Class 4

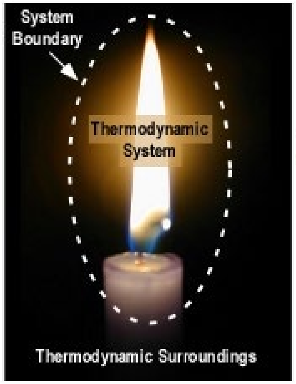
The first law of thermodynamics

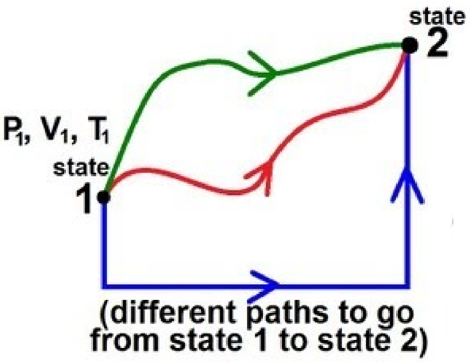
Steam power trains are still in use on touristic railways (Simpelveld)

Roadmap Engineering Thermodynamics

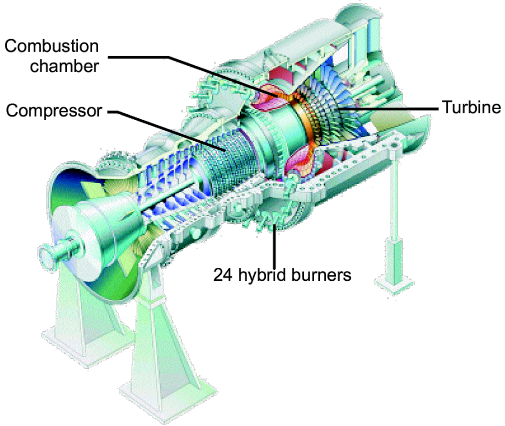
- Using thermodynamics for practical applications requires knowledge of:

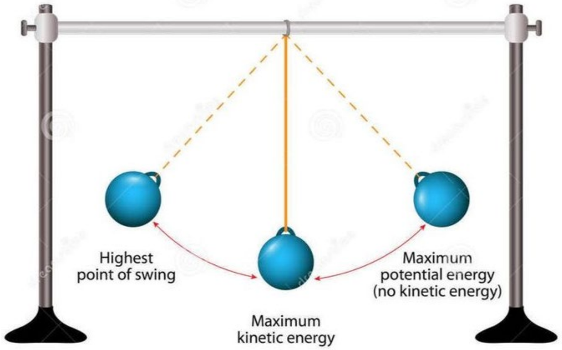
Concepts and definitions (Class 1) → Various forms of energy (Class 2)

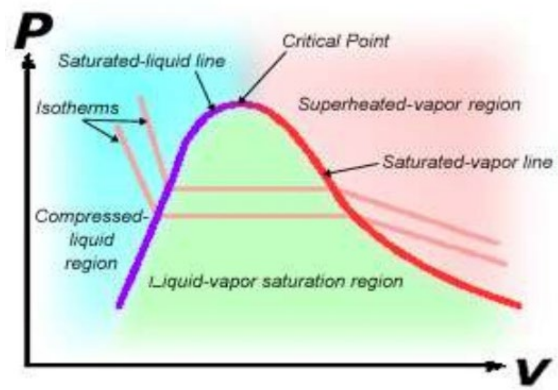




Power cycles (Class 6 – 11) ← Laws of Thermo (Class 4 and 5) ← Properties of Substances (Class 3, 9)

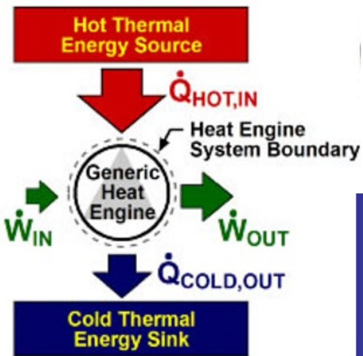




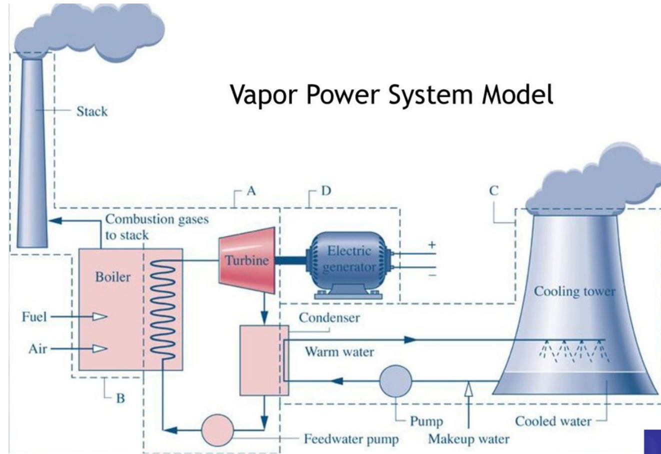


Roadmap Engineering Thermodynamics

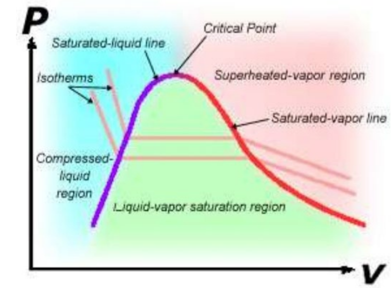
Thermodynamic cycles (Class 6)

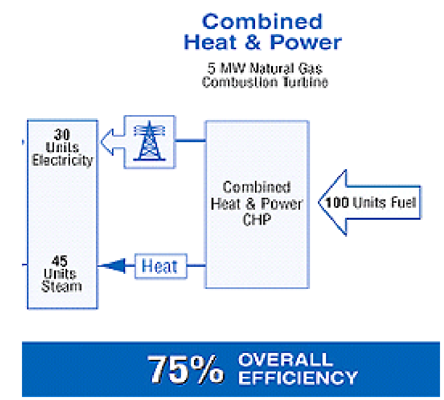


Vapor power cycles – Rankine cycle (Class 7, 8)

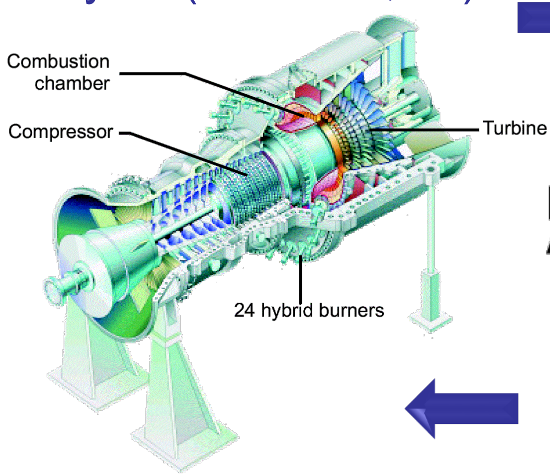


Properties of water (Class 3)

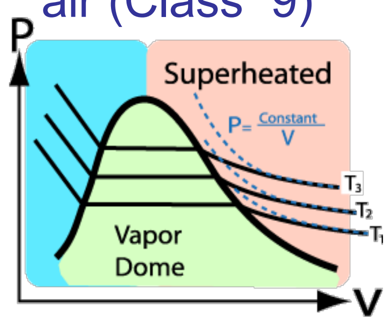




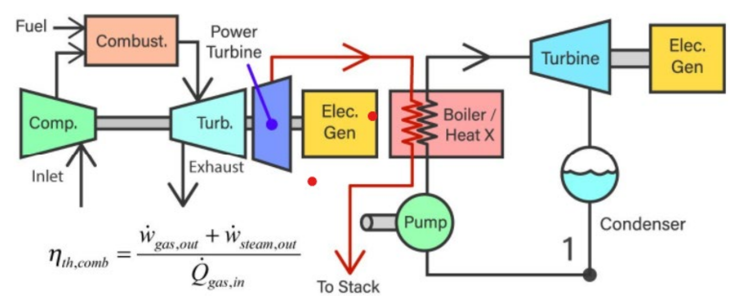
Gas power cycles – Brayton cycle (Class 10, 11)



Properties of air (Class 9)

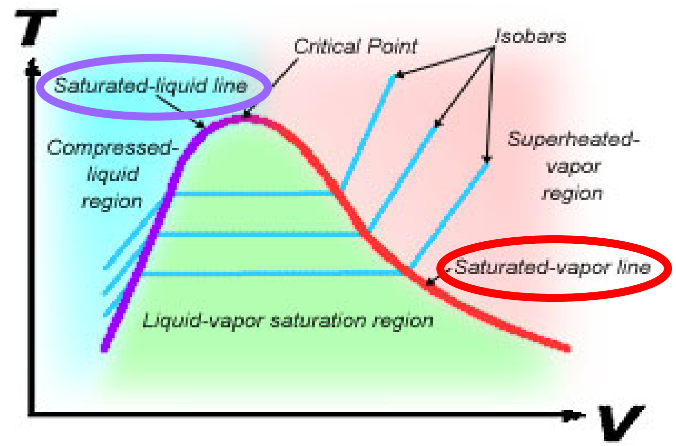


Combined cycles
Combined heat & power (Class 8, 11)



Recapitulate class 3

- Pure substances change phases
  - Solid, liquid, gas phase
  - Saturated mixtures of them
- Different regions P – v – T diagram
  - Vapor dome, critical point
  - Saturated liquid and saturated vapor line
  - Liquid-vapor saturated region
    - Saturated mixture, constant dependent P_{sat} and T_{sat} in the mixture region
    - Quality of the mixture: $x = \dfrac{v - v_l}{v_v - v_l} \rightarrow v = v_l + x(v_v - v_l)$
  - Compressed liquid region
  - Superheated vapor region
- Tables to find values of v, u, s and h
- Specific heat of a liquid



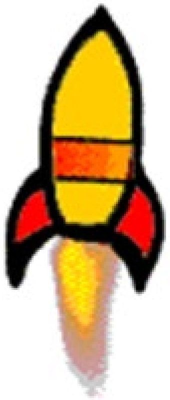
T-v diagram of water showing the vapor dome and the different regions

Content Class 4

- **The first law of thermodynamics**

- Conservation of energy, **first law of thermodynamics**
  - Closed system / open system
- Conservation of mass
- Application to steady-state steady-flow processes
  - Turbines
  - Compressors
  - Pumps, blowers
  - Nozzles and diffusers
  - Throttling valves
  - Heat exchangers
  - Mixing device

Air being heated inside the cylinder shows energy transfer in a closed system

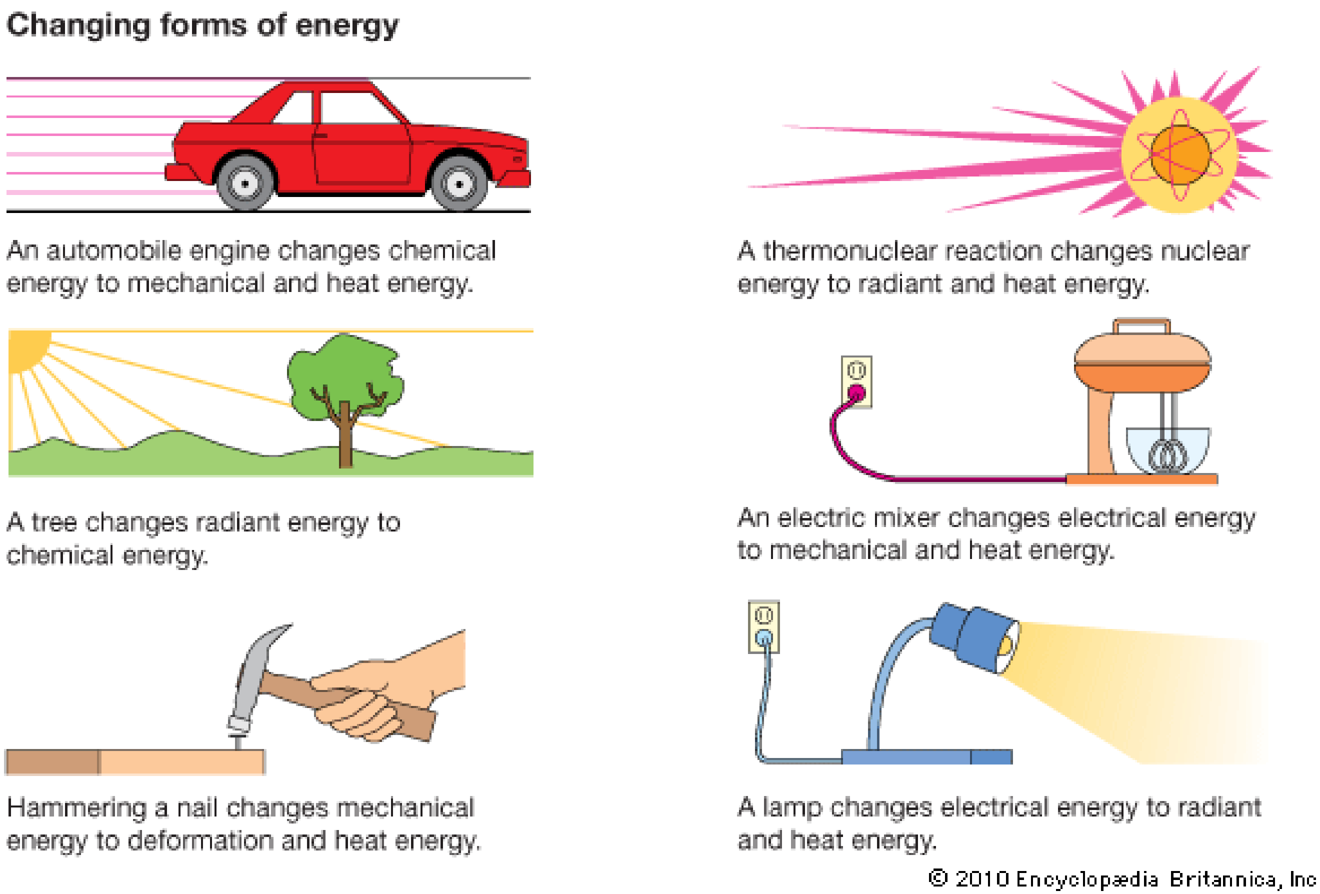


A rocket demonstrates some of the energy flows that can occur in an open system

- **Learning goal:** explain the laws of thermodynamics, apply these to thermodynamic systems and interpret the effects

The First Law of Thermodynamics

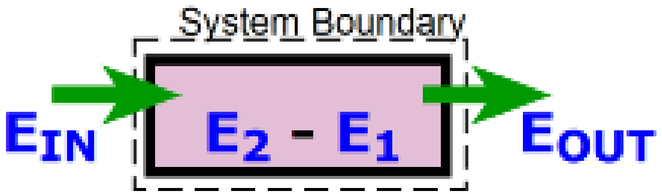
- One of the most fundamental principles of nature, **the conservation of energy principle,** is formulated in the **first law of thermodynamics**
- It states that energy can change from one form to an other during an interaction but the total amount of energy remains constant



The First Law of Thermodynamics

First law of thermodynamics = conservation of energy = energy cannot be destroyed or created but only be transformed into another form

- We already met the zeroth law of thermodynamics, and in class 5 we will also meet the second and third law of thermodynamics
- In this class we will elaborate the formula for the conservation of energy for a closed and an open system and apply it to all kinds of thermodynamical devices
- $\Delta E = E_{in} - E_{out} = E_1 - E_2$

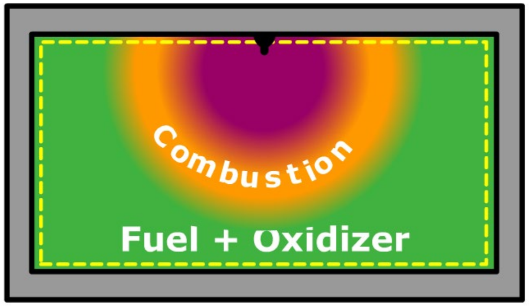


- The change in energy within the system is the energy that flows into the system minus energy that flows out of the system

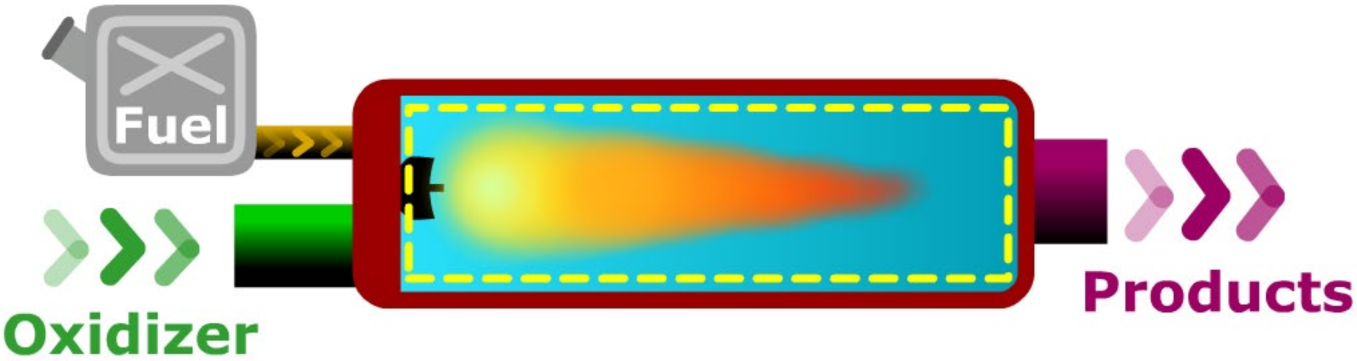
Combustion in open and closed system

- Mathematically the first law is different for open and closed systems
- What is the difference between open and closed systems?
- Mass crossing the system boundary, so also the mass plays a role in analyzing the systems

Combustion in a closed system, only heat can cross the system boundary



Combustion in an open system, also mass (fuel, oxidizer and combustion products) can cross the system boundary



Conservation of mass

- Like energy also mass is conserved
- Like energy mass cannot be destroyed or created

Log	+	Fire	→	Ashes	+	Smoke
30 kg		1 kg		28 kg		3 kg

- Even though the matter may change from one form to another, the same number of atoms exists before and after the change takes place

- Mass balance:

$$m_{in} = m_{out}$$

$$\boxed{\begin{matrix}2\text{ kg}\\ H_2\end{matrix}} + \boxed{\begin{matrix}16\text{ kg}\\ O_2\end{matrix}} \longrightarrow \boxed{\begin{matrix}18\text{ kg}\\ H_2O\end{matrix}}$$

Mass is conserved even during chemical reactions

Closed systems / Control mass

- **Closed system:** mass cannot cross the system boundary, but energy (heat and work) can cross the system boundary

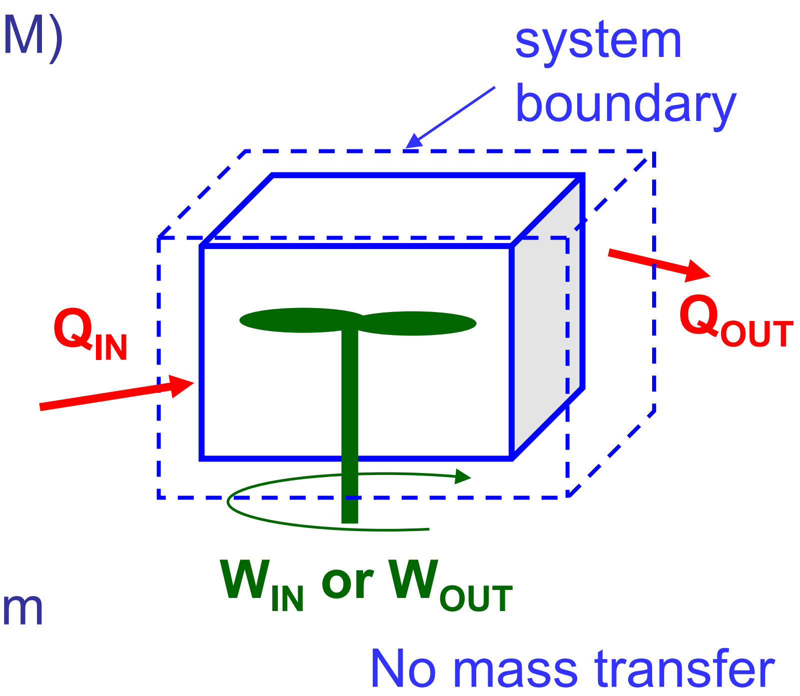
- Closed system is called **control mass** (CM)

- No change of mass for a closed system

- The mass balance
  - $m_{cm} = \text{constant} \rightarrow \frac{dm_{cm}}{dt} = \dot{\text{m}} = 0$

- During time, the mass of the closed system does not change

- Energy can change due to work and heat transfer



Closed systems / Control mass

- Energy balance: $\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{cm}}{dt} \quad [\frac{J}{s} = W]$

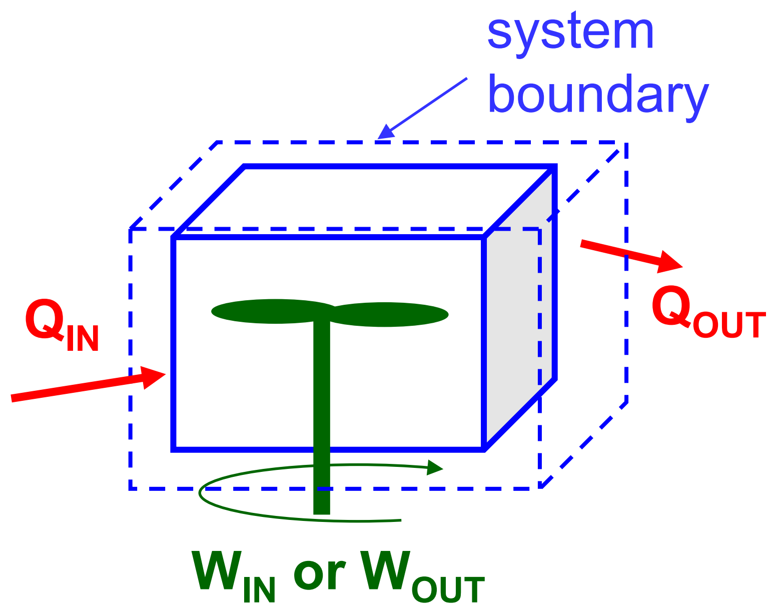
  - Energy in the control mass: $E_{cm} = U + KE + PE \approx U$ **(*)**
  - Energy transfer: $\dot{E}_{in,out} = \dot{Q}_{in,out} + \dot{W}_{in,out}$

- Alternative notations

- Total energy

  $E_{in} - E_{out} = \Delta E_{cm}$ [J]
- Specific energy

  $e_{in} - e_{out} = \Delta e_{cm}$ [J/kg]



No mass transfer

(*) In engineering applications often KE and PE are constant → E ≈ U & ΔE ≈ ΔU

Closed systems / Control mass

- The total energy change for a closed system is:

$$\Delta E_{cm} = E_{in} - E_{out} = (Q_{in} + W_{in}) - (Q_{out} + W_{out})$$

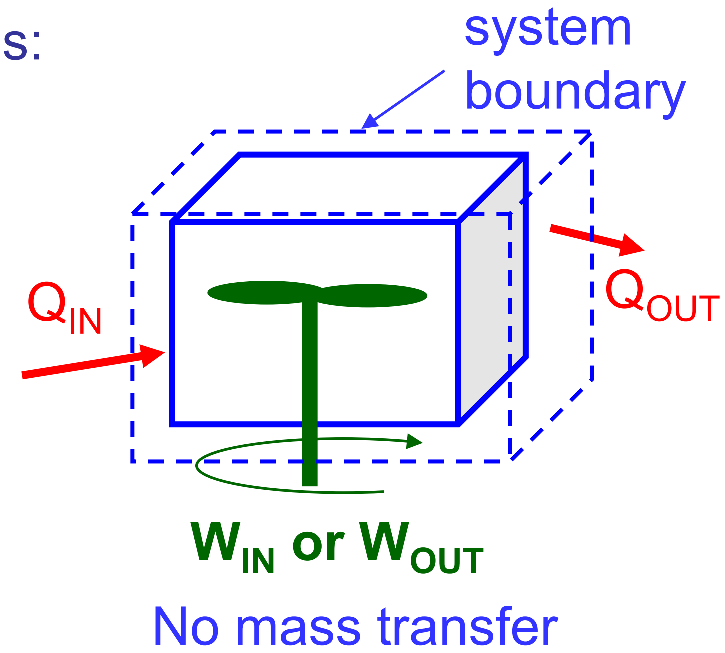
$$\Delta E_{cm} = (Q_{in} - Q_{out}) - (W_{out} - W_{in}) = Q_{net} - W_{net} \approx \Delta U_{cm}$$

- This results in the first law for closed systems:

- Total energy (J): $\Delta U_{cm} = Q_{net} - W_{net}$

- Per unit mass (J/kg): $\Delta u_{cm} = q_{net} - w_{net}$

- Differential form: $du_{cm} = \delta q_{net} - \delta w_{net}$

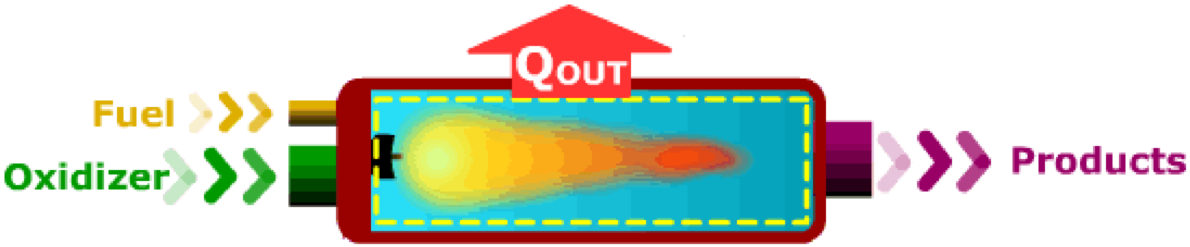


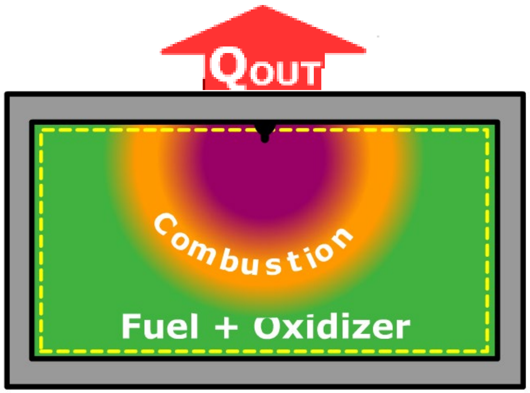
Open systems / Control volume

- **Open system:** both mass and energy (heat and work) can cross the system boundary

- Open system is called a **control volume** (CV)

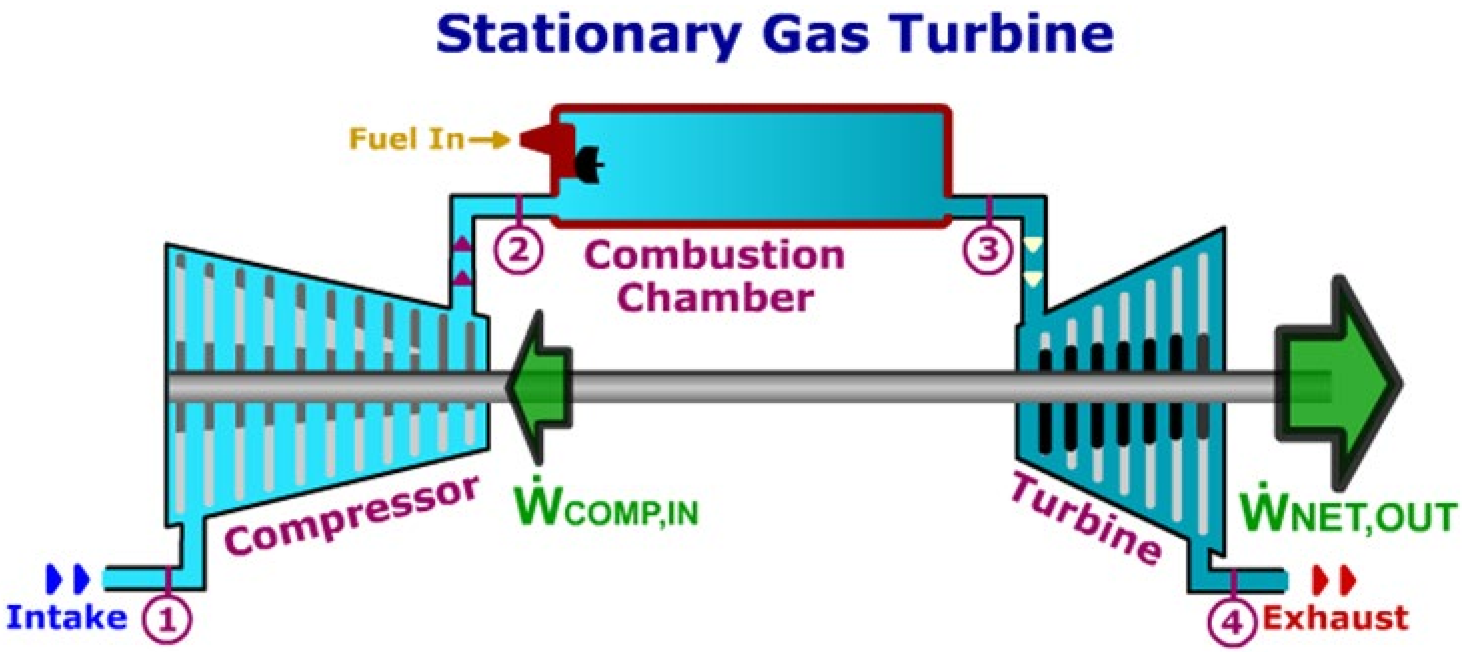
- Compare combustion in open and closed systems



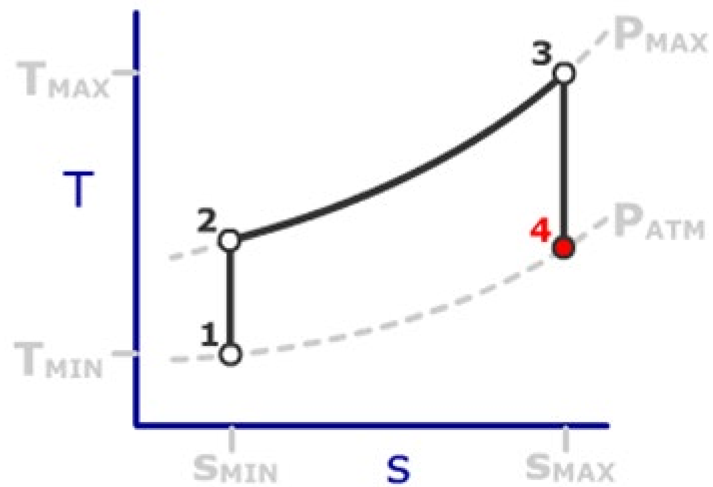


- Closed system only change of energy
- Open system change of mass and energy
  - The mass flow has to be taken into account

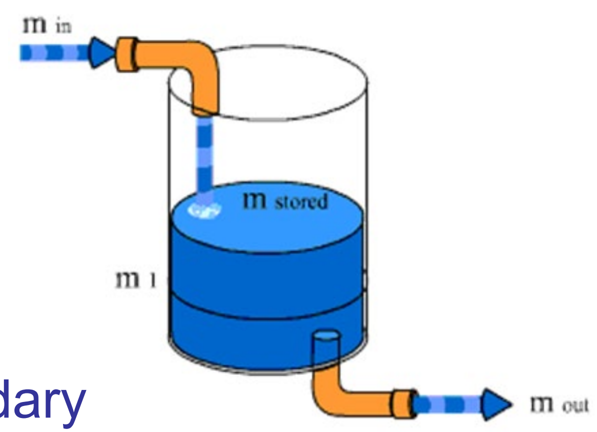
Open systems / Control volume



- A gas turbine or steam turbine cycle is analyzed as an open system
- The first law is applied to all individual components of the cycle



Open systems / Control volume



- For an open system, the mass balance is:

$$\dot{m}_{in} - \dot{m}_{out} = \frac{dm_{cv}}{dt} \quad \left[\frac{kg}{s}\right]$$

  - $\dot{m}_{in,out}$ = mass transferred across system boundary per unit time [kg/s]
  - m_{cv} = mass contained within the system boundary in the open system / control volume [kg]
  - $\frac{dm_{cv}}{dt}$ = change of mass per unit time in the open system

- On a time interval:

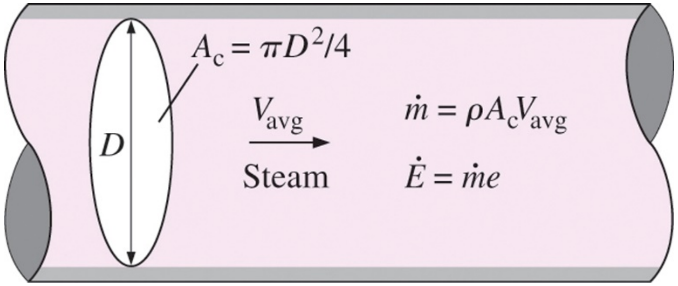
$$\Delta m = \int \frac{dm_{cv}}{dt} dt = \int_{t=t_1}^{t_2} [\dot{m}_{in}(t) - \dot{m}_{out}(t)]\, dt = m_{cv}(t_2) - m_{cv}(t_1)$$

- So the mass balance for an open system is:

$$m_{in} - m_{out} = \Delta m_{cv} \quad [kg]$$

Mass flow and volume flow

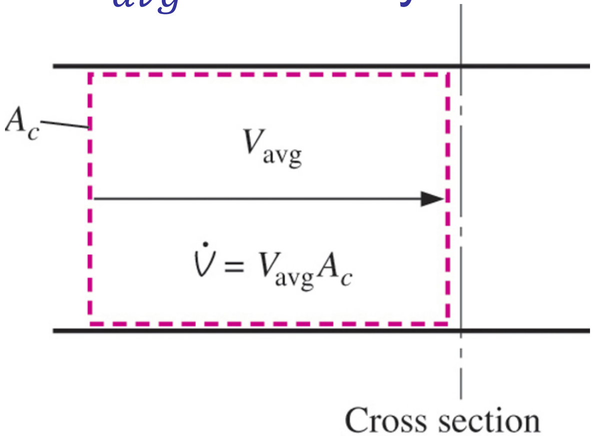
- Relation between **mass flow** and **volume flow**
- Assume a fluid flowing through a pipe



- **Mass flow:** amount of mass per unit time → $\dot{m}$ (kg/s)
- **Volume flow:** amount of volume per unit time → $\dot{V}$ (m^3/s)

$$\dot{m} = \rho\dot{V} = \rho A_c \boldsymbol{V}_{avg} = \frac{A_c \boldsymbol{V}_{avg}}{v} = \frac{\dot{V}}{v}$$

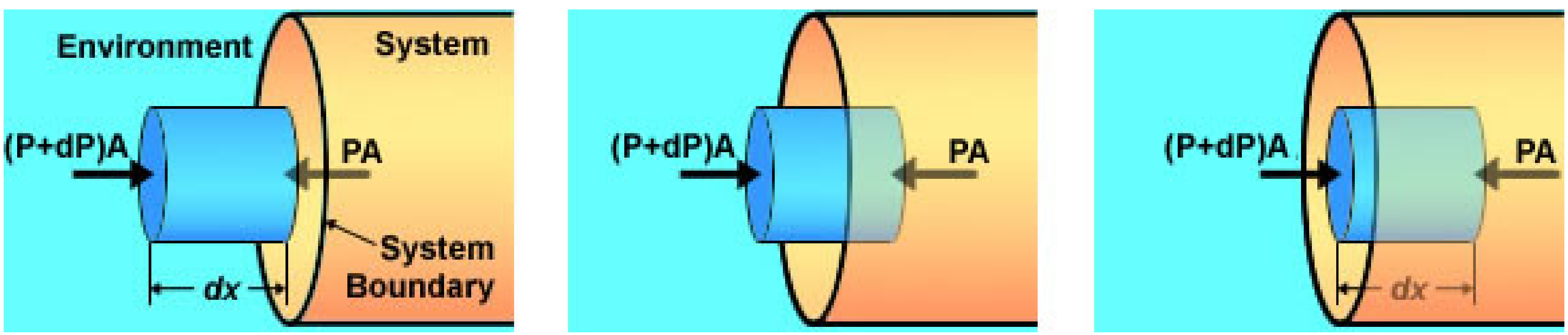
$\boldsymbol{V}_{avg}$ = velocity



- ρ = 1/ v = density [kg/m^3]
- v = specific volume [m^3/kg]
- $\dot{V}$ = $A_c \boldsymbol{V}_{avg}$ = volume flow rate [m^3/s]
- A_c = cross-sectional flow area [m^2]
- $\boldsymbol{V}_{avg}$ = velocity perpendicular to area A_c [m/s]

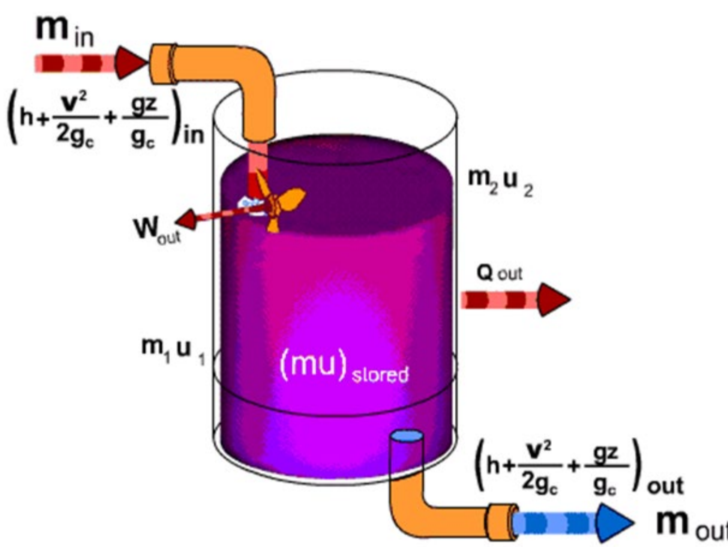
Recall: Flow work & enthalpy in open systems

- **Flow work** is the work required to push mass across the system boundary and into the open system
  - Carries energy u + ke + pe per unit mass flow
  - Does flow work Pv per unit mass flow
  - Recall enthalpy, h = u + Pv
  - Total energy entering / leaving system due to mass transfer is u + ke + pe + Pv = h + ke + pe per unit mass flow.



Open systems / Control volume

- In an open system a change in energy can occur by:
  - Mass flowing in and out, including flow work (h + ke + pe)
  - Work (w)
    - Mechanical work: present if e.g. a rotating shaft crosses the boundary
    - Boundary (PdV) work: present if $dV_{CV}/dt \neq 0$
  - Heat Transfer (q)



- The energy inside the system can change due to an increase or decrease of mass

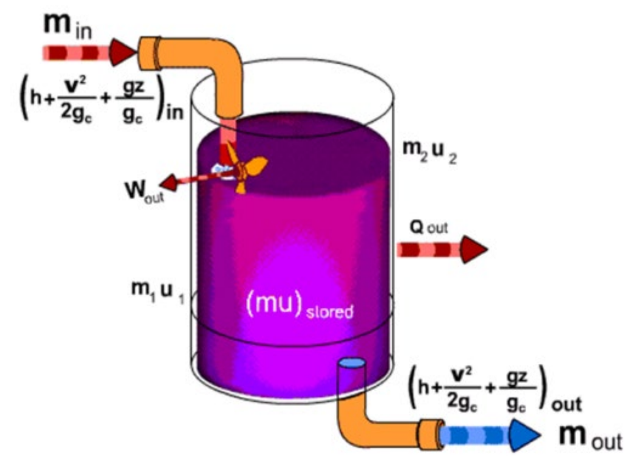
- The energy balance for an open system:

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{cv}}{dt} \quad [\frac{J}{s} = W]$$

Open systems / Control volume

- Energy balance:

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{cv}}{dt} \quad [\frac{J}{s} = W]$$



  - Energy in the control volume:

$$E_{cv} = m_{cv}(u + ke + pe)$$

  - Energy transfer:

$$\dot{E}_{in,out} = \dot{Q}_{in,out} + \dot{W}_{in,out} + \dot{m}_{in,out}(h + ke + pe)$$

- Filling in results in the first law of thermodynamics for an open system / control volume

$$\frac{dE_{cv}}{dt} = [\dot{Q}_{\boldsymbol{in}} + \dot{W}_{\boldsymbol{in}} + \dot{m}_{in,i}(h_i + ke_i + pe_i)] - [\dot{Q}_{out} + \dot{W}_{out} + \dot{m}_{out,j}(h_j + ke_j + pe_j)]$$

Open systems / Control volume

- First law (energy conservation) for an open system

$$\frac{dE_{cv}}{dt} = [\dot{Q}_{\boldsymbol{in}} + \dot{W}_{\boldsymbol{in}} + \dot{m}_{in,i}(h_i + ke_i + pe_i)] -$$

$$[\dot{Q}_{out} + \dot{W}_{out} + \dot{m}_{out,j}(h_j + ke_j + pe_j)]$$

- Apply to closed system, no mass flow in and out reduces the equation for an open system to the equation for the closed system→ $\dot{\mathrm{m}}_{in,out} = 0$

$$(Q_{in}+W_{in}) - (Q_{out} + W_{out}) = E_{in} - E_{out}$$
$$(Q_{in}-Q_{out}) - (W_{out} - W_{in}) = E_{in} - E_{out}$$
$$Q_{net} - W_{net} = E_{in} - E_{out}$$

- First law closed systems

$$\Delta E_{cm} = \Delta U_{cm} = Q_{net} - W_{net}$$

$$du = \delta\mathrm{q} - \delta\mathrm{w}$$

Steady - State Steady - Flow Processes

- Many open systems of engineering interest operate continuously for long periods of time with relatively small changes in the operating conditions
- Under these conditions, the systems are often modeled as operating at **steady - state steady - flow** (**SSSF**)
- Along with neglecting the effects of kinetic and potential energy (NKEPE), the SSSF assumption is one of the most widely used assumptions in thermodynamics

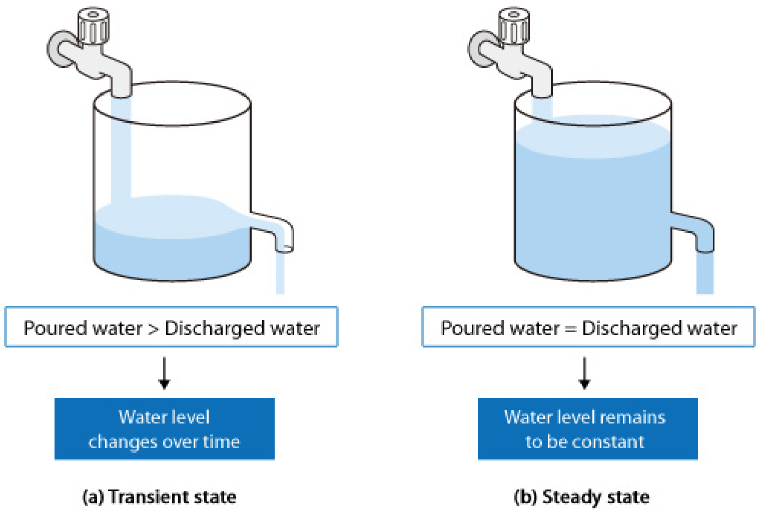
Many thermodynamic systems such as power plants operate under steady - state steady – flow (SSSF) conditions. SSSF operation is probably a good assumption when analyzing the turbofan engines powering an airplane cruising at a constant altitude and speed, but not during take-off when both the engine load and operating conditions are changing rapidly.

Steady - State Steady - Flow Processes

- **Steady - state (SS) process**

$$\frac{d(\ )_{CV}}{dt} = 0$$

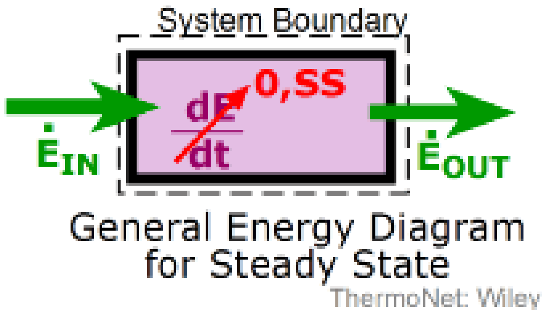
where ( )$_{CV}$ is any property of the system (e.g. m or E)



- **Steady - flow (SF) process**

$$\frac{d(\dot{\ })_{IN,OUT}}{dt} = 0$$

where $(\dot{\ })_{CV}$ is any transfer across the system boundary (e.g. $\dot{E}$, $\dot{Q}$, $\dot{W}$ or $\dot{m}$)



- All properties of the system are independent of time

Steady - State Steady - Flow Processes

- **Steady-state steady-flow (SSSF) processes:** all properties of the system are independent of time, so the right-hand side becomes zero

- The mass balance reduces to:

$$\sum_{i=1}^{N} \dot{m}_{in,i} - \sum_{j=1}^{M} \dot{m}_{out,j} = \cancel{\frac{dm_{CV}}{dt}}^{0,\ SS} \Rightarrow \sum_{i=1}^{N} \dot{m}_{in,i} = \sum_{j=1}^{M} \dot{m}_{out,j}$$

- If there is only one stream (i.e. 1-inlet and 1-outlet) it reduces to a rather simple expression:

$$\dot{m}_{in} = \dot{m}_{out} = \dot{m} \quad [kg/s]$$

Steady - State Steady - Flow Processes

- **Steady-state steady-flow (SSSF) processes:** all properties of the system are independent of time, so the right-hand side becomes zero

- The energy balance reduces to:

$$\dot{E}_{in} - \dot{E}_{out} = \cancel{\frac{dE_{CV}}{dt}}^{0,\ SS} \Rightarrow \dot{E}_{in} = \dot{E}_{out}$$

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{i=1}^{N} \dot{m}_{in,i}(h_i + ke_i + pe_i) =$$
$$\dot{Q}_{out} + \dot{W}_{out} + \sum_{j=1}^{N} \dot{m}_{out,j}(h_j + ke_j + pe_j)$$

- If there is only one stream and dividing by mass flow rate it becomes:

$$q_{in} + w_{in} + (h + ke + pe)_{in} =$$
$$q_{out} + w_{out} + (h + ke + pe)_{out}$$

Steady - State Steady - Flow Processes

- In summary, one stream steady-state steady-slow (SSSF) processes

- **Mass Balance**

$$\dot{m}_{in} = \dot{m}_{out} = \dot{m} \quad [kg/s]$$

- **Energy Balance**

$$q_{in} + w_{in} + (h + ke + pe)_{in} =$$
$$q_{out} + w_{out} + (h + ke + pe)_{out} \quad [kJ/kg]$$

- These are the most general form for SSSF processes

Next slides: the energy balance will be applied to several thermodynamic devices e.g. a turbine, compressor, pump, boiler, condenser, nozzle, heat exchanger

BREAK

https://www.cafepress.com/+thermodynamics+mugs

Turbines

- **Turbine:** is a **work output device** which converts incoming enthalpy and kinetic energy of a fluid into shaft work
- Enthalpy → Shaft work

- Used in
  - Almost all power plants
  - Some propulsion systems (e.g. turbofan and turbojet engines)

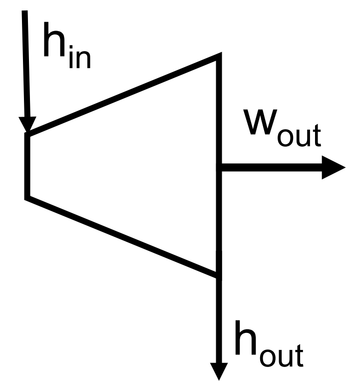
- Working fluids
  - Liquids (e.g. hydro power plants)
  - Vapors (e.g. steam power plants)
  - Gases (e.g. gas power plants)

Steam Turbine Blades from a Calpine Geothermal Plant

DKB

Turbines

- Common assumptions for **turbine**:
  - SSSF
  - Adiabatic, no heat transfer (q=0)
  - No work input (w_{in}=0)
  - Neglect kinetic and potential energies



- **Turbine energy balance** (single stream)

  $q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$

  $\rightarrow h_{in} = w_{out} + h_{out}$

- Specific work output: $w_{out} = h_{in} - h_{out} \;\; in \; [\frac{kJ}{kg}]$
- Power output: $\dot{W}_{out} = \dot{m}(h_{in} - h_{out})$ in $[\frac{\mathrm{kJ}}{s}]$

Compressors

- **Compressor:** is a **work input device** used to increase the pressure and enthalpy of gases and vapors. Often like turbine run in reverse
- Shaft work → increase pressure/enthalpy of vapor/gas

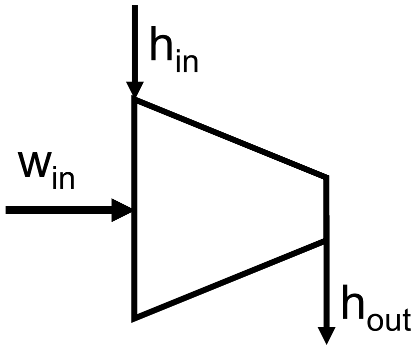
- Used in
  - Gas power plants (e.g. gas turbine engine)
  - Turbo propulsion systems (e.g. turbofan and turbojet engines)
  - Industry (e.g. supply high pressure gas)

- Working fluids
  - Gas (gas turbine)
  - Vapor (cooling system)
  - Not Liquid (pump used)

Reciprocating compressor, driven by a small gasoline engine, used to provide com-pressed air for pneumatic tools

Compressors

- Common assumptions for **compressor**:
  - SSSF
  - Adiabatic, no heat transfer ($q=0$)
  - No work output ($w_{out}=0$)
  - Neglect kinetic and potential energies



- **Compressor energy balance (single stream)**

$$q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$$

$$\rightarrow w_{in} + h_{in} = h_{out}$$

- Specific work input: $w_{in} = h_{out} - h_{in}$ in $[\frac{\text{kJ}}{\text{kg}}]$
- Power work input: $\dot{W}_{in} = \dot{m}(h_{out} - h_{in})$ in $[\frac{\text{kJ}}{\text{s}}]$

Pumps, Fans and Blowers

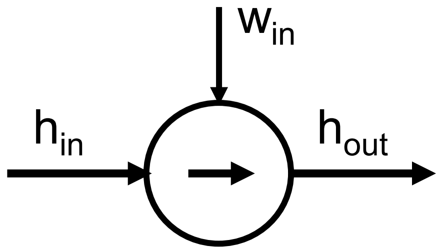
- **Pumps, fans and blowers:** Work input device, all belong to a class of devices that use mechanical work input to increase the pressure and/or velocity of a fluid
  - **Pumps:** are used for pressurizing or moving liquids
  - **Fans & Blowers:** primarily used as "air handlers" to move air through ducts and equipment

- Working fluids
  - Liquid (pump)
  - Air (fans, blowers)

Feed water pumps in a steam power plant

Pumps, Fans and Blowers

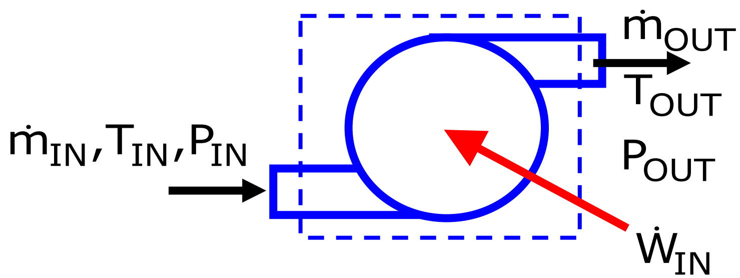
- Common assumptions for **pumps, fans, blowers:**
  - SSSF
  - No heat transfer (adiabatic, q=0)
  - No work output (w_{out}=0)
  - Neglect kinetic and potential energies



- **Pump, fan, blower energy balance**

$$q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$$

$$\rightarrow w_{in} + h_{in} = h_{out}$$

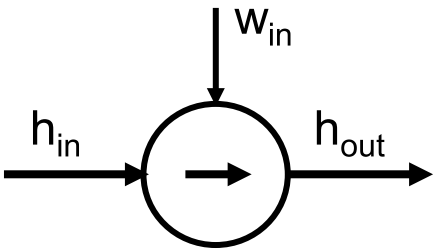


Pump Schematic

- Specific work input: $w_{in} = h_{out} - h_{in}$ in $[\frac{\text{kJ}}{\text{kg}}]$
- Power work input: $\dot{W}_{in} = \dot{m}(h_{out} - h_{in})$ in $[\frac{\text{kJ}}{\text{s}}]]$

Pumps, Fans and Blowers

- **For a pump in general:** $w_{in} = h_{out} - h_{in}$ in [kJ/kg]



- For a pump assuming incompressible liquid (ICL)

  $\rightarrow dv = 0$ and $T_{in} = T_{out} \rightarrow u_{in} = u_{out}$

- Recall: $dh = du + d(Pv) = du + Pdv + vdP = du + vdP$

  $\rightarrow \Delta h = h_{out} - h_{in} = u_{out} - u_{in} + v_l(P_{out} - P_{in})$

- as $u = u(T) \rightarrow \Delta h = h_{out} - h_{in} = v_l(P_{out} - P_{in})$

  $\rightarrow w_{in} = v_l(P_{out} - P_{in})$ in [kJ/kg]

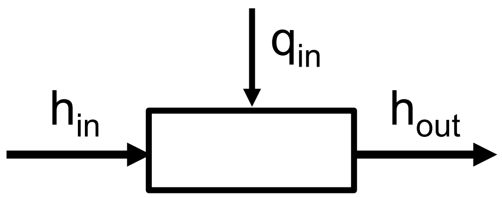
Steam Boilers, Combustion Chambers

- **Steam boilers and combustion chambers:** heat input device belong to a class of devices in which heat is add to a working fluid resulting in a temperature rise and/or vaporization
  - **Boiler:** used to heat water, vaporize and superheat steam
  - **Combustion chamber:** Heats gas by combustion of fuel
- Heat is converted into enthalpy
- Used in
  - Almost all power plants
  - Some propulsion systems (e.g. turbofan turbojet engines)
- Working fluid
  - Liquid (e.g. steam power plants)
  - Gases (e.g. gas turbines)

Steam boiler *Stoomgemaal De Tuut* in Apeltern

Boilers, Combustion Chambers

- Common assumptions for **boilers, combustion chambers:**
  - SSSF
  - No heat output (q_{out}=0)
  - No work (w=0)
  - Neglect kinetic and potential energies



- **Boilers, combustion chamber energy balance**

$$q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$$

$$\rightarrow q_{in} + h_{in} = h_{out}$$

- Specific heat input: $q_{in} = h_{out} - h_{in}$ in [kJ/kg]
- Power input: $\dot{Q}_{in} = \dot{m}\,(h_{out} - h_{in})$ in [kJ/s = kW]

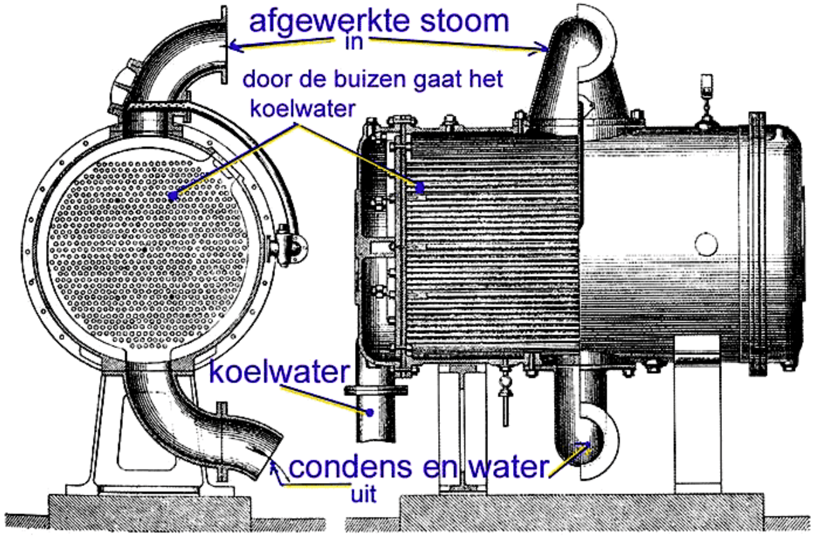
Condensers

- **Condensers:** Heat output device used to condense vapor (steam) to liquid (water) after passing through a steam turbine or to condense a cooling fluid in a refrigeration system to reject heat

- Enthalpy is converted into heat

- Used in
  - Almost all power plants
  - Almost all refrigeration systems

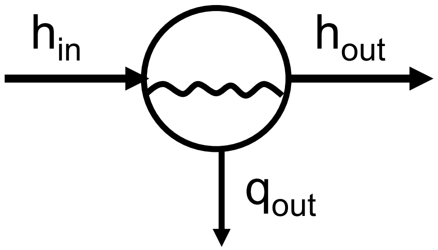
- Working fluid
  - Liquid (e.g. steam power plants, refrigeration systems, airco’s)



Hoe werkt een stoomturbine (www.stoomturbine.nl)

Condensers

- Common assumptions for **condensers:**
  - SSSF
  - No heat input (q_{in}=0)
  - No work (w=0)
  - Neglect kinetic and potential energies



- **Condenser energy balance**

$$q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$$

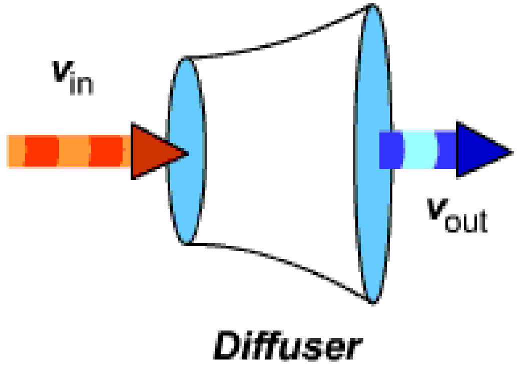
$$\rightarrow h_{in} = q_{out} + h_{out}$$

- Specific heat output: $q_{out} = h_{in} - h_{out}$ in [kJ/kg]
- Power output: $\dot{Q}_{out} = \dot{m}\,(h_{in} - h_{out})$ in [kJ/s = kW]

Nozzles and Diffusers

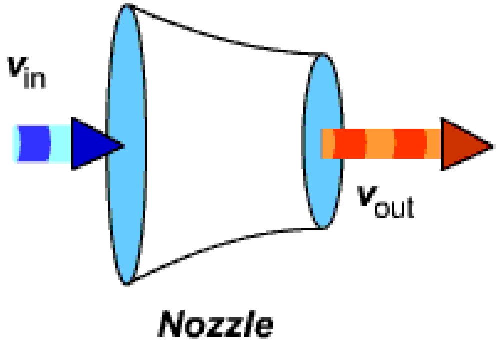
- **Nozzles** and **diffusers** are ducts of varying area which are intended to increase or decrease the velocity of the flow

A **diffuser** converts high speed, low pres-sure flow to low speed, high pressure flow



Engine intake is configured as diffuser to slow incoming air and provide uniform flow into compressor

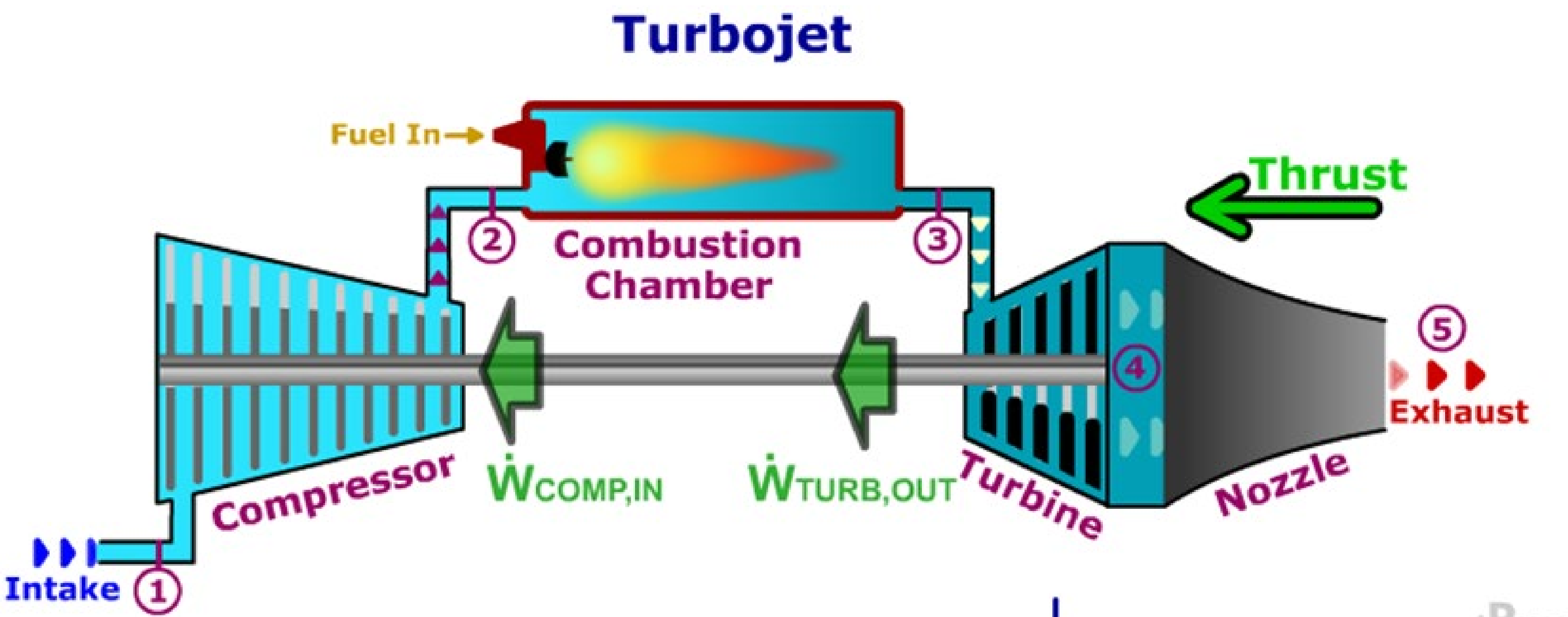
A **nozzle** converts high pressure, low speed flow to low pressure, high speed flow



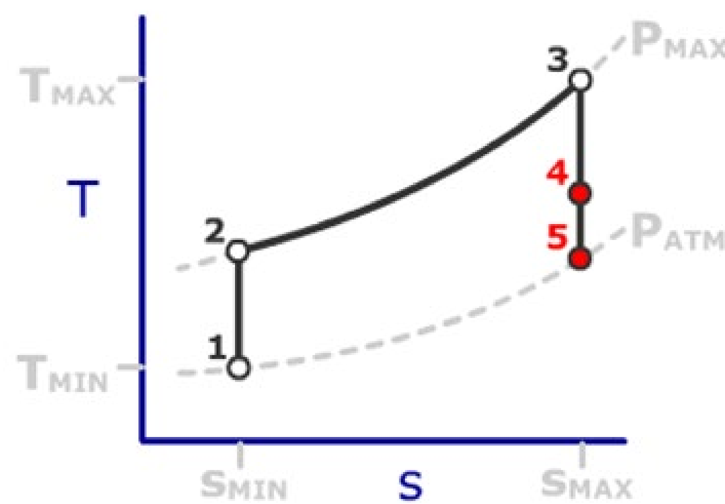
Nozzles accelerate hot gases exiting the engine to provide propulsive thrust

- On next page, see a nozzle in a turbojet engine

Nozzles and Diffusers

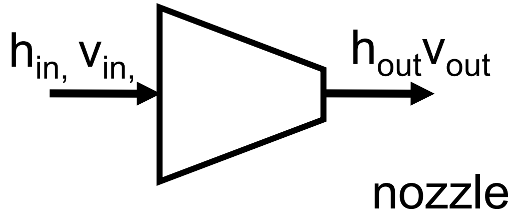


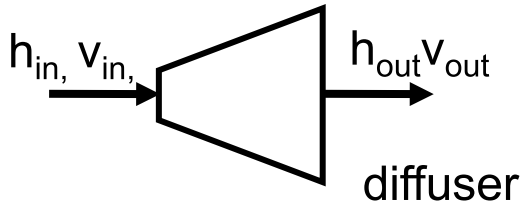
- Nozzle in a turbojet engine to accelerate the velocity of the exhaust gasses
- A diffuser is sometimes placed t the inlet to decrease the velocity of the inlet flow



Nozzles and Diffusers

- Common assumptions for **nozzles and diffusers:**
  - SSSF
  - No work or heat transfer (w=0 and q=0)
  - Neglect changes in pe





- **Energy balance nozzle, diffuser**

$$q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$$

$$\rightarrow \quad h_{in} + ke_{in} = h_{out} + ke_{out} \quad \text{with} \quad ke = \frac{1}{2}v^2$$

$$\rightarrow \left(h + \frac{v^2}{2}\right)_{in} = \left(h + \frac{v^2}{2}\right)_{out}$$

Throttling

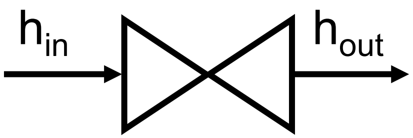
- **Throttling** is the process of reducing the pressure in a fluid stream by insertion of a restriction into the flow path
- Throttling may be used as a means of controlling the flow rate (valves and flow regulators), maintaining a constant downstream pressure (pressure regulator), or measuring the flow rate (flow metering orifices)
- Reduces pressure and for a lot of substances temperature is reduced, this principle is used in refrigeration

Throttling valve

This piping installation, used to control the coolant flow to a large diesel engine in an oilfield, illustrates several types of throttling devices, including valves, flow metering orifices and flow regulators.

Throttling

- Common assumptions **throttling**:
  - SSSF
  - No work or heat transfer (w=0 and q=0)
  - Neglect changes in pe and ke



- **Energy balance throttling**

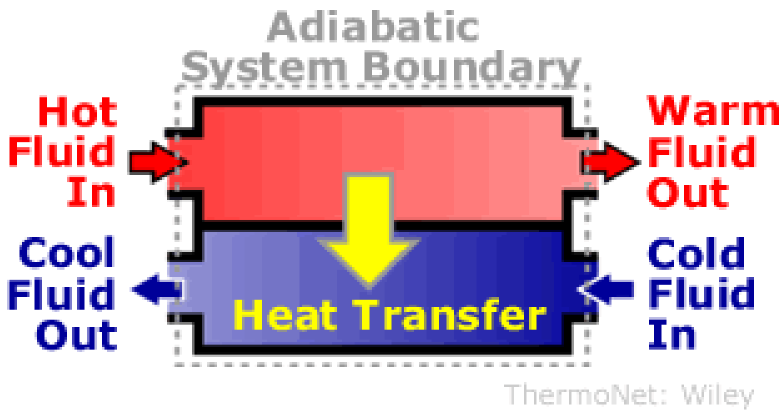
$$q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$$

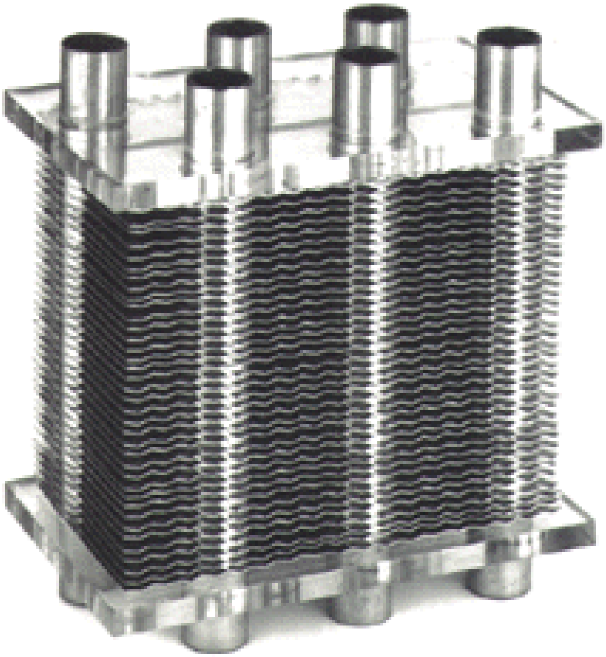
$$\rightarrow h_{in} = h_{out}$$

- Isenthalpic process (h = constant $\rightarrow$ $dh = 0$)

Heat Exchangers

- A heat exchanger allows transfer of heat from one fluid to another without mixing
- Fluids can be gas or liquid
- Example gas: Car radiator
  Air conditioner

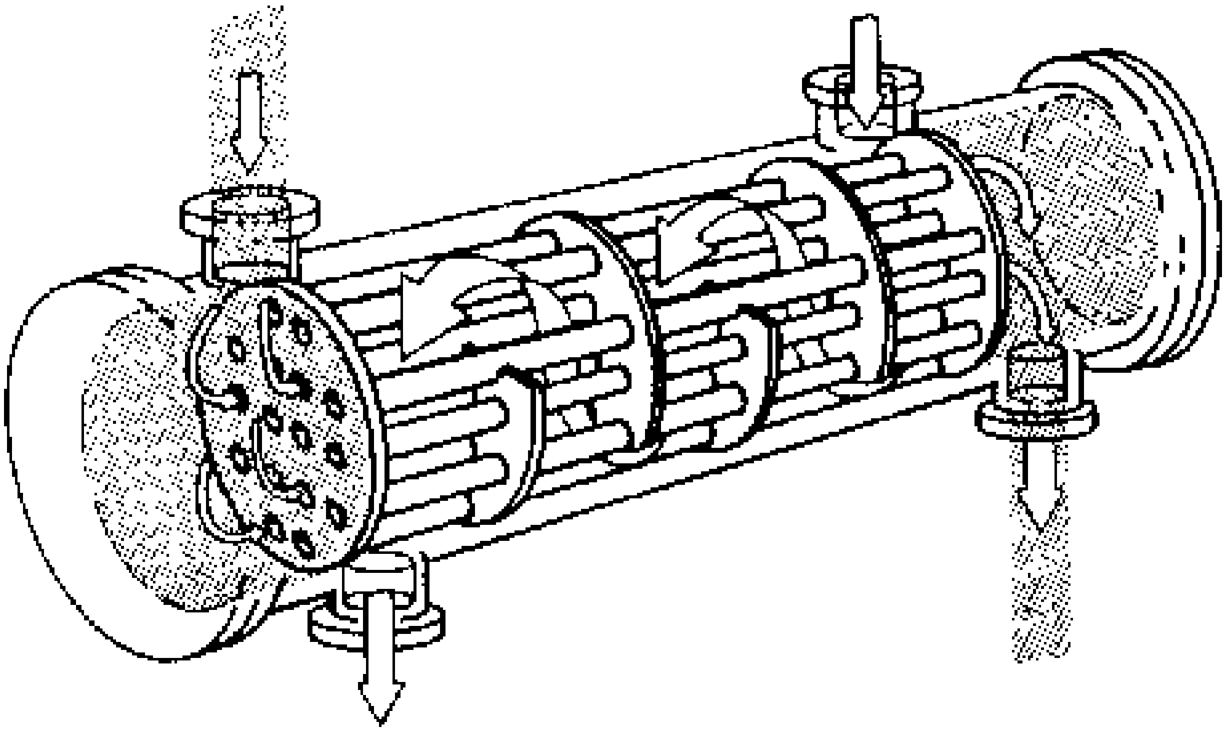




This is a section from an air-cooled cross-flow heat exchanger, such as that used in automobile radiators and home air-conditioners. Water or refrigerant flowing through the tubes is cooled by air flowing across them. The corrugated metal plates act as fins to conduct heat away from the tubes and transfer it into the air, enhancing the cooling effectiveness of the exchanger.

Heat Exchangers

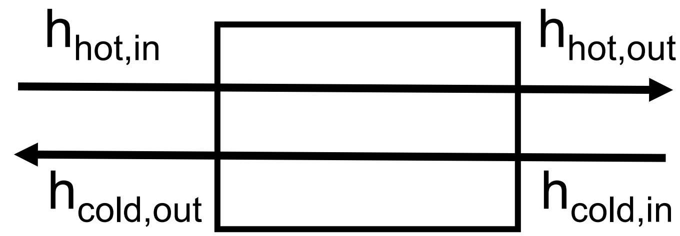
- A heat exchanger allows transfer of heat from one fluid to another without mixing
- Fluids can be gas or liquid
- Example water: Condenser in a power plant



The "shell-and-tube" exchanger shown here consists of a bundle of tubes, typically made of a good thermal conductor such as copper, enclosed in a steel vessel. The tube-side fluid enters through a manifold in the end of the exchanger, flows through the tubes, and exits from a manifold at the other end. The shell-side fluid flows back and forth over the tubes; if it is hotter than the tube-side fluid, heat will be transferred through the tube walls and into the tube-side fluid.

Heat Exchangers

- Common assumptions **heat exchanger**
  - SSSF
  - **Externally** adiabatic (q=0)
  - No work (w=0)
  - Neglect kinetic and potential energies



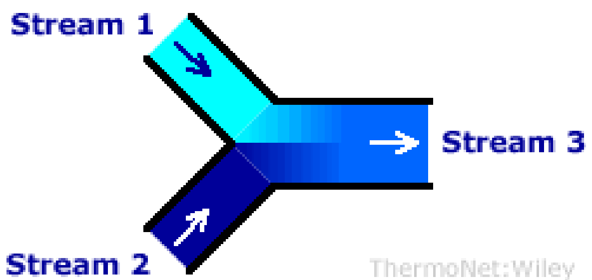
- **Heat exchanger energy balance (more streams take mass flow into account !!)**

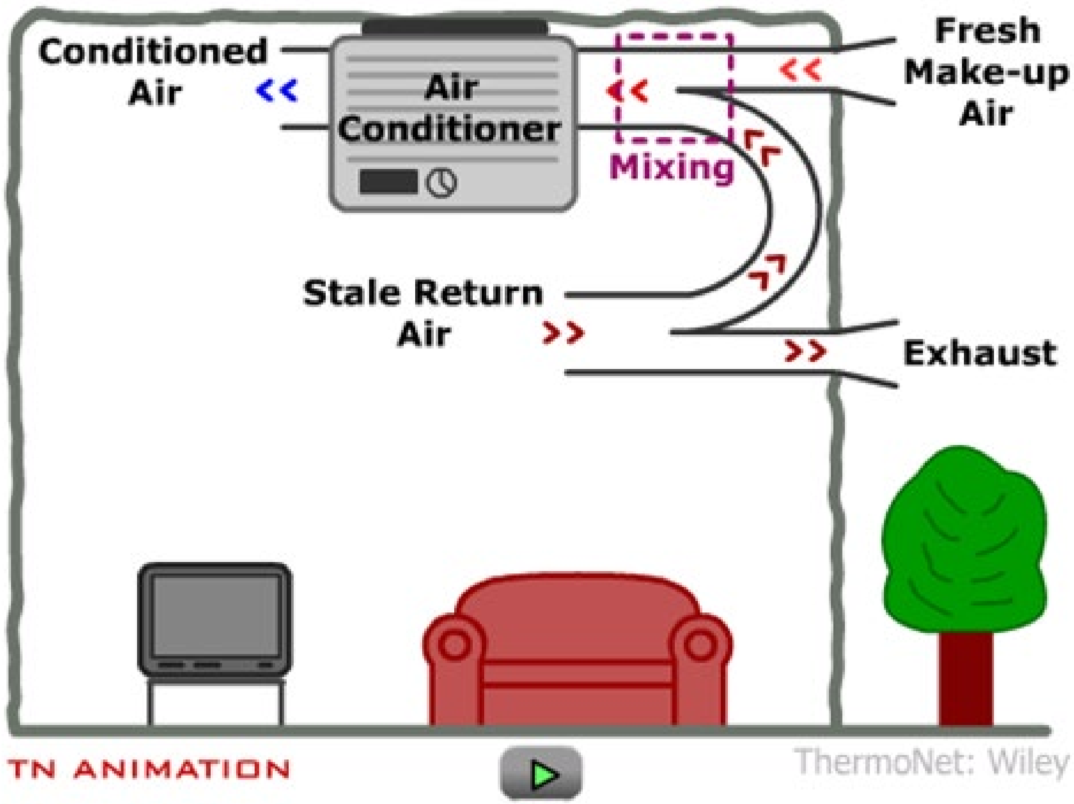
$$\left[\cancel{\dot{Q}_{in} + \dot{W}_{in}} + \sum[\dot{m}(h + \cancel{ke + pe})]_{in}\right] - \left[\cancel{\dot{Q}_{out} + \dot{W}_{out}} + \sum[\dot{m}(h + \cancel{ke + pe})]_{out}\right] = 0$$

- Energy balance: $\rightarrow\ \dot{m}_{cold}\left(h_{out,cold} - h_{in,cold}\right) = \dot{m}_{hot}\left(h_{in,hot} - h_{out,hot}\right)$

Mixing Devices

- Two or more inlet streams are combined into a single outlet stream using a **mixing device**
- A mixing device may be as simple as a sink faucet, where hot and cold inlet water streams are combined into a single warm outlet stream

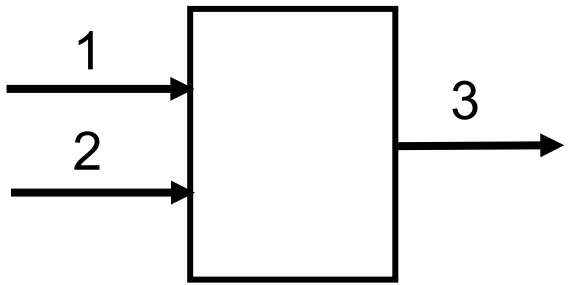




- Mixing devices are very common in industrial processes and power plants

Mixing Devices

- Common assumptions **mixing device**
  - SSSF
  - Adiabatic (q=0) and no work (w=0)
  - Neglect kinetic and potential energies



- **Energy balance** (Streams 1 & 2 mix to form 3)

$$\left[\cancel{\dot{Q}_{in} + \dot{W}_{in}} + \sum[\dot{m}(h + \cancel{ke + pe})]_{in}\right] - \left[\cancel{\dot{Q}_{out} + \dot{W}_{out}} + \sum[\dot{m}(h + \cancel{ke + pe})]_{out}\right] = 0$$

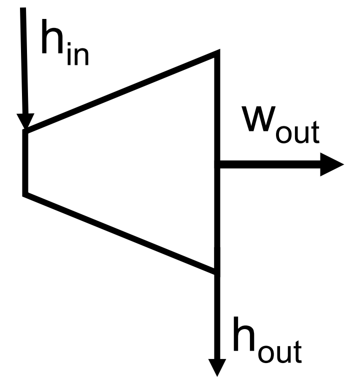
- Energy balance:→ $\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$

- In a mixing device also **conservation of mass** → $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$

Example open system: Steam turbine

- Steam expands from 50 bar, 400°C to 4 bar, 150°C in a steam turbine
- What is the specific work delivered?
- What is the power at a mass flow rate of 36 ton steam/hour?

- **Solution:** start with the general energy balance for an open system



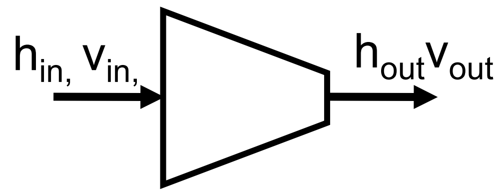
$$q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$$

- For a turbine pe, ke are neglected, there is no heat transfer (q) and the energy balance reduces to $\rightarrow h_{in} - h_{out} = w_{out}$
- Table A6 gives the h values: $h_{in} = 3196$ kJ/kg, $h_{out} = 2753$ kJ/kg
- Specific work delivered: $w_{out} = h_{in} - h_{out} = 3196 - 2753 = 443$ kJ/kg
- Convert mass flow to kg/s: $\dot{m} = 36$ ton/h $\rightarrow$ 10 kg/s
- The power delivered: $\dot{W} = \dot{m} \cdot w_{out} = 10 \cdot 443 = 4.43$ MW

Example open system: Nozzle

- Steam expands from 50 bar, 400°C to 4 bar, 150°C in a nozzle.
- What is the exit velocity (assume the exit velocity to be much larger than the inlet velocity)?

- **Solution:** start with the general energy balance for an open system



$$q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$$

- For the nozzle pe is neglected, there is no heat transfer (q) and no work (w) involved and $v_{in} << v_{out}$ the energy balance reduces to

  $\rightarrow h_{in} + ke_{in} = h_{out} + ke_{out}$ with $ke = 1/2v^2$ $(KE = 1/2mv^2)$

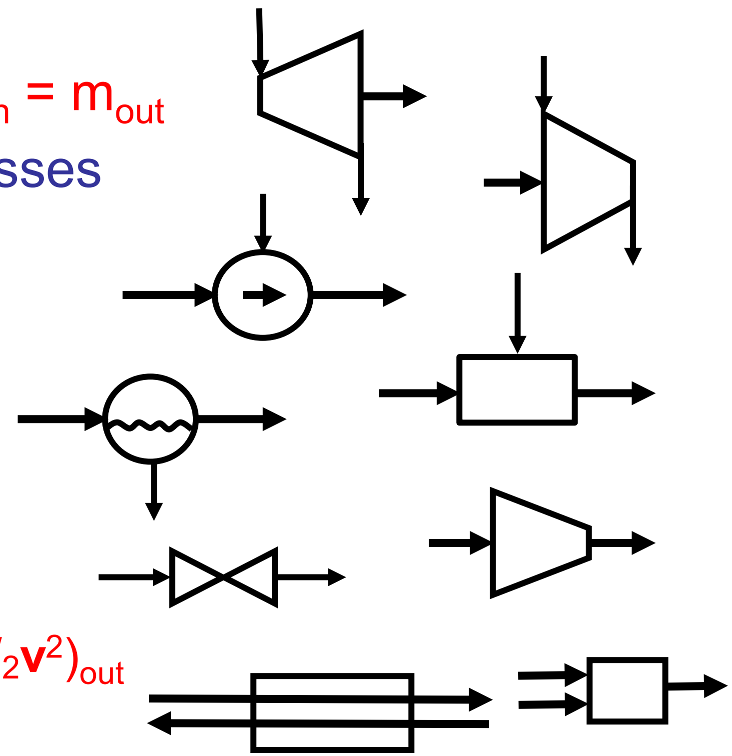
  $\rightarrow 2h_{in} + v^2_{in} = 2h_{out} + v^2_{out} \rightarrow v_{out} = [2(h_{in} - h_{out})]^{0.5}$

- Table A6 gives the h values: h_{in}= 3196 kJ/kg, h_{out} = 2753 kJ/kg
- The exit velocity is: $v_{out} = [2(3196 - 2753)\cdot 10^3]^{0.5} = 941$ m/s

Recapitulate class 4

- **Conservation of energy, first law of thermodynamics**
  - Closed system $du = \delta q - \delta w \rightarrow \Delta u = q_{net} - w_{net} \rightarrow \Delta U = Q_{net} - W_{net}$
  - Open system $q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$

- **Conservation of mass in open systems** $m_{in} = m_{out}$
- Application to steady-state steady-flow processes
  - Turbines $w_{out} = h_{in} - h_{out}$
  - Compressors $w_{in} = h_{out} - h_{in}$
  - Pumps $w_{in} = v(P_{out} - P_{in})$
  - Blowers $w_{in} = h_{out} - h_{in}$
  - Boilers $q_{in} = h_{out} - h_{in}$
  - Condensers $q_{out} = h_{in} - h_{out}$
  - Nozzles and diffusers $(h + {}^{1}/_{2}\mathbf{v}^2)_{in} = (h + {}^{1}/_{2}\mathbf{v}^2)_{out}$
  - Throttling valves $h_{in} = h_{out}$
  - Heat exchangers $\dot{m}_{cold}\left(h_{out,cold} - h_{in,cold}\right) = \dot{m}_{hot}\left(h_{in,hot} - h_{out,hot}\right)$
  - Mixing device $\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$

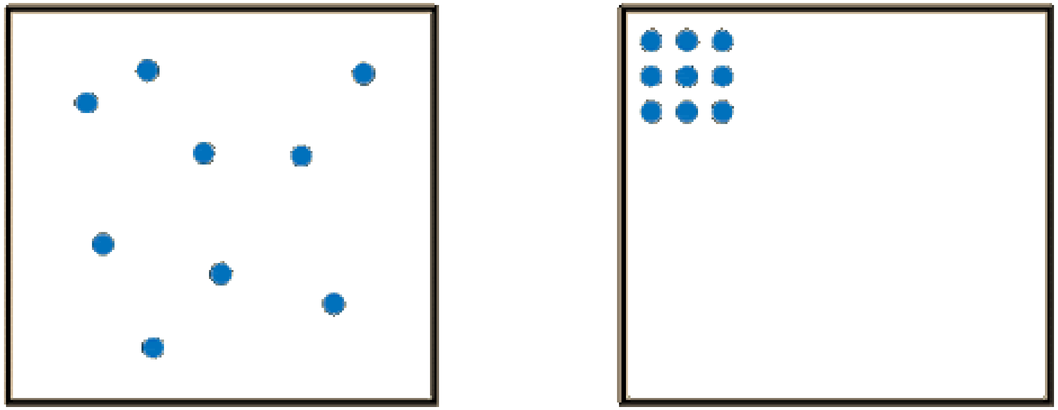


Schematic devices

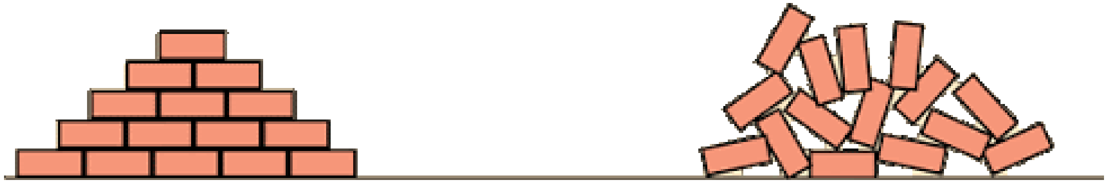
Next Class 5: Second law of thermodynamics

- Direction of processes
- Reversible and irreversible processes
- Entropy
- Second law of thermodynamics
- Second law applied to processes
- Isentropic efficiencies

If the particles represent gas molecules at normal temperatures inside a closed container, which of the illustrated configurations came first?



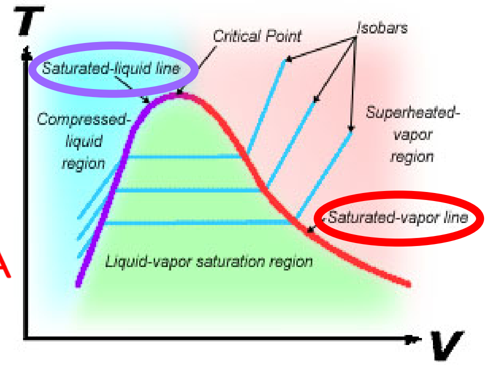
If you tossed bricks off a truck, which kind of pile of bricks would you more likely produce?



- Based on observations during your live you know what the answers are, but how can this be prected and why does the other case not occur? The first law of thermodynamics, conservation of energy is still obeyed

Keep in mind: Important formulas

- Specific volume $v=V/m$ [m^3/kg] and density $\rho=1/v=m/V$ [kg/m^3]
- Volume work $\delta w = Pdv$ or $\delta W = PdV$
- Enthalpy $h = u + Pv$, where u is internal energy, P is pressure, v is volume
- Efficiency $\eta_{thermal} = \frac{Net\ electrical\ power\ output}{Rate\ of\ fuel\ energy\ input} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$
- Different phases in phase diagrams



- Mixture fraction $x = \frac{v - v_l}{v_v - v_l} \rightarrow v = v_l + x(v_v - v_l)$
- Conservation of mass $m_{in} = m_{out}$, mass flow rate $\dot{m} = \rho v A$
- Conservation of energy, first law of thermodynamics
  - Closed system $du = \delta q_{net} - \delta w_{net} \rightarrow \Delta u = q_{net} - w_{net}$
  - Open system $q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$