3. PROCESSES

- Non-flow Process: In a closed system (such as a piston-cylinder device)

  W and Q are transferred, but not mass

- Flow Process: Open system (such as a turbine)

  There are W, Q, and mass flow

  - Steady state
  - Unsteady state

3.1 Steady-State Steady-Flow Processes

- Properties of the flowing fluid are constant with respect to time
- Fluid flow rate is constant with respect to time
- Heat and work flow rates are constant with respect to time
- The control volume does not move relative to the coordinate frame of reference.

  i.e., there is no work due to acceleration of the control volume.

These are applicable to long-term steady operation of devices such as turbines compressors, nozzles, boilers, condensers, etc.

We need to write the first law of thermodynamics as a rate equation, although "time" is not quite a relevant parameter in thermodynamics. We will assume that "rate" is constant, i.e, the mass, heat, and work flow rates are constant.

First law as a rate equation:

$$\frac{\delta Q}{dt} = \frac{dU}{dt} + \frac{\delta W}{dt} + \frac{d(KE)}{dt} + \frac{d(PE)}{dt} \quad \text{in Watts}$$

Define:

$$\frac{\delta Q}{dt} = \dot{Q} \quad \text{and} \quad \frac{\delta W}{dt} = \dot{W} \quad \text{all constants}$$

$$\frac{dU}{dt} + \frac{d(KE)}{dt} + \frac{d(PE)}{dt} = \frac{dE}{dt}$$

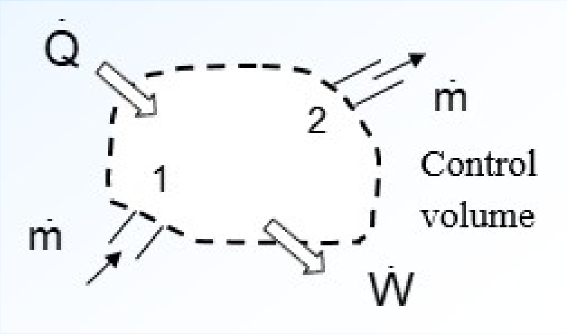
$$\dot{Q} = \dot{W} + \underbrace{\frac{dE}{dt}}$$

Change in total energy wrt time

$$\frac{dE}{dt} = 0 \quad \Rightarrow \quad \dot{Q} = \dot{W}$$

This is true there is no change in the system properties.

However, this is not the equation for a flow system. There is mass flowing in and out of the control volume. Energy change occurs due to this mass flow.



Define: $\frac{dm}{dt} = \dot{m}$ constant mass flow rate in and out of the control volume

Energy flowing into the sytem at boundary (1):

$\dot{m}\, u_1$ Internal energy of the fluid moving in per unit time

$\dot{m}\, g\, z_1$ Potential energy of the fluid moving in per unit time

$\dot{m}\, \frac{c_1^2}{2}$ Kinetic energy of the fluid moving in per unit time

$\dot{m}\, v_1\, P_1$ Flow work

Flow work $\dot{m}\, v_1\, P_1$ $\quad \left(\frac{kg}{s}\right)\left(\frac{m^3}{kg}\right)\left(\frac{N}{m^2}\right) = \frac{(N)\ (m)}{s} = \frac{J}{s} = W$

Energy flowing out of the sytem at boundary (2):

- $\dot{m}\, u_2$ Internal energy of the fluid moving out per unit time
- $\dot{m}\, g\, z_2$ Potential energy of the fluid moving out per unit time
- $\dot{m}\, \frac{c_2^2}{2}$ Kinetic energy of the fluid moving out per unit time
- $\dot{m}\, v_2\, P_2$ Flow work

$$\dot{Q} + \dot{m}\left(u_1 + g\, z_1 + \frac{c_1^2}{2} + v_1\, P_1\right) = \dot{m}\left(u_2 + g\, z_2 + \frac{c_2^2}{2} + v_2\, P_2\right) + \dot{W}$$

The combination, u + v P, (internal energy + flow work), occurs frequently.

Define: $u + P\,v = h$ specific enthalpy (per unit mass)

$$\dot{Q} + \dot{m}\left(h_1 + g\,z_1 + \frac{c_1^2}{2}\right) = \dot{m}\left(h_2 + g\,z_2 + \frac{c_2^2}{2}\right) + \dot{W}$$

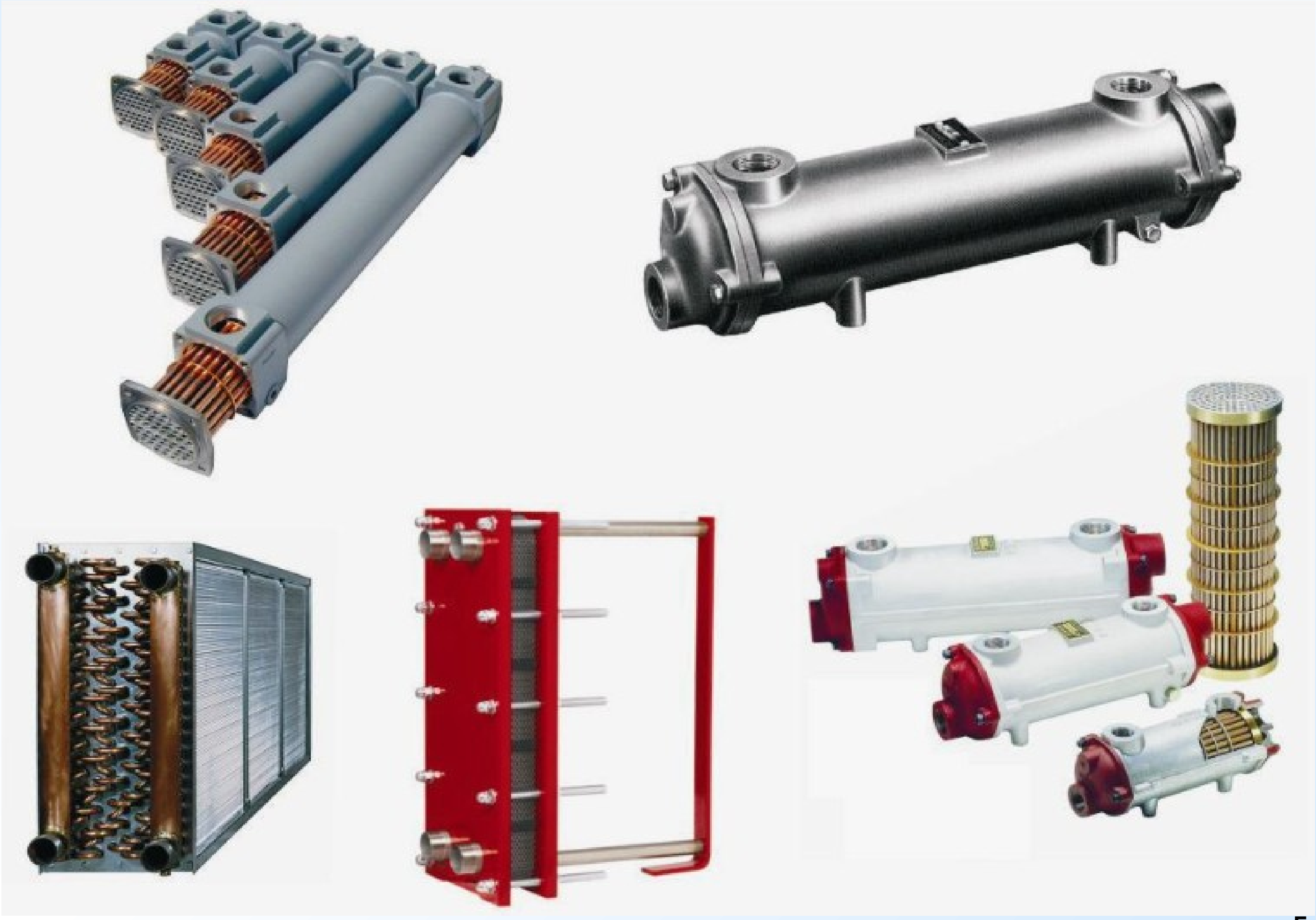
First law equation for an open system.

$$\dot{Q} = \dot{m}\left[\left(h_2 - h_1\right) + \underbrace{g\left(z_2 - z_1\right)}_{\text{often neglected}} + \underbrace{\frac{c_2^2 - c_1^2}{2}}_{\text{sometimes neglected}}\right] + \dot{W}$$

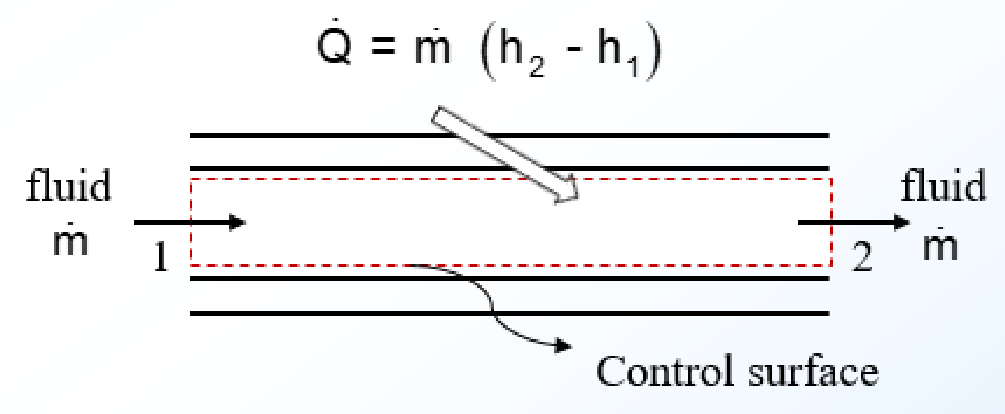
Devices: Heat Exchangers, Boilers, Condensers, Nozzles, Turbines

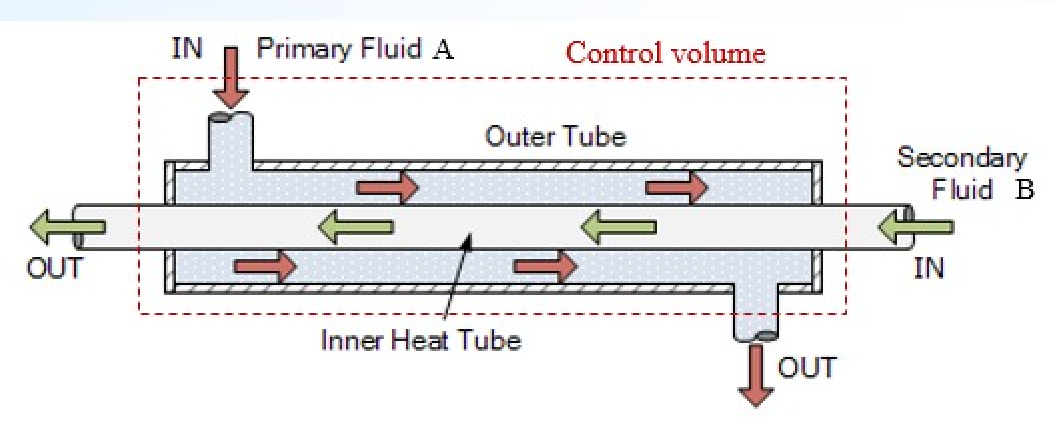
Compressors, Throttling Valves

Heat Exchanger: It is a system that transfers heat (thermal energy) from one medium (fluid) to another usually without contact.



Typical schematic diagrams of heat exchangers:



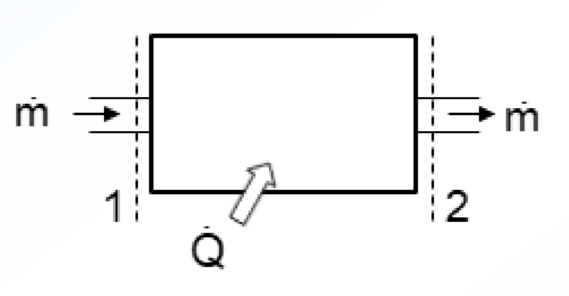


$$\dot{Q} = 0$$

$$\dot{W} = 0$$

$$\dot{m}_A \left(h_{2,A} - h_{1,A}\right) = \dot{m}_B \left(h_{2,B} - h_{1,B}\right)$$

Example: N_2 gas is heated in a heat exchanger.



At 1: $T_1 = 35\ ^\circ C$ $P_1 = 550$ kPa $h_1 = 35$ J/kg

At 2: $T_2 = 1000\ ^\circ C$ $P_1 = 500$ kPa $h_2 = 1040$ J/kg

Find $\dot{Q}$ per unit mass flow rate, in kJ/kg

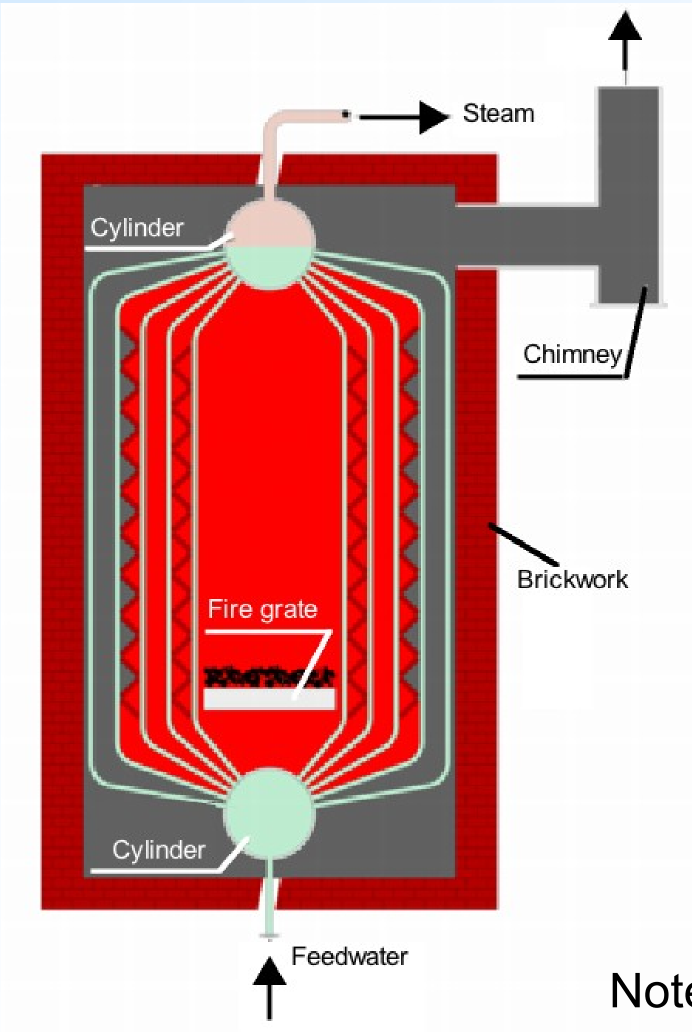
$z_2 - z_1 = 0$ No change in the potential energy

$c_2 - c_1 = 0$ No change in the kinetic energy

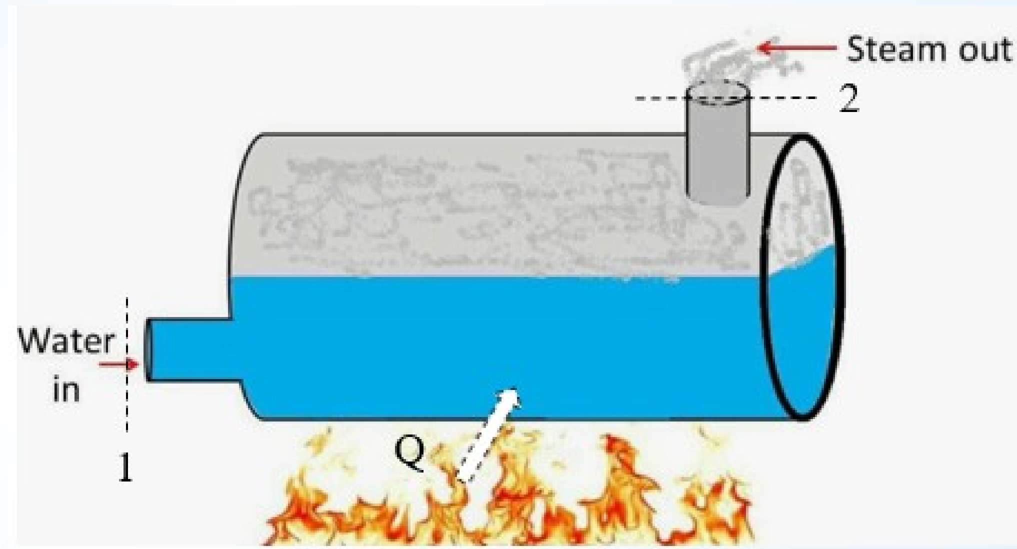
$\dot{W} = 0$ No work is done (except the flow work)

$$\dot{Q} = \dot{m}\left(h_2 - h_1\right) \Rightarrow \frac{\dot{Q}}{\dot{m}} = 1000 \text{ kJ / kg of } N_2$$

Boiler: It is an apparatus designed to convert liquid to vapor.



Schematic diagram of a boiler:



$$\dot{Q} = \dot{m}\,(h_2 - h_1)$$

Note that $z_2 - z_1$ may not be negligible for a large boiler.

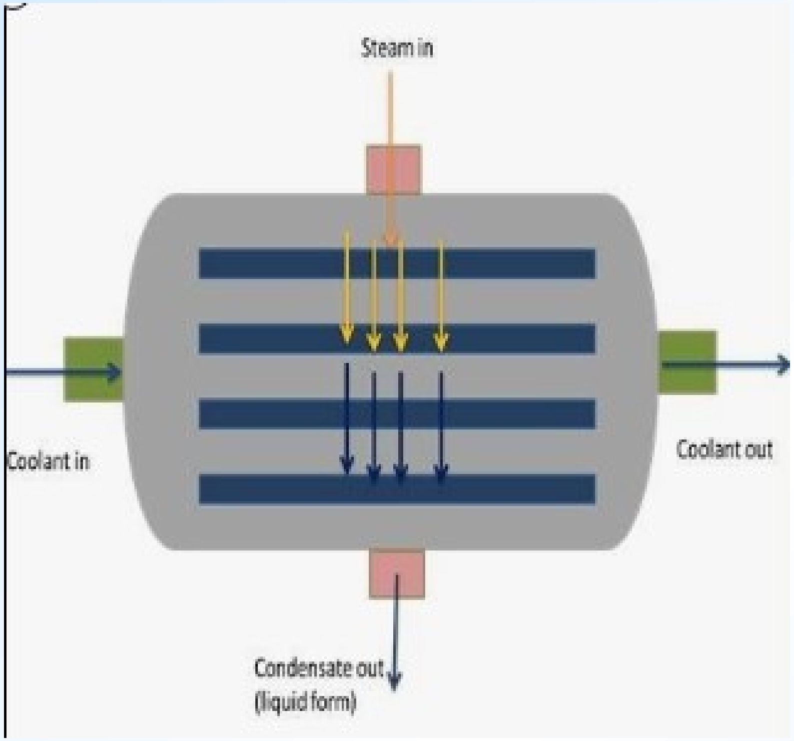
Example:

A boiler uses coal at a rate of 3000 kg/h in producing steam with a specific enthalpy of 2700 kJ/kg from feed water with a specific enthalpy of 280 kJ/kg. The heating value of coal is 28000 kJ/kg, of which 80 % is useful in producing steam. Find the rate of steam production.

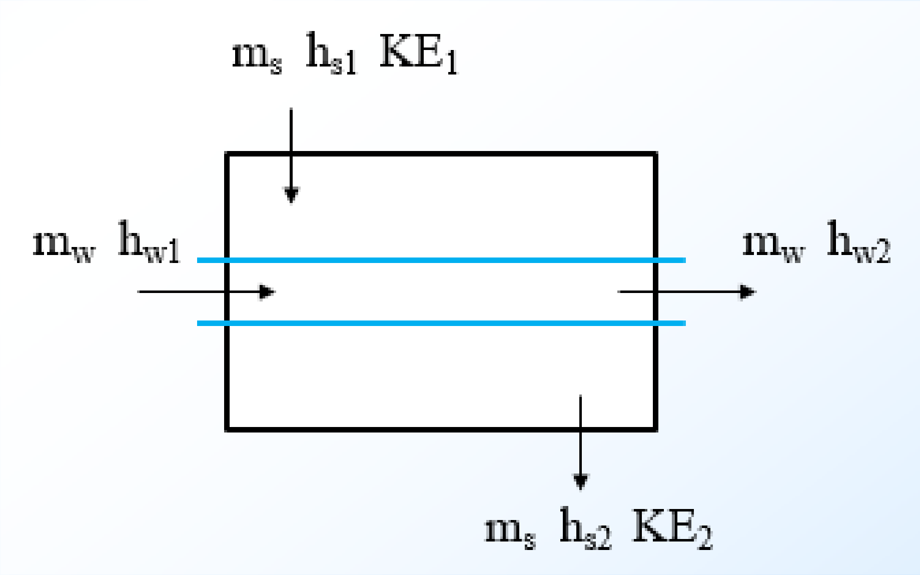
$$\dot{Q} = (3000 \text{ kg/h})\ (28000 \text{ kJ/kg})\ (0.80) = 67\ 200\ 000 \text{ kJ/h}$$

$$\dot{Q} = \dot{m}\ (h_2 - h_1) \quad \text{or} \quad \dot{m} = \frac{\dot{Q}}{h_2 - h_1} = \frac{67\ 200\ 000}{2700 - 280} = 27\ 768.6 \text{ kg steam/h}$$

Condenser: It is an apparatus designed to convert vapor to liquid.



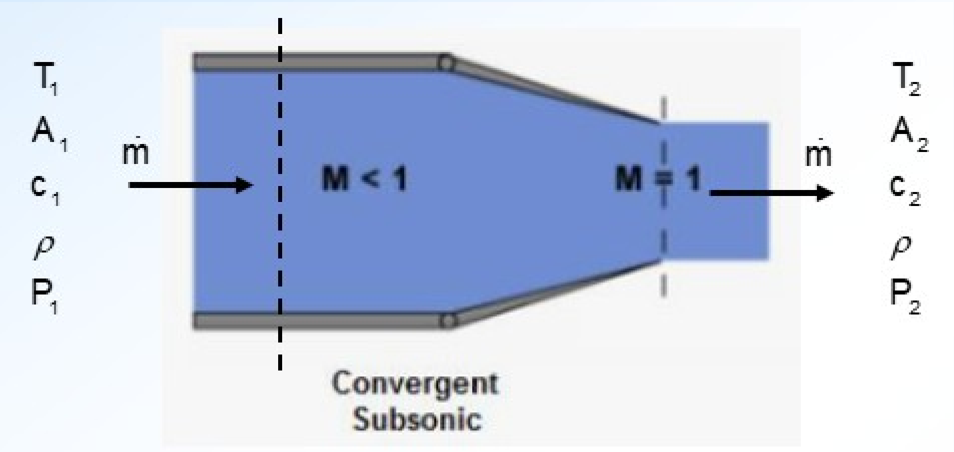
Schematic diagram of a condenser:



If mass flow rate of steam is not neglected:

$$\dot{m}_s \left(h_{s,1} - h_{s,2} + \frac{c_{s,1}^2 - c_{s,2}^2}{2} \right) = \dot{m}_w \left(h_{w,2} - h_{w,1} \right)$$

Nozzles and Diffusers



Assume that the flow is incompressible, i.e., ρ (or v) does not change.

Also, $\dot{m} = A \rho c = \text{constant}$

cross-sectional area — density — speed

$$\dot{m} = A \rho c = \frac{A\,c}{v} \Rightarrow \frac{(m^2)\ (m/s)}{m^3/kg} = kg/s$$

There is continuity of mass.

$$\dot{m} = A_1 \rho c_1 = A_2 \rho c_2 \Rightarrow \boxed{c_2 = \frac{A_1}{A_2} c_1}$$

For incompressible flow, such as flow of a liquid (water), the velocity ratio is inversely proportionak with area ratio

For compressible flow, such as flow of a gas (air), density, ρ (or specific volume, v) also changes.

Distinguish between compressible fluid and compressible flow.

Liquids are incompressible fluids (for all practical purposes) and they flow incompressiby, i.e, density remains constant during flow.

Whereas, gases are compressible fluids, but they may flow incompressiby if the density remains constant during the flow.

First law when Q = 0, W = 0, and ΔU = 0:

$$0 = h_2 - h_1 + \frac{c_2^2 - c_1^2}{2}$$

$$0 = P_2\, v_2 - P_1\, v_1 + \frac{c_2^2 - c_1^2}{2}$$

$$0 = P_2 v_2 - P_1 v_1 + \frac{c_2^2 - c_1^2}{2}$$

If $c_1 << c_2$ and $v_2 = v_1$

incompressible flow

$$c_2 = \sqrt{2 (P_1 - P_2) v}$$

If $c_1 << c_2$ and

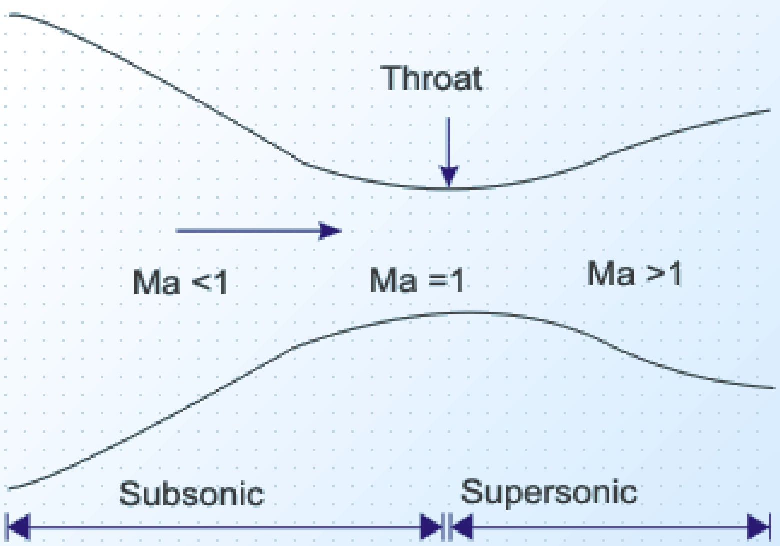
compressible flow

$$c_2 = \sqrt{2 (h_1 - h_2)}$$

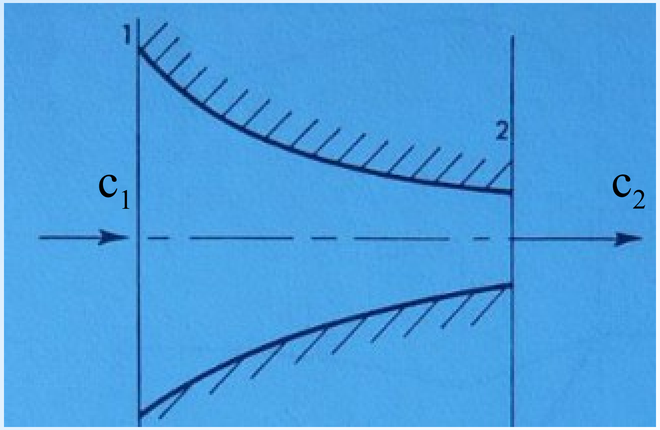
High speed can be obtained, with pressre drop, at the expense of enthalpy.

Here is another common type

Converging-diverging nozzle



Converging nozzle



c_2 < speed of sound in the fluid (gas)

If we keep on decreasing A_2, what happens?

There comes a turn around point where the flow will be choked, i.e., further decrease of the area does not give us further increase in c_2.

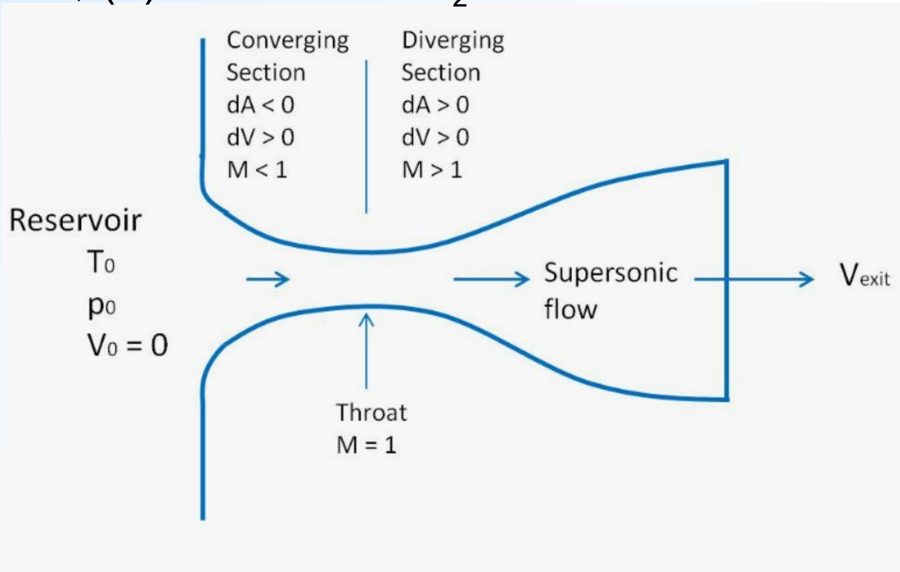
This (choking) occurs when c_2 = speed of sound.

Strangely enough, from this point on, if we increase the area, the pressure will keep on decreasing and c_2 will keep on increasing. Then, we will have a converging-diverging nozzle with speeds, c_2, higher than the speed of sound (Mach number more than 1), with the same formula:

$$c_2 = \sqrt{2\,(h_1 - h_2)} \qquad \dot{m} = \frac{A\,c}{v}$$

Example:

A nozzle is supplied with steam having a specific enthalpy of 270 kJ/kg, at a rate of m = 9.1 kg/min. At the outlet, c_2 = 1070 m/s. Assume $c_1 \approx 0$ (negligible) and Q = 0 (adiabatic). Specific volume at the outlet v_2 = 18.7 m³/kg. Determine: (a) h_2 = ? at the exit; (b) Outlet area A_2 = ?



(a) $$\dot{Q} = 0 = \dot{m}\left(h_2 - h_1\right) + \dot{m}\,\frac{c_2^2}{2}$$

$$h_2 = h_1 - \frac{c_2^2}{2}$$

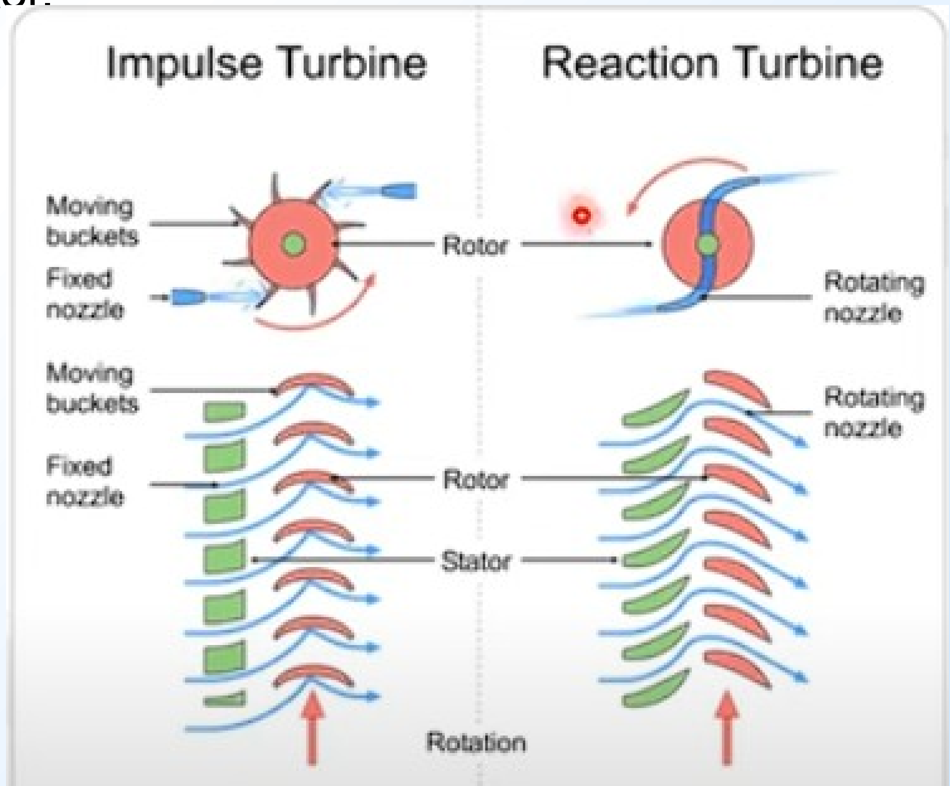
$$h_2 = 2780 - \frac{(1070)^2}{2}\;\frac{1}{1000\ \text{kJ/J}}$$

$$= 2208\ \text{kJ/kg}$$

(b) $$A_2 = \dot{m}\,\frac{v_2}{c_2} = (9.1)\left(\frac{1}{60\ \text{s/min}}\right)\left(\frac{1875}{1070}\right) \cong 0.00266\ \text{m}^2$$

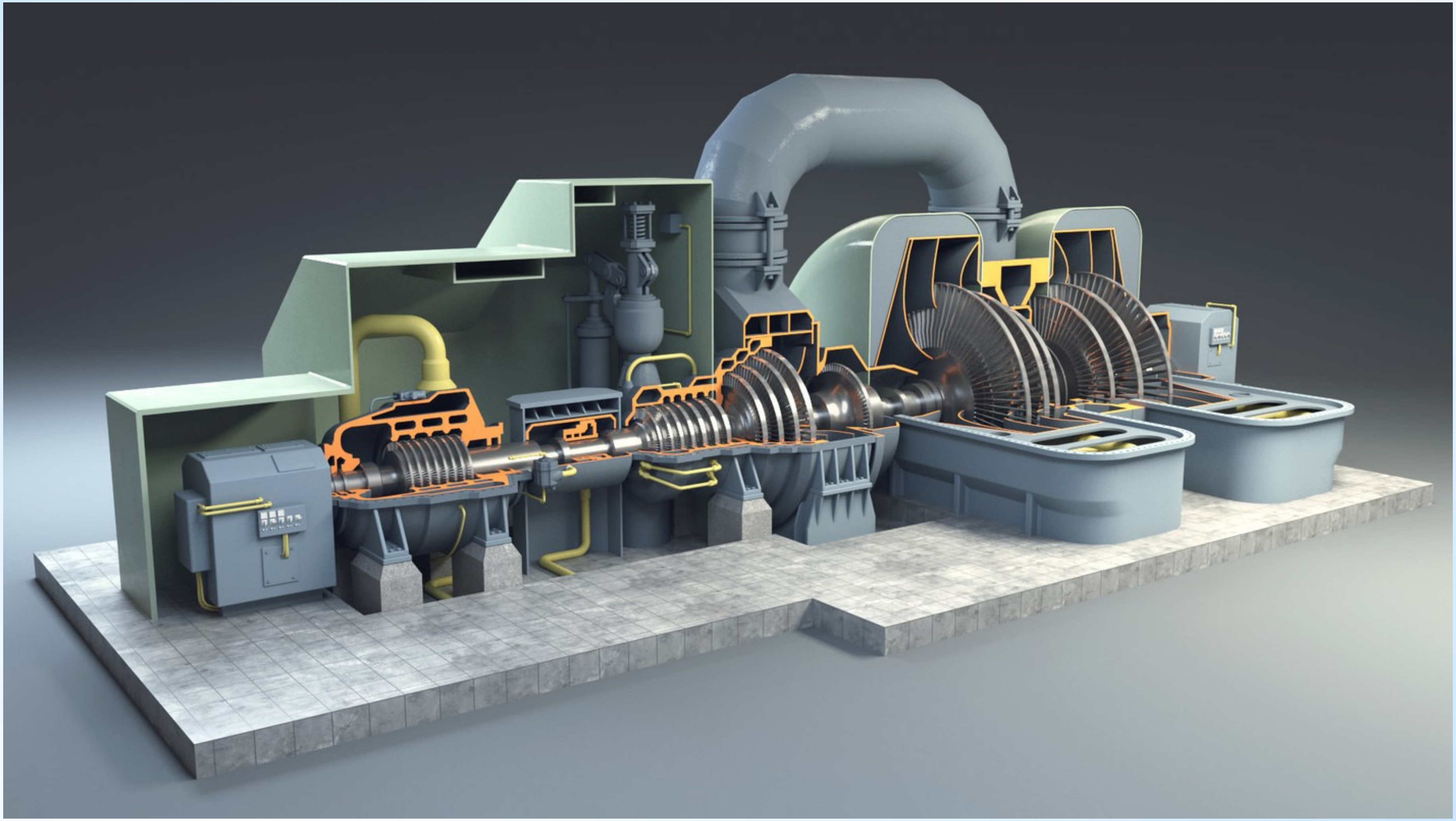
Turbines

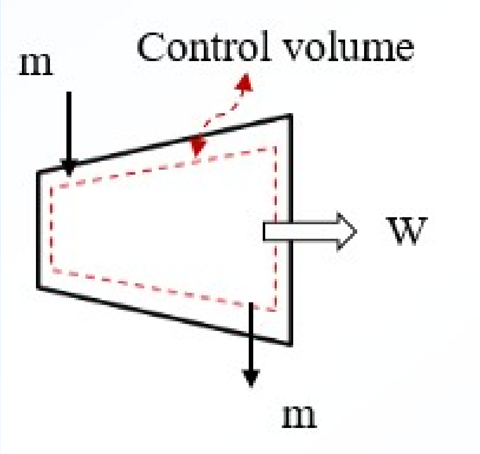
The term “turbine’ was taken from the Latin word "Turbo", which means to spin. A turbine is one type of mechanical device, used to change the energy of steam, flowing water, wind, and gas to mechanical energy (rotation or spin of a shaft). The same shaft operates an electric generator.



Types: Steam, Gas, Water, Wind

Steam Turbine





Schematic diagram of a steam or gas turbine

$\dot{W} = \dot{m}\ (h_1 - h_2)$ If velocities are negligible

Example:

A steam turbine uses 3600 kg steam / h. At the inlet, steam velocity c_1 = 27.5 m/s and h_1 = 3000 kJ / kg steam. The steam leaves the turbine with velocity c_2 = 182.5 m/s and h_2 = 2220 kj / kg steam. If the process is adiabatic (Q = 0), find the output of the turbine.

$\dot{W} = \dot{m}\ (h_1 - h_2) + \dot{m} \left(\frac{c_1^2 - c_2^2}{2} \right)$ If velocities are not negligible

$$\dot{W} = \dot{m}\,\left(h_1 - h_2\right) + \dot{m}\left(\frac{c_1^2 - c_2^2}{2}\right) \qquad \dot{m} = 3600\ \text{kg/h} = 1\ \text{kg/s}$$

$$\dot{W} = (1)\ (3000 - 2220) + (1)\left(\frac{(27.5)^2 - (182.5)^2}{2}\right)\left(\frac{1}{1000\ \text{J/kJ}}\right)$$

$$\dot{W} = 780 - \underbrace{16.3}_{\text{negligible?}} \cong 764\ \text{kW}$$

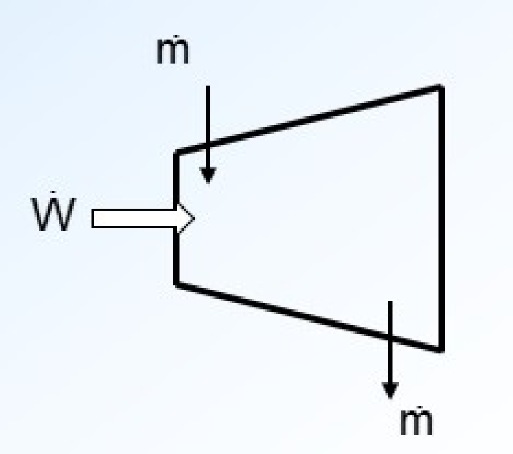
Pump and Compressor

Moving hydraulic fluid through a system requires either a pump or compressor. Both achieve this goal, but through different operating methods. Pumps have the ability to move liquids or gases. Compressors typically only move gas due to its natural ability to be compressed. Pumps and compressors both have very high pressure rises.

Pump

Compressor

$$\dot{W} = \dot{m}\left(h_1 - h_2\right)$$ work input, so negative



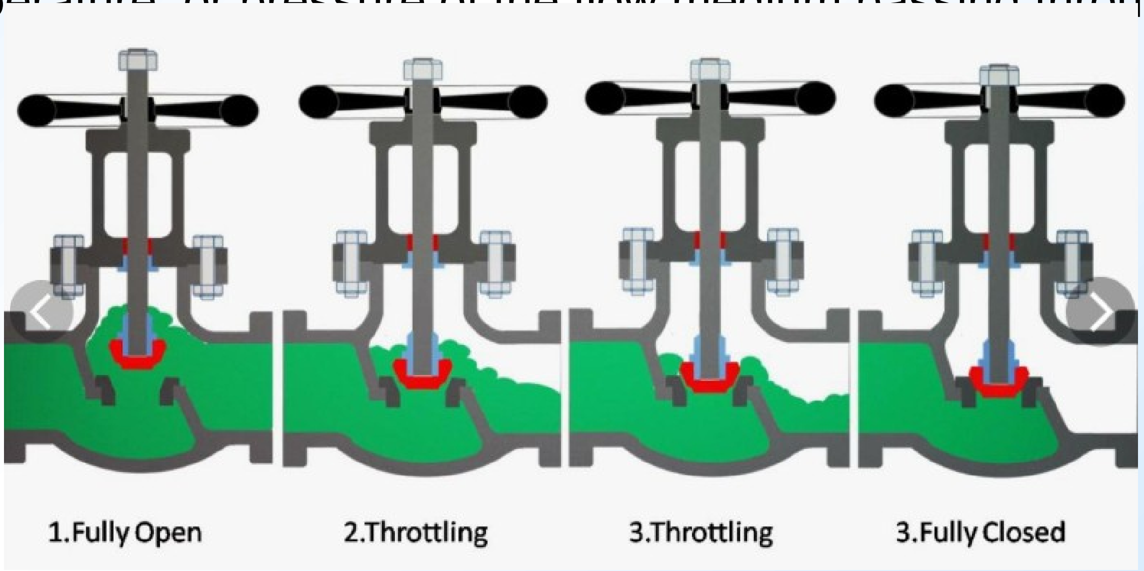
A compressor has rotors and diffusers. The rotors direct the gas onto the stationary diffusers at high speed. The gas slows down the gas (opposite of nozzles), building pressure instead.

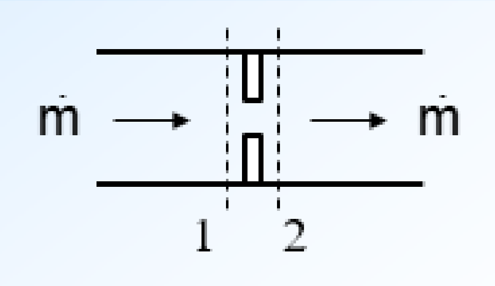
$$\dot{W} = \dot{m}\left(h_1 - h_2\right)$$

Throttling Valve

Throttling valves are used in many industrial processes where the fluid needs to be lowered in pressure. The process is called throttling because when the fluid expands in a higher pressure area, the energy used to increase the pressure is lost as it decompresses into the lower pressure area.

They are basically regulating valves as the discs of the throttling valves can regulate the flow, temperature, or pressure of the flow medium passing through it.

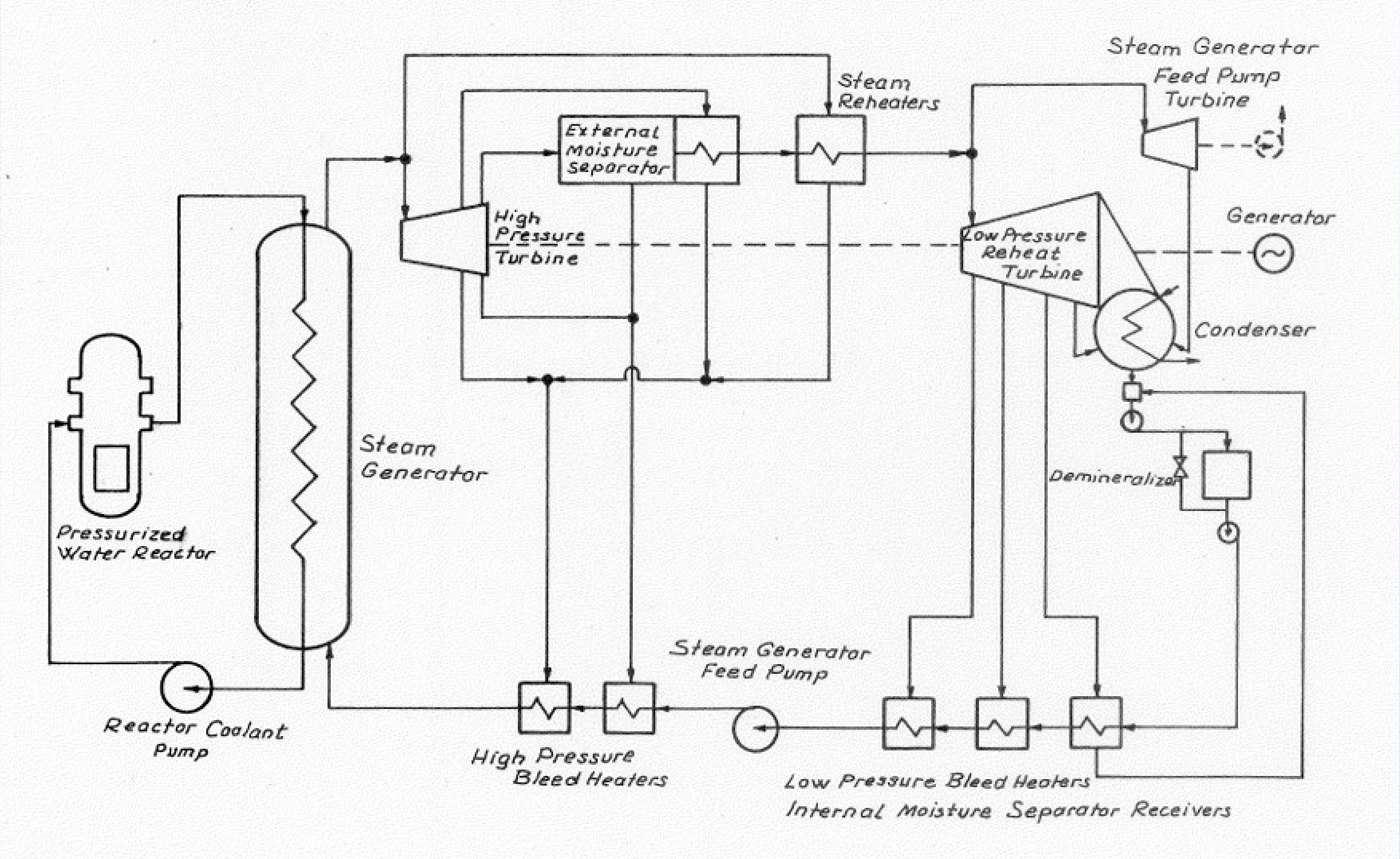




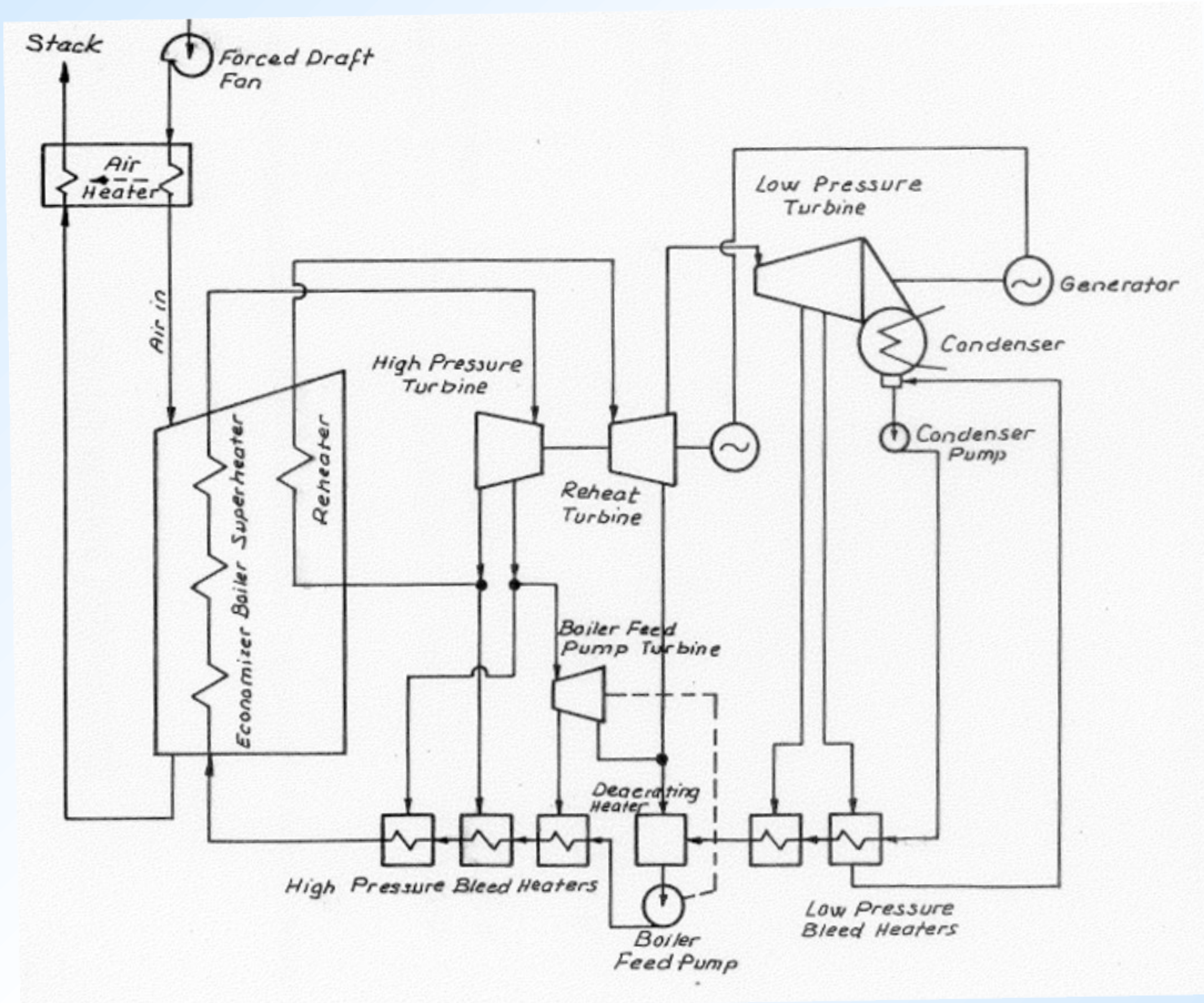
Throttling valve: $h_1 = h_2$

$$u_1 + P_1 v_1 = u_2 + P_2 v_2$$

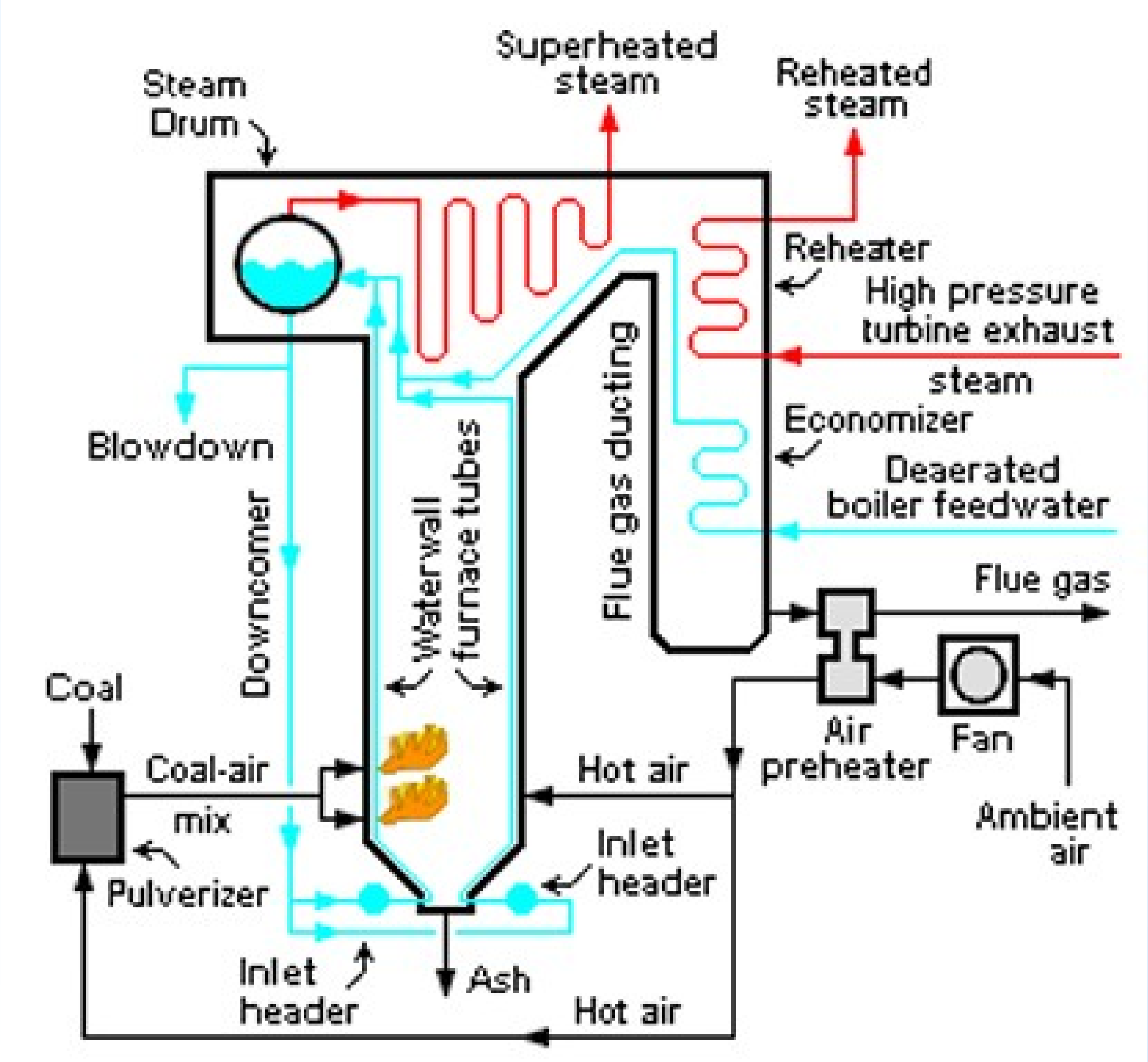
All these devices (heat exchangers, turbine, pumps, etc.) are used in power (electricity) generating power plants.



Schematic diagram of a nuclear power plant



Schematic diagram of a conventional power plant

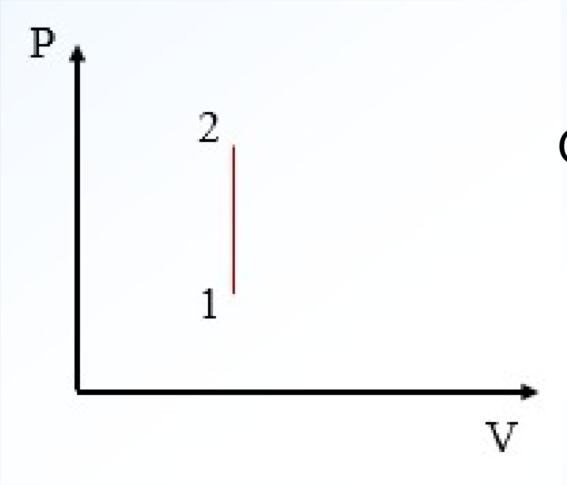


Flow path of air (hot gases) in a steam generating unit

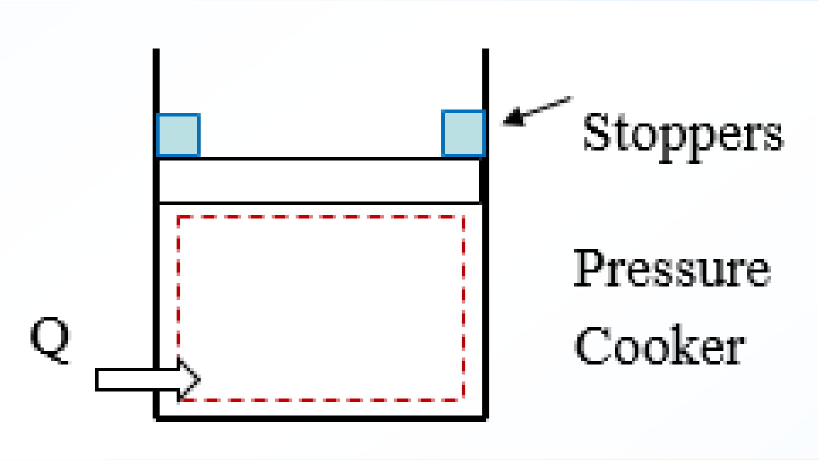
3.2 Non-flow Processes

First law of thermodynamics – Energy Balance: $\dot{Q} = \left(U_2 - U_1\right) + \dot{W}$

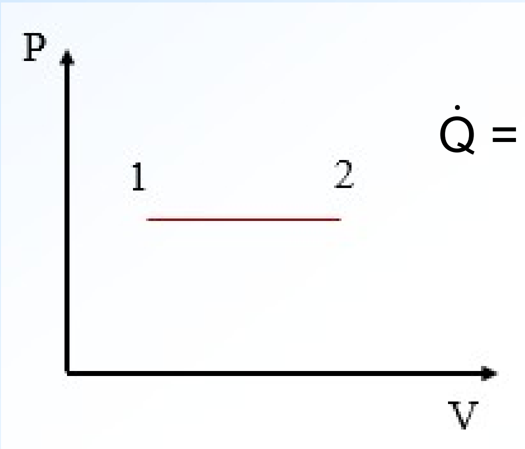
3.2.1 Constant-volume Process



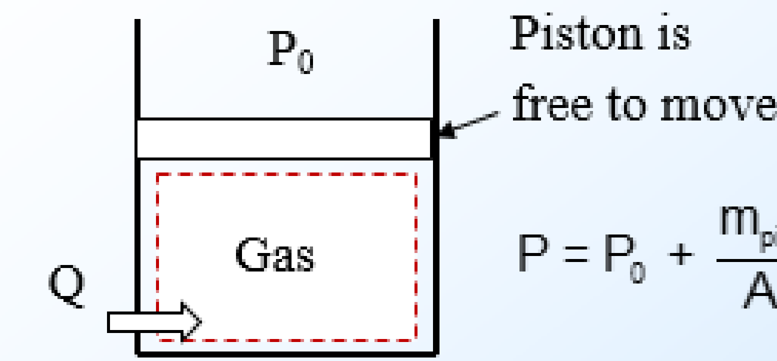
$$\dot{Q} = \left(U_2 - U_1\right)$$
$$= \dot{m}\left(u_2 - u_1\right)$$



3.2.2 Constant-pressure Process



$$\dot{Q} = (U_2 - U_1) + \dot{W}$$



$$P = P_0 + \frac{m_{pist}\, g}{A_{pist}}$$

Work done

by the system:

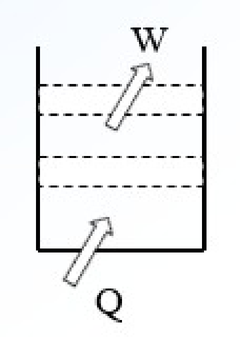
$$\dot{W} = \underbrace{\left(P_0 + \frac{m_{pist}\, g}{A_{pist}}\right)}_{P} \underbrace{(A_{pist})\;(L)}_{V_2 - V_1}$$

$$\dot{W} = (P)\;(V_2 - V_1)$$

$$\dot{Q} = U_2 - U_1 + \dot{W} = U_2 - U_1 + P\;(V_2 - V_1) = U_2 + P_2\,V_2 - (U_1 + P_1\,V_1)$$

$$= H_2 - H_1 = m\;(h_2 - h_1)$$

Example:



During a non-flow process, m = 0.5 kg of steam is cooled at constant pressure from $V_1 = 0.3\ m^3$ to $V_2 = 0.028\ m^3$. It is measured that Q = - 900 kJ and W = - 81.6 kJ. Find P and Δu (change in the specific internal energy).

$$Q = \left(U_2 - U_1\right) + W \qquad -900 = (0.5)\left(u_2 - u_1\right) - 81.6$$

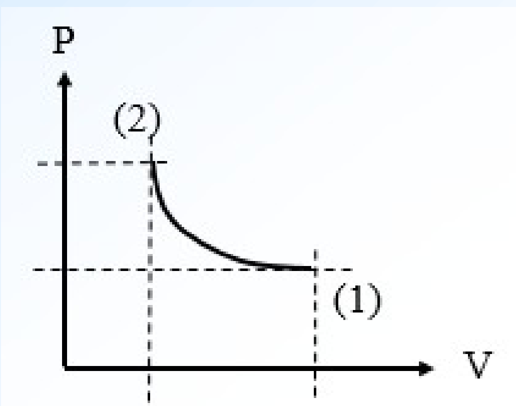
$$u_2 - u_1 = \frac{-900 + 81.6}{0.5} = -1636.8\ \text{kJ/kg} = \Delta u$$

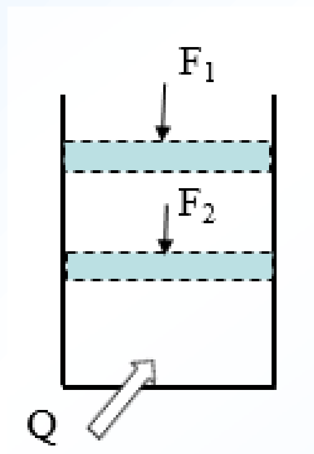
$$W = P\left(V_2 - V_1\right) \quad \Rightarrow \quad P = \frac{W}{V_2 - V_1} = \frac{-81.6}{0.028 - 0.3} = 300\ \text{kPa}$$

3.2.3 Adiabatic Process

$Q = 0 \quad \Rightarrow \quad 0 = U_2 - U_1 + W \quad \Rightarrow \quad W = U_1 - U_2$

3.2.4 Polytropic Process





$P V^n = \text{constant}$

n: Index of expansion

or compression

Constant for a given gas

$$\text{Work} = \int_1^2 P(V)\, dV = \int_1^2 \frac{P_1 V_1^n}{V^n}\, dV = \int_1^2 \frac{P_2 V_2^n}{V^n}\, dV = \frac{P_1 V_1 - P_2 V_2}{n - 1}$$

$$Q = U_2 - U_1 + W = U_2 - U_1 + \frac{P_1 V_1 - P_2 V_2}{n - 1}$$