Thermodynamics I
Chapter 4
First Law of Thermodynamics
Open Systems

Mohsin Mohd Sies

Fakulti Kejuruteraan Mekanikal, Universiti Teknologi Malaysia

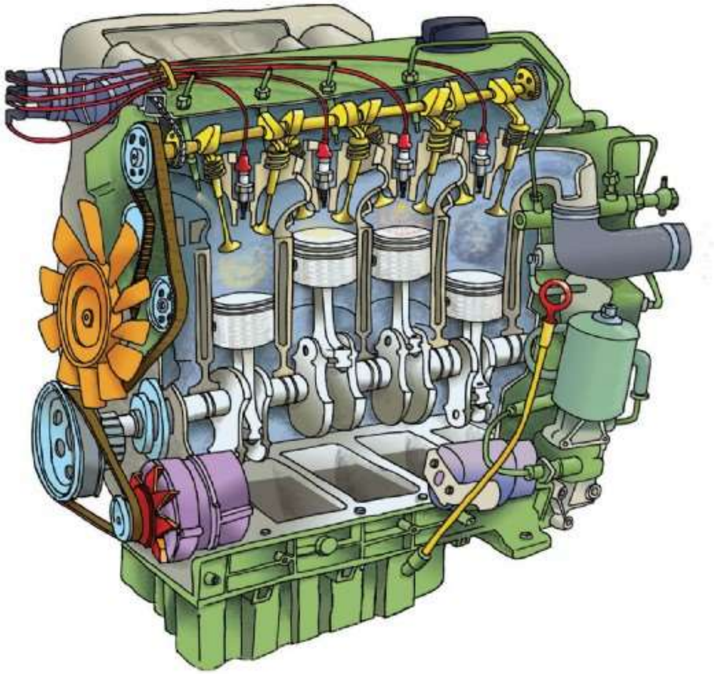
First Law of Thermodynamics (Motivation)

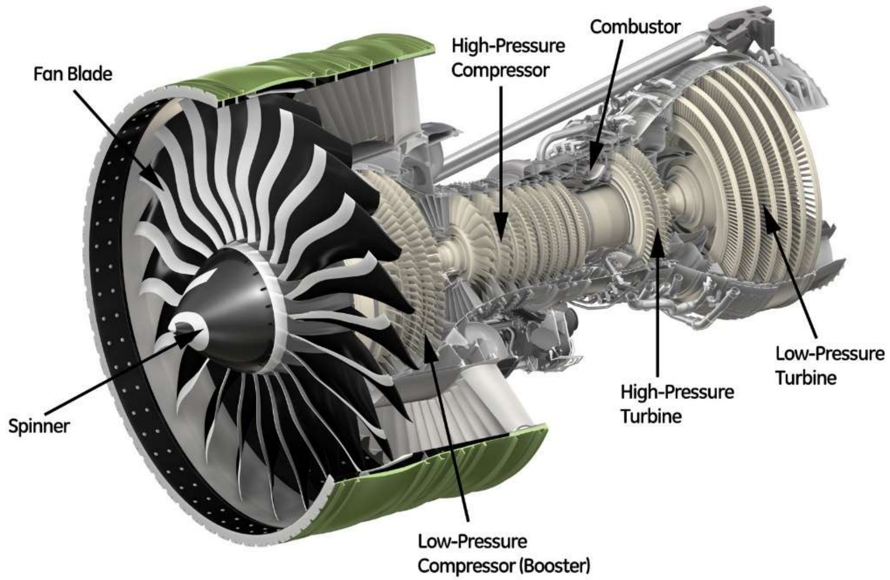
A system changes due to interaction with its surroundings.

Interaction study is possible due to conservation laws.

Various forms of conservation laws are studied in this chapter in the form of balance equations.

Examples of Open Systems



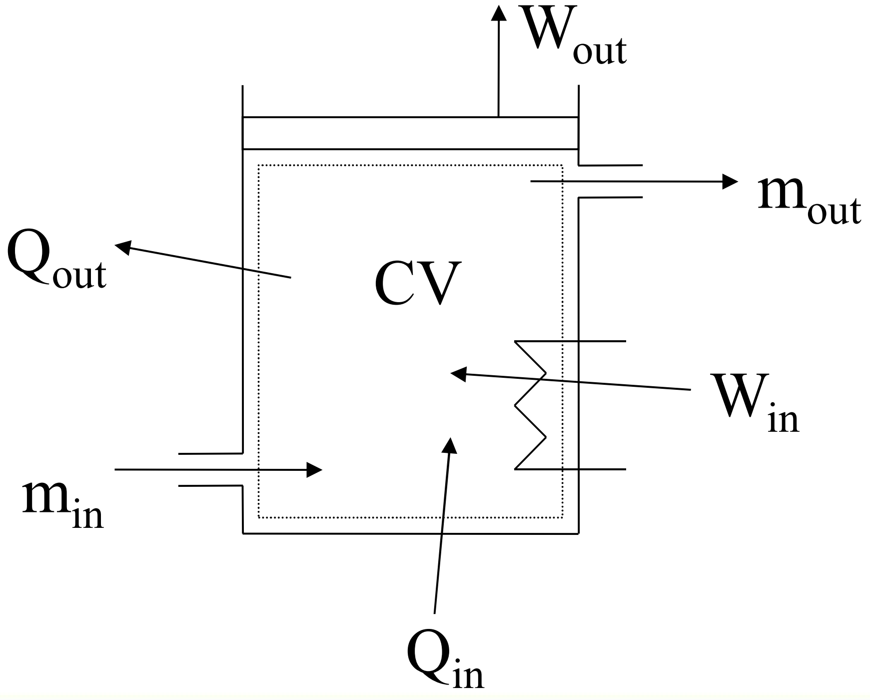

Fan Blade
High-Pressure Compressor
Combustor
Spinner
Low-Pressure Compressor (Booster)
High-Pressure Turbine
Low-Pressure Turbine

1ST LAW FOR OPEN SYSTEMS

Energy and Mass can enter/leave an open system

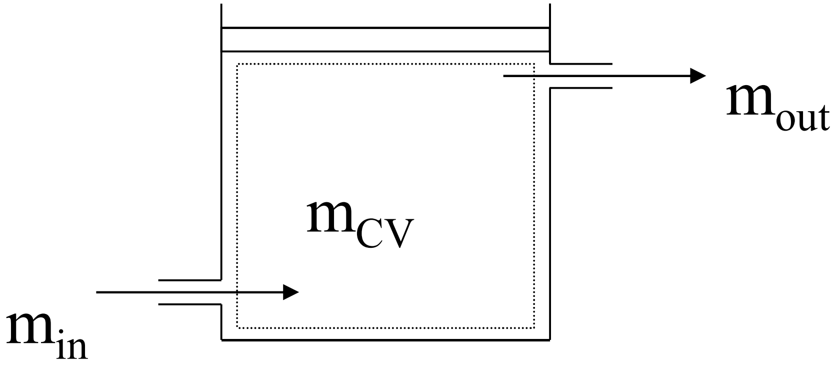
Divided into two parts:

- Conservation of Mass Principle
- Conservation of Energy Principle



Mass Conservation (Mass Balance)

Mass Balance:



$$\Delta m_{CV} = \sum m_{in} - \sum m_{out}$$

Net change of mass of CV

Total of all mass entering

Total of all mass exiting

$$\frac{dm_{CV}}{dt} = \sum \frac{dm_{in}}{dt} - \sum \frac{dm_{out}}{dt}$$

Rate of change of mass of CV

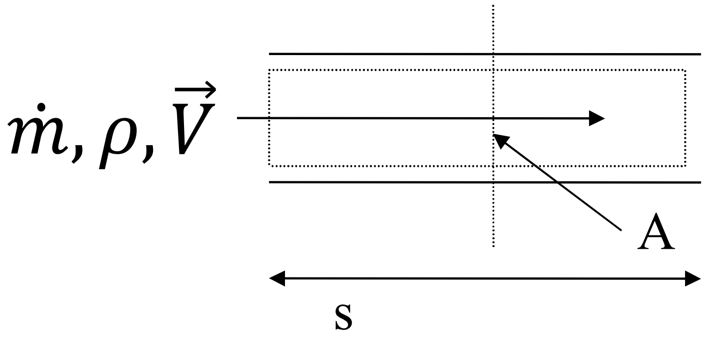
Total of all mass flow rates for all inlet channels

Total of all mass flow rates for all exit channels

Mass flow rates and Speed for a channel

$$m = \rho V$$

$$m = \rho s A$$



For flow rates;

$$\frac{dm}{dt} = \rho \frac{ds}{dt} A$$

$$\dot{m} = \rho \vec{V} A$$

but

$$sA = V$$

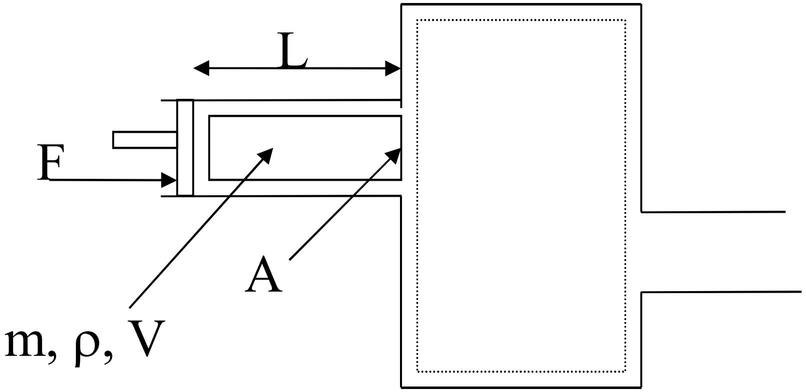
$$\frac{ds}{dt} A = \dot{V}$$

Thus;

$$\boxed{\dot{m} = \rho \vec{V} A = \frac{\vec{V} A}{v} = \rho \dot{V} = \frac{\dot{V}}{v}}$$

Flow Work

For an amount of mass to cross a boundary, it needs a force (work) to push it; called Flow Work , w_{flow}



The force that pushes the fluid;

$$F = PA$$

Work that is involved;

$$W = \int F \cdot ds$$

$$W_{flow} = F \cdot L$$

$$= PA \cdot L$$

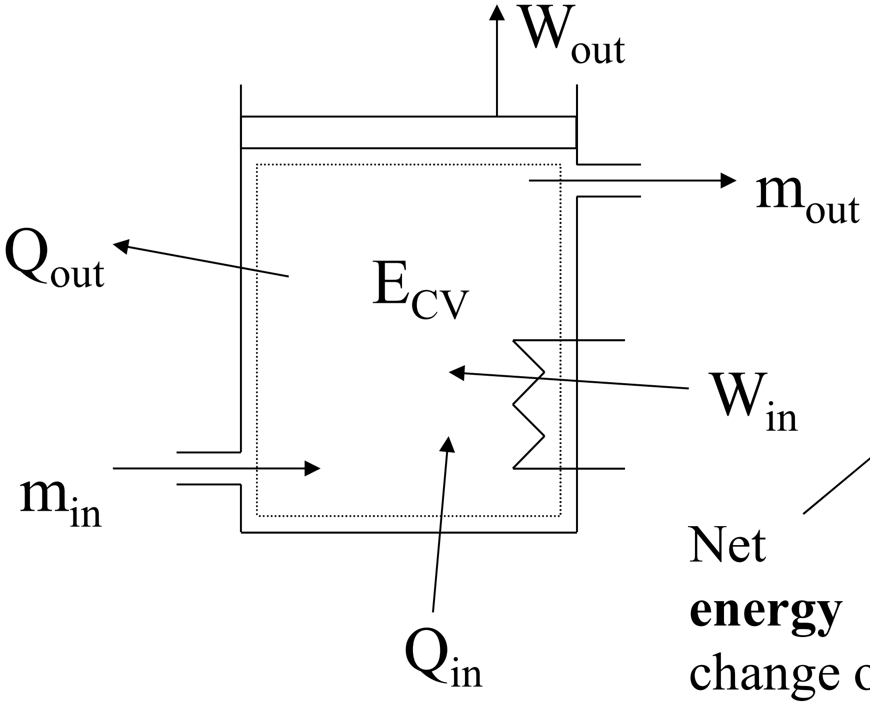
$$= PV$$

$$\boxed{w_{flow} = pv}$$

Conservation of Energy for Open Systems

Energy can enter/leave an open system via

Heat, Work AND Mass Flow Entering/Leaving



$$\Delta E_{CV} = \underbrace{Q - W} + E_{in} - E_{out}$$

Net **energy** change of **CV**

Net energy transfer by **heat/work**

Total energy of **entering mass**

Total energy of **exiting mass**

Energy of a Flowing Mass

An amount of mass possesses energy, E, e

$$e = u + ke + pe$$

but a flowing mass also possesses flow work, so

the Energy for a flowing mass; $\mathbf{e_{flow}}$

$$\begin{aligned} e_{flow} &= u + ke + pe + w_{flow} \\ &= u + pv + ke + pe \end{aligned}$$

but $u + pv = h$ (enthalpy)

$$\boxed{\mathbf{e_{flow} = h + ke + pe}}$$ (energy for a flowing mass)

Energy Balance for an Open System

can be written as;

$$\Delta E_{CV} = Q - W + E_{flow_{in}} - E_{flow_{out}}$$

or;

$$\Delta e_{CV} = q - w + e_{flow_{in}} - e_{flow_{out}}$$

$$= q - w + (h + ke + pe)_{in} - (h + ke + pe)_{out}$$

$$= q - w + \sum_{in} \underbrace{(h + ke + pe)} - \sum_{out} \underbrace{(h + ke + pe)}$$

Total of all work **except** flow work

For each inlet

For each outlet

but;

$$\Delta e_{CV} = (\Delta u + \Delta ke + \Delta pe)_{CV}$$

so;

$$(\Delta u + \Delta ke + \Delta pe)_{CV} = q - w$$

$$+ \sum_{in} (h + ke + pe) - \sum_{out} (h + ke + pe)$$

Energy Balance in other forms;

$$\Delta E_{CV} = Q - W + \sum_{in}(H + KE + PE) - \sum_{out}(H + KE + PE)$$

Rate form;

$$\boxed{\frac{dE_{CV}}{dt} = \dot{Q} - \dot{W} + \sum_{in} \dot{m}(h + ke + pe) - \sum_{out} \dot{m}(h + ke + pe)}$$

↑

(general form of Energy Balance for an Open System)

USUF, Transient Flow, Unsteady Flow

The general form of Energy Balance can also be used for the Uniform State, Uniform Flow system (***USUF)***, or sometimes called ***Transient Flow.***

Charging and *Discharging* cases of Transient Flow can be analyzed using the simplified form of the general energy balance below

$$\Delta E_{CV} = \dot{Q} - \dot{W} + \sum_{in} m(h + ke + pe) - \sum_{out} m(h + ke + pe)$$

$$\Delta U + \Delta KE + \Delta PE = \dot{Q} - \dot{W} + \sum_{in} m(h + ke + pe) - \sum_{out} m(h + ke + pe)$$

Steady Flow Process

Criteria;

All *system properties* (intensive & extensive) do not change with time

m_{cv}= constant; Δm_{CV}= 0

V_{CV}= constant; ΔV_{CV}= 0

E_{CV}= constant; ΔE_{CV}= 0

Fluid properties at all *inlet/exit channels* do not change with time (Values might be different for different channels)

$$(\dot{m}, \vec{V}, A, etc)$$

Heat and work interactions do not change with time

$$\dot{Q} = constant$$

$$\dot{W} = constant$$

Implication of Criterion 1 (**Mass**)

$\Delta m_{CV} = 0$,

From Mass Conservation;

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = \Delta m_{CV}$$

$$\boxed{\sum \dot{m}_{in} = \sum \dot{m}_{out}}$$

Recall that

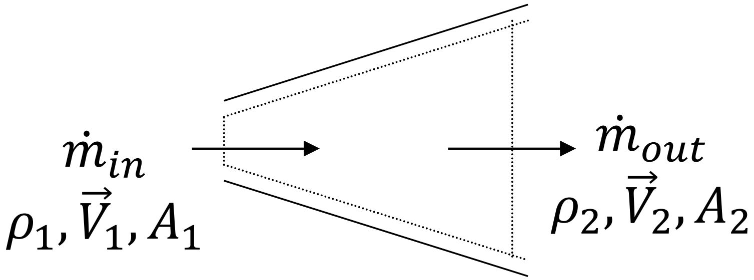
$$\dot{m} = \rho \vec{V} A = \frac{\vec{V} A}{v}$$

so

$$\boxed{\sum_{i=1}^{n} \rho_i \vec{V}_i A_i \bigg|_{in} = \sum_{o=1}^{k} \rho_o \vec{V}_o A_o \bigg|_{out}}$$

Implication of Criterion 1 (**Mass**) ctd.

for 1 inlet/ 1 exit;



$$\dot{m}_{in} = \dot{m}_{out}$$

$$\rho_1 \vec{V}_1 A_1 = \rho_2 \vec{V}_2 A_2$$

Implication of Criterion 1

(Volume)

$\Delta V_{CV} = 0,$

$\therefore$ $\boxed{W_B = 0 \text{(boundary work = 0)}}$

$$\Delta E_{CV} = Q - W + \Sigma E_{flow(in)} - \Sigma E_{flow(out)}$$

$$W = W_{electrical} + W_{shaft} + \underbrace{\cancel{W_{boundary}}}_{0} + \underbrace{\cancel{W_{flow}}}_{\text{in } \mathbf{h}} + W_{etc.}$$

$\boxed{\text{W not necessarily 0, only } W_B \text{ is 0}}$

Implication of Criterion 1

(**Energy**)

$\Delta E_{CV} = 0,$

From Energy Conservation;

$$\underbrace{\cancel{\frac{dE_{CV}}{dt}}}_{= 0} = \dot{Q} - \dot{W} + \sum_{in} \dot{m}(h + ke + pe) - \sum_{out} \dot{m}(h + ke + pe)$$

Rearrange to get Steady State, Steady Flow Energy Equation

(SSSF)

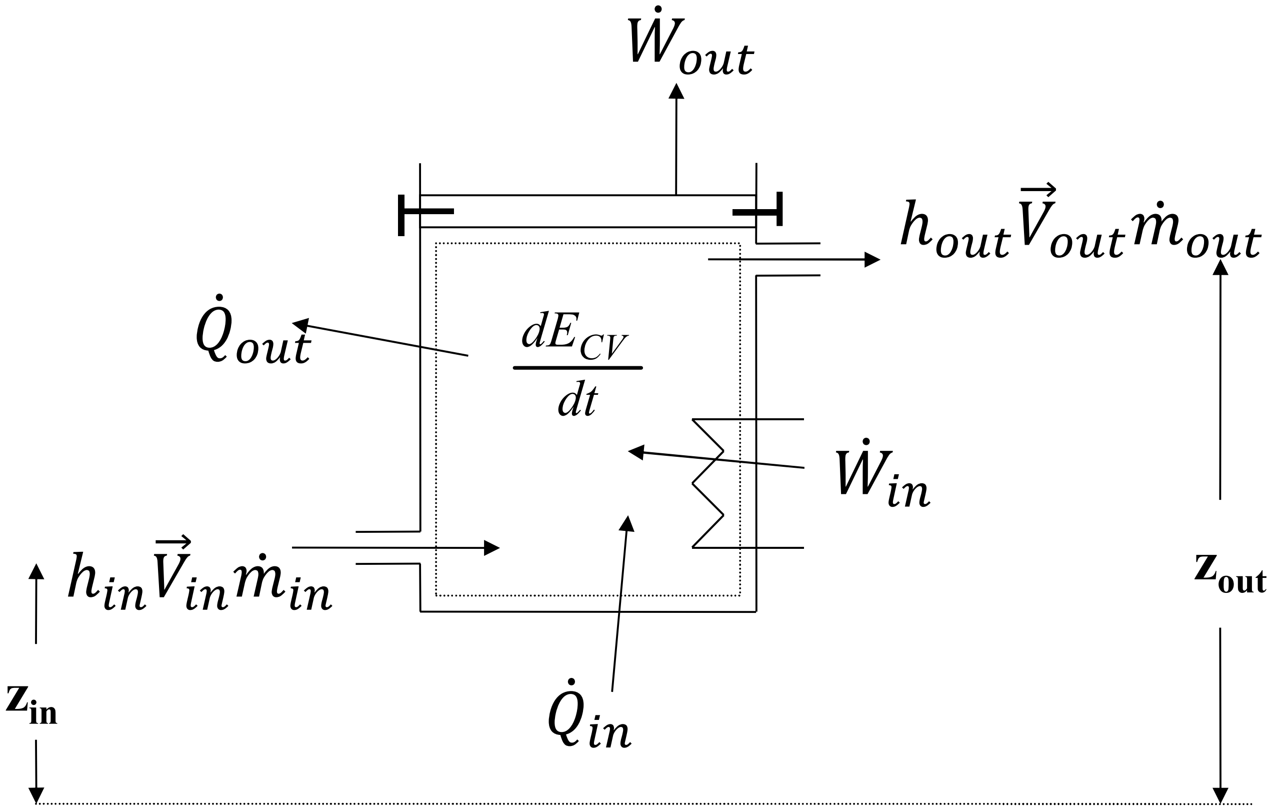
$$\boxed{\dot{Q} - \dot{W} = \sum_{out} \dot{m}(h + ke + pe) - \sum_{in} \dot{m}(h + ke + pe)}$$

SSSF

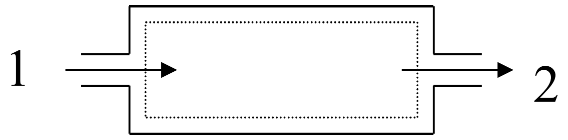
$$\dot{Q} - \dot{W} = \sum_{out} \dot{m}\underbrace{\left(h + \frac{\vec{V}^2}{2} + gz\right)}_{\text{For each exit channel}} - \sum_{in} \dot{m}\underbrace{\left(h + \frac{\vec{V}^2}{2} + gz\right)}_{\text{For each inlet channel}}$$

For each **exit** channel

For each **inlet** channel



SSSF energy equation for 1 inlet / 1 exit



Mass

$$\dot{m}_{in} = \dot{m}_{out} \quad \text{or} \quad \dot{m}_1 = \dot{m}_2$$

Energy

$$\dot{Q} - \dot{W} = \dot{m}_2\left(h_2 + \frac{\vec{V}^2{}_2}{2} + gz_2\right) - \dot{m}_1\left(h_1 + \frac{\vec{V}^2{}_1}{2} + gz_1\right)$$

$$\dot{m}_1 = \dot{m}_2 = \dot{m}$$

$$\dot{Q} - \dot{W} = \dot{m}\left[(h_2 - h_1) + \left(\frac{\vec{V}^2{}_2}{2} - \frac{\vec{V}^2{}_1}{2}\right) + (gz_2 - gz_1)\right]$$

$$\frac{\dot{Q}}{\dot{m}} - \frac{\dot{W}}{\dot{m}} = (h_2 - h_1) + \left(\frac{\vec{V}^2{}_2}{2} - \frac{\vec{V}^2{}_1}{2}\right) + (gz_2 - gz_1)$$

$$\boxed{q - w = \Delta h + \Delta ke + \Delta pe \quad \text{(1 inlet / 1 exit)} \quad \text{(} \Delta = \text{exit} - \text{inlet)}}$$

SSSF energy equation for multiple channels but neglecting Δke, Δpe

$$\dot{Q} - \dot{W} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in}$$

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$

SSSF Applications

For devices which are *open systems*

(a)
- Nozzle & Diffuser
- Turbine & compressor
- Throttling valve @ porous plug

(b)
- Mixing/Separation Chamber
- Heat exchanger(boiler, condenser, etc)

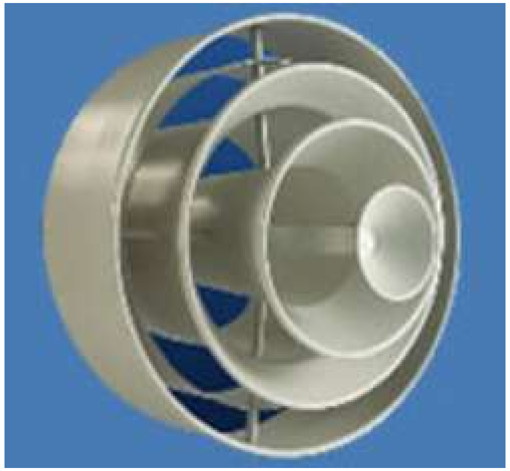
2 categories;

1 inlet / 1 outlet
Multiple inlet / outlet

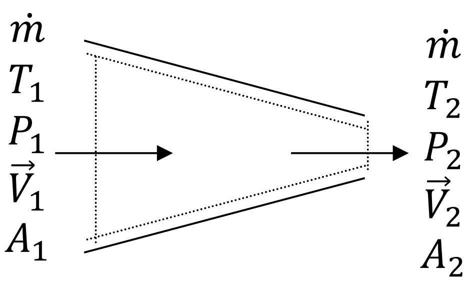
Analysis starts from the general SSSF energy equation;

$$\boxed{\dot{Q} - \dot{W} = \sum_{out} \dot{m}(h + ke + pe) - \sum_{in} \dot{m}(h + ke + pe)}$$

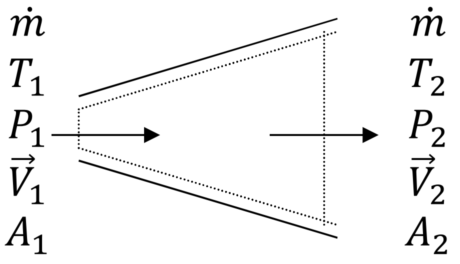
Nozzle & Diffuser ($\Delta KE \neq 0$) (To change fluid velocity)



Nozzle & Diffuser ($\Delta KE \neq 0$) (To change fluid velocity)



Nozzle $\vec{V} \uparrow$



Diffuser $\vec{V} \downarrow$

Assumptions

$$\left.\begin{array}{l}\text{Const. volume} \rightarrow w_B = 0 \\ \text{No other work}\end{array}\right\} w_{CV} = 0$$

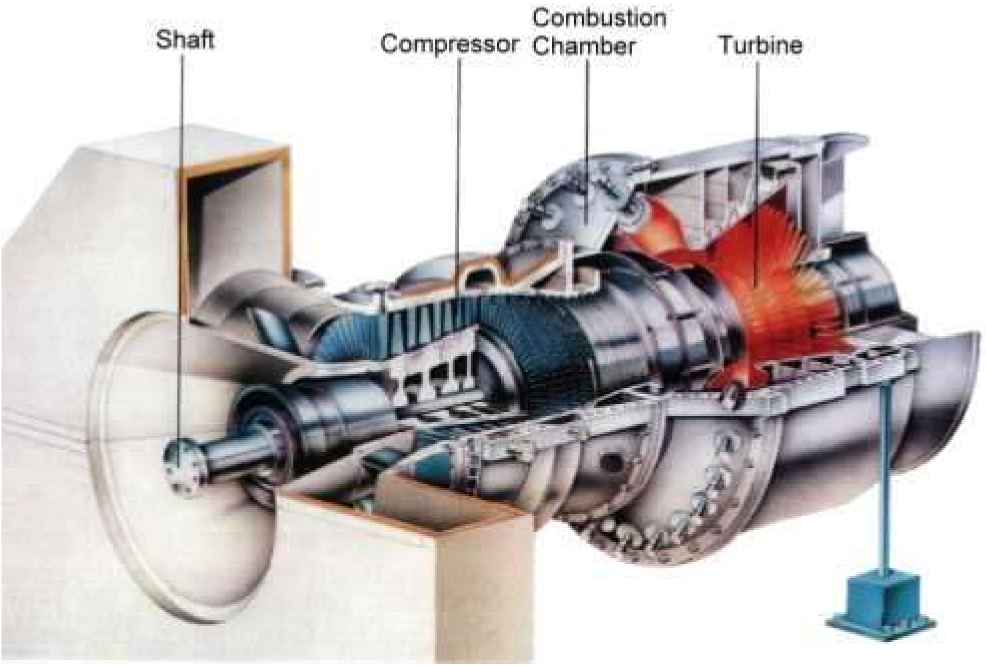
Small difference in height → $\Delta pe = 0$

$$\dot{Q} - \dot{W} = \sum_{out} \dot{m}(h + ke + pe) - \sum_{in} \dot{m}(h + ke + pe)$$

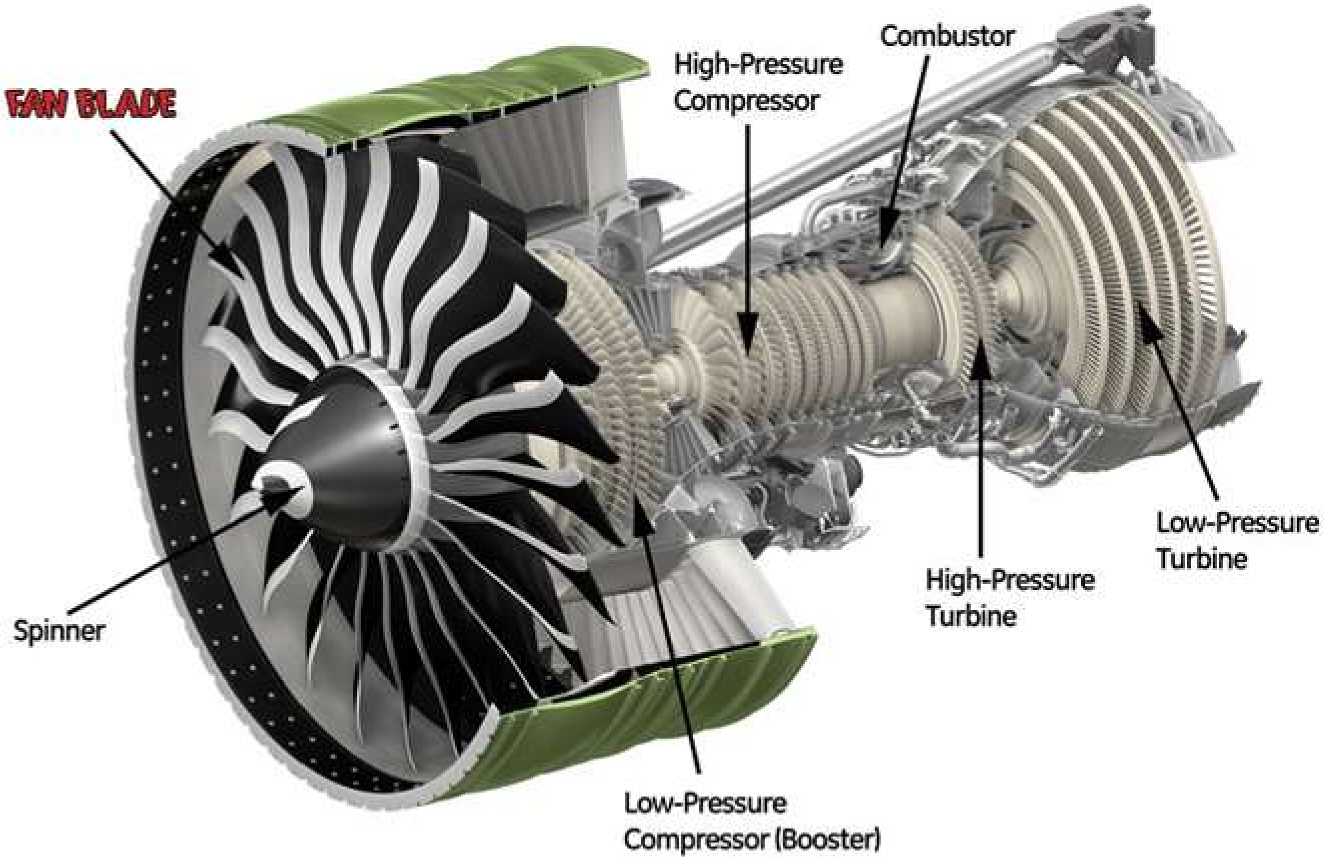
1 inlet / 1 outlet

$$q - \cancel{w} = \Delta h + \Delta ke + \Delta \cancel{pe} \qquad q = \Delta h + \Delta ke$$

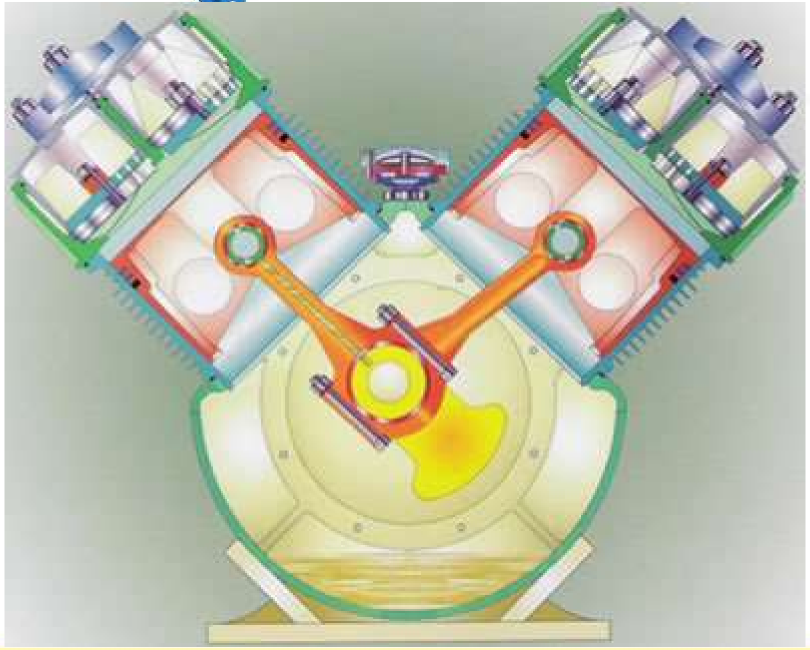
Turbine ($w_{CV} \neq 0$)



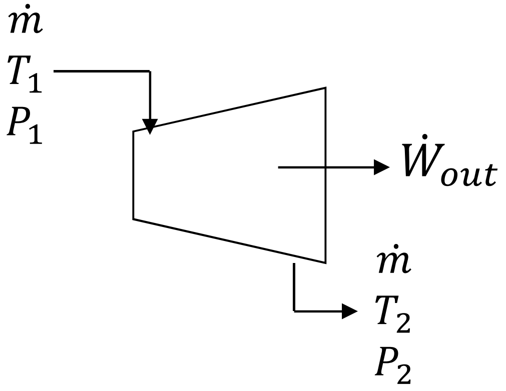
Turbine & Compressors ($w_{CV} \neq 0$)



Compressors (Reciprocating) ($w_{CV} \neq 0$)

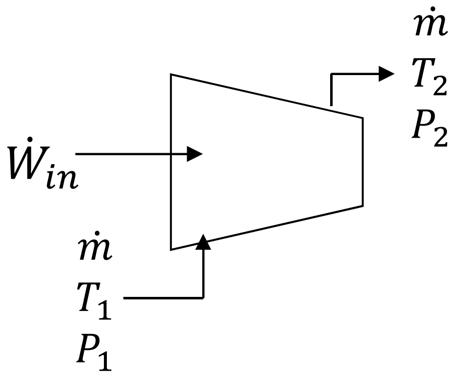


Turbine & Compressor ($w_{CV} \neq 0$)



Turbine

produces work (W +ve)
from expansion of
fluid (ΔP -ve)



Compressor

increases pressure (ΔP +ve)
using work supplied (W –ve)

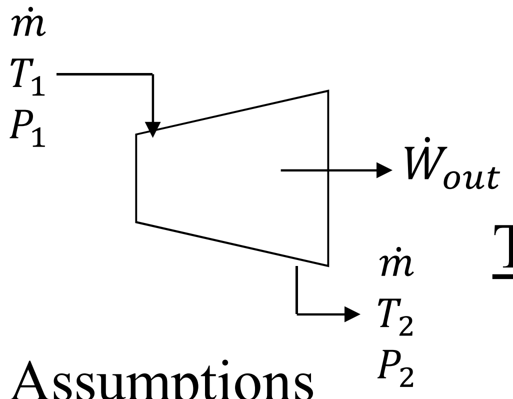
Assumptions

Const. volume → $w_B = 0$
Involves other work

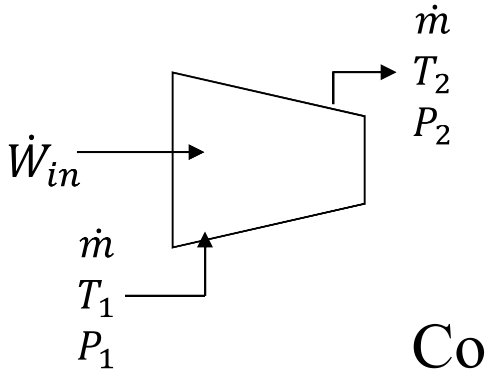
$\left.\right\} w_{CV} \neq 0$

Small difference in height → $\Delta pe = 0$

Turbine & Compressor ($w_{CV} \neq 0$)



Turbine



Compressor

Assumptions

Const. volume → $w_B = 0$
Involves other work
} $w_{CV} \neq 0$
Small difference in height → $\Delta pe = 0$

$$\dot Q - \dot W = \sum_{out} \dot m(h + ke + pe) - \sum_{in} \dot m(h + ke + pe)$$

1 inlet / 1 outlet

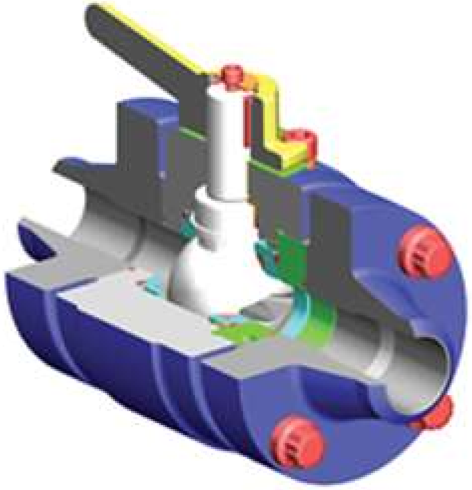
$$\dot Q - \dot W = \dot m(\Delta h + \Delta ke + \cancel{\Delta pe})$$

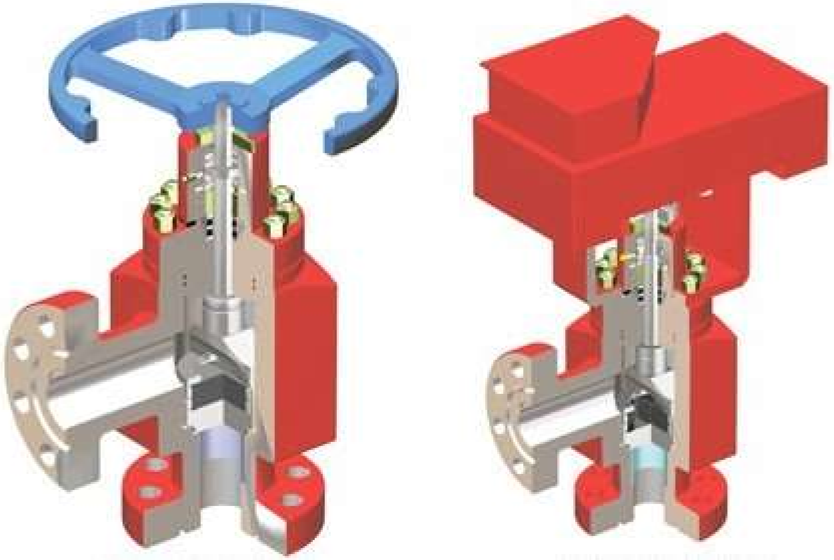
Commonly insulated (q=0), and also
$\Delta ke \approx 0$ (since $\Delta ke << \Delta h$)

$$-\frac{\dot W}{\dot m} = \Delta h = h_2 - h_1$$

Throttling valve/Porous plug (const.enthalpy, $h = c$)

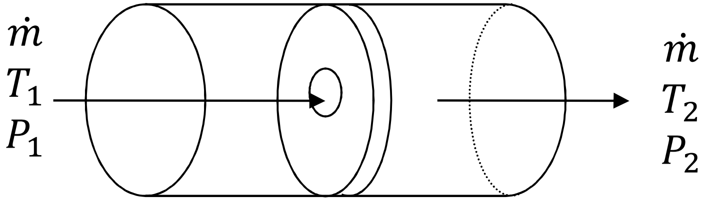
To reduce pressure without involving work

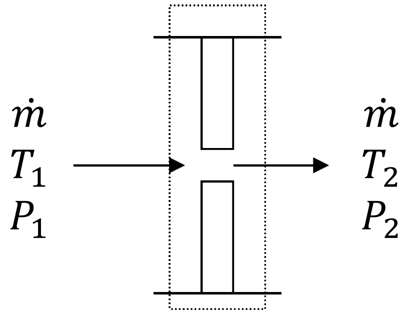




Throttling valve/Porous plug (const.enthalpy, $h = c$)

To reduce pressure without involving work





Assumptions

W = 0

Δke = 0 , Δpe = 0

Q ≈ 0 (system too small)

$$\dot{Q} - \dot{W} = \sum_{out} \dot{m}(h + ke + pe) - \sum_{in} \dot{m}(h + ke + pe)$$

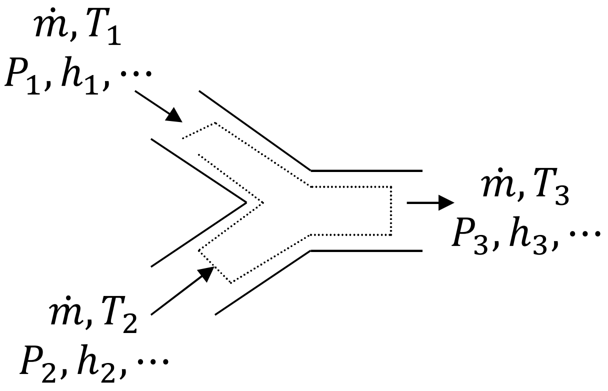
1 inlet / 1 outlet

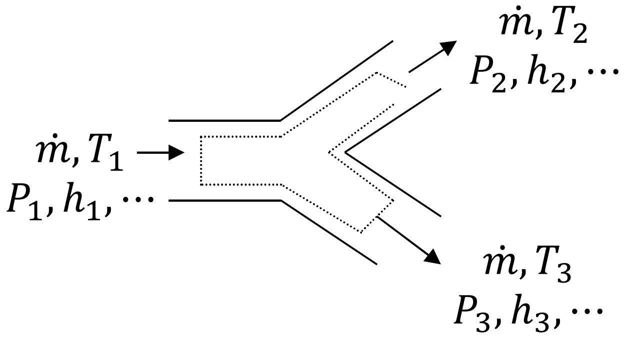
$$\cancel{q} - \cancel{w} = \Delta h + \Delta \cancel{ke} + \Delta \cancel{pe}$$

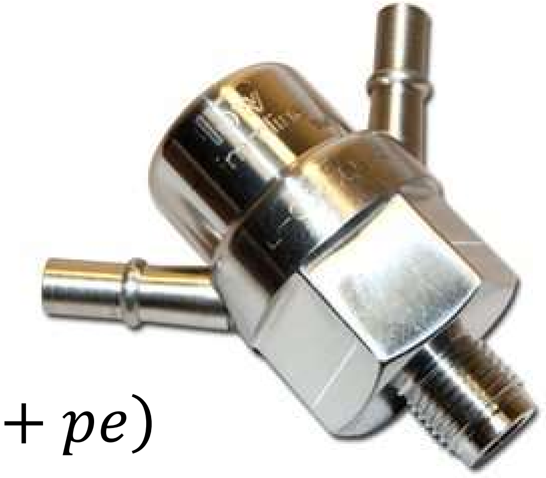
$$\Delta h = 0$$

$$\boxed{h_1 = h_2 \quad \text{For throttling valves}}$$

Mixing/Separation Chamber / T junction pipe







Assumptions

$W_B = 0$

Same pressure at all channels

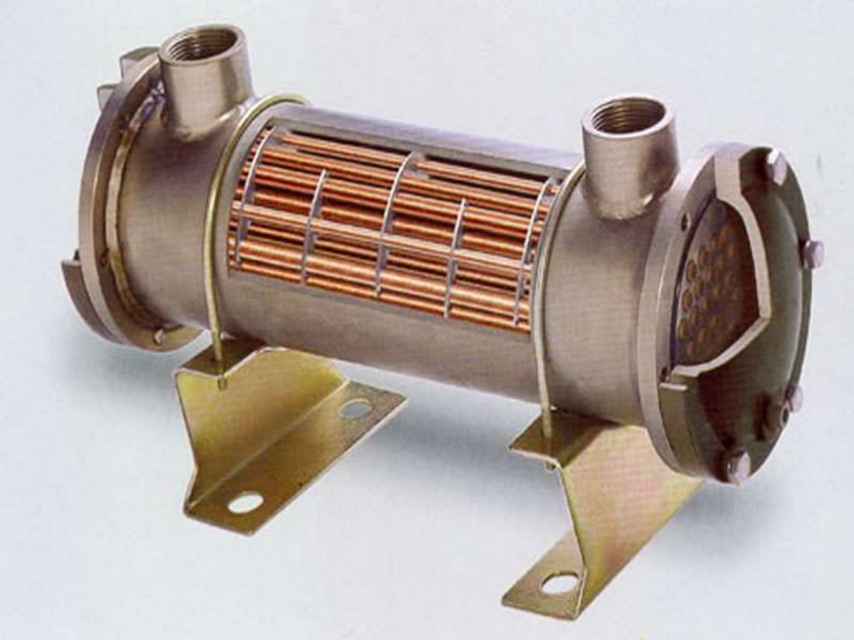
Other assumptions made accordingly

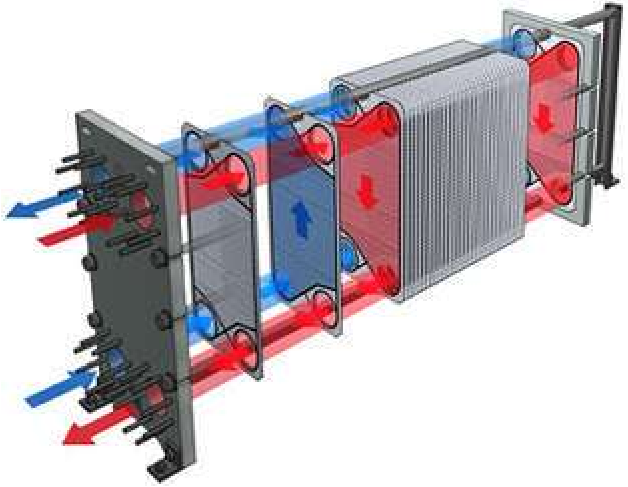
$$\dot{Q} - \dot{W} = \sum_{out} \dot{m}(h + ke + pe) - \sum_{in} \dot{m}(h + ke + pe)$$

also

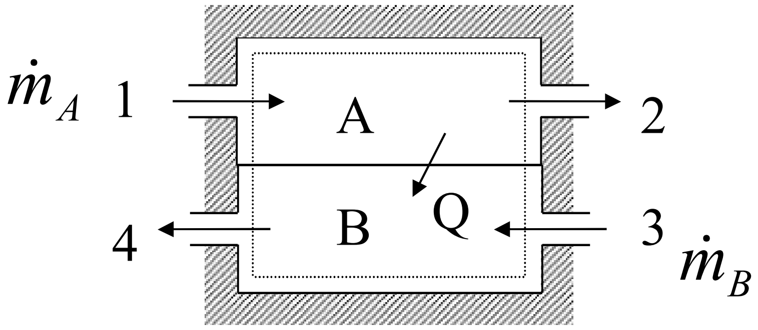
$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$

Heat Exchangers





Heat Exchangers



Assumptions *(System encompasses the whole heat exchanger)*

No work involved, W = 0

Insulated, Q = 0

Δke = 0 , Δpe = 0

$$\cancel{\dot{Q}} - \cancel{\dot{W}} = \sum_{out} \dot{m}(h + \cancel{ke} + \cancel{pe}) - \sum_{in} \dot{m}(h + \cancel{ke} + \cancel{pe})$$

$$\sum \dot{m}_{in} h_{in} = \sum \dot{m}_{out} h_{out}$$

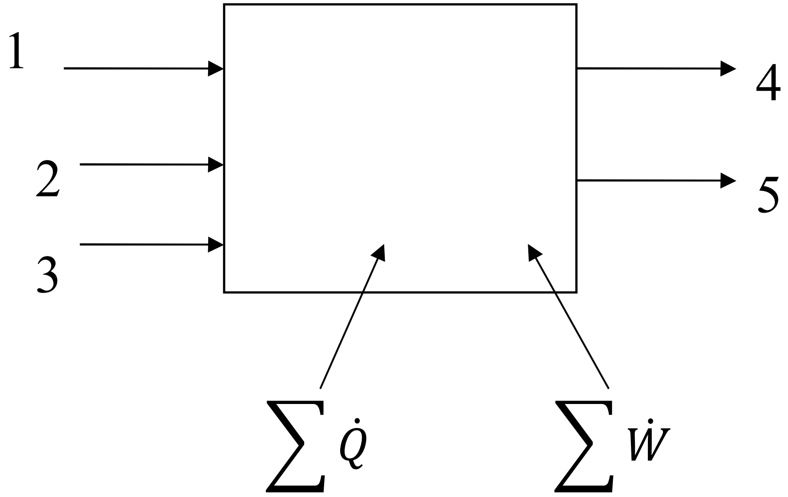
$$\dot{m}_A h_1 + \dot{m}_B h_3 = \dot{m}_A h_2 + \dot{m}_B h_4$$

$$\dot{m}_A \left(h_1 - h_2\right) = \dot{m}_B \left(h_4 - h_3\right)$$

also

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$

General device (Black box analysis)



Assumptions made according to situation...

$$\dot{Q} - \dot{W} = \sum_{out} \dot{m}(h + ke + pe) - \sum_{in} \dot{m}(h + ke + pe)$$

also $$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$