneous & heterogeneous systems



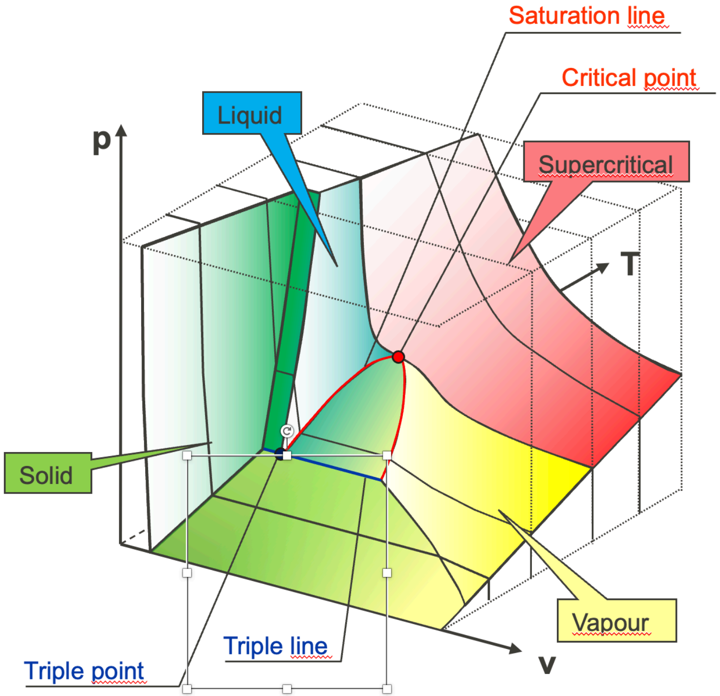
Gas



Liquid



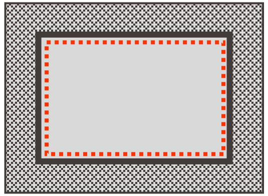
Gas & Liquid



Thermodynamic States

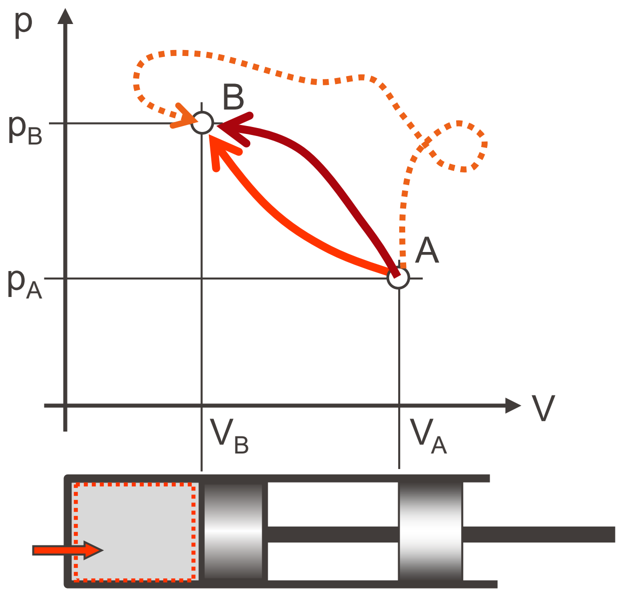
- Description of fluid's properties in system via thermodynamic state properties
  - Mass
  - Volume
  - Pressure
  - Temperature
  - Internal energy
  - Enthalpy
  - Entropy

Specific values (per unit mass)



Thermodynamic States

- Transfer of work and heat into and from system change state of fluid
  - Starting state in A, end state in B
  - Different processes (trajectories) possible for same start & end states
  - Different processes involve different sequences of heat and work transfer
  - All thermodynamic states properties defined for a fixed state → independent of process



Thermodynamic States

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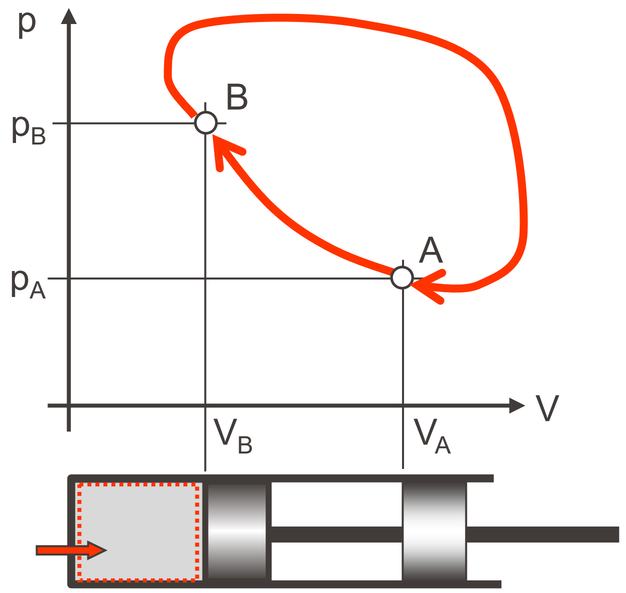

- Definition of cycle
  - Sequence of processes leads system back to initial state
  - Process describes closed line

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
4. Define assumptions → Identify suitable simplifying assumptions
5. Thermodynamic analysis → Apply physical laws
6. Discussion → Critical analysis of results & assumptions

Outlook for W2

- Thermodynamics crash course
  - 1st law for closed/open systems
  - Cycle characteristics
  - Formulation of 2nd law
  - Carnot cycles, real-life limitations

Exercises W1

- Theory questions
- Reversed Brayton Cycle
- Rankine Cycle