CHAPTER

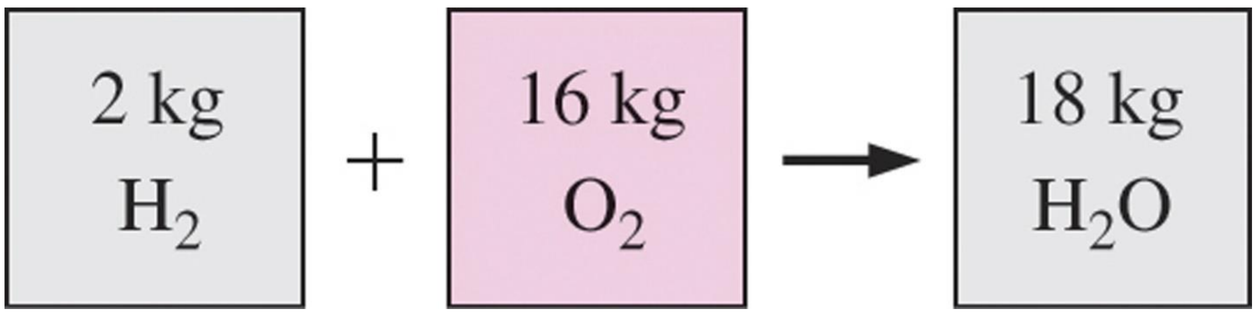
4

The First Law of Thermodynamics for *Control Volumes*

Conservation of mass: Mass, like energy, is a conserved property, and it cannot be created or destroyed during a process.

Closed systems: The mass of the system remain constant during a process.

Control volumes: Mass can cross the boundaries, and so we must keep track of the amount of mass entering and leaving the control volume.



Mass is conserved even during chemical reactions.

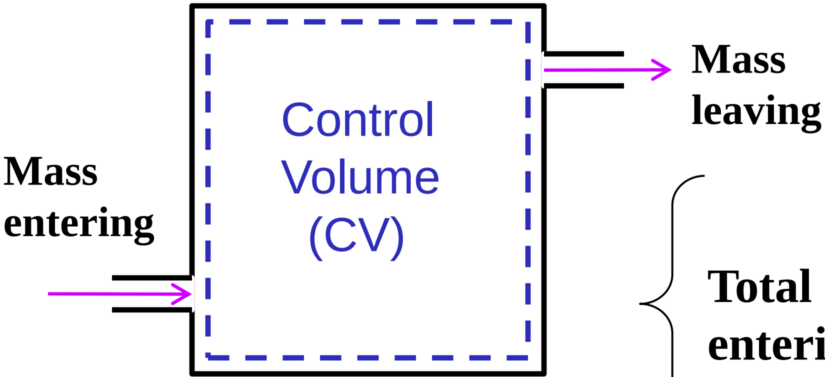
Mass m and energy E can be converted to each other according to $E = mc^2$

where c is the speed of light in a vacuum, which is $c = 2.9979 \times 10^8$ m/s.

The mass change due to energy change is absolutely negligible.

Conservation of mass principle

Control volume can be thought of a region of space through which mass flows.



$$\left\{ \begin{array}{l} \textbf{Total mass} \\ \textbf{entering} \\ \textbf{CV} \end{array} \right\} - \left\{ \begin{array}{l} \textbf{Total mass} \\ \textbf{leaving CV} \end{array} \right\} = \left\{ \begin{array}{l} \textbf{Net change} \\ \textbf{in mass} \\ \textbf{within CV} \end{array} \right\}$$

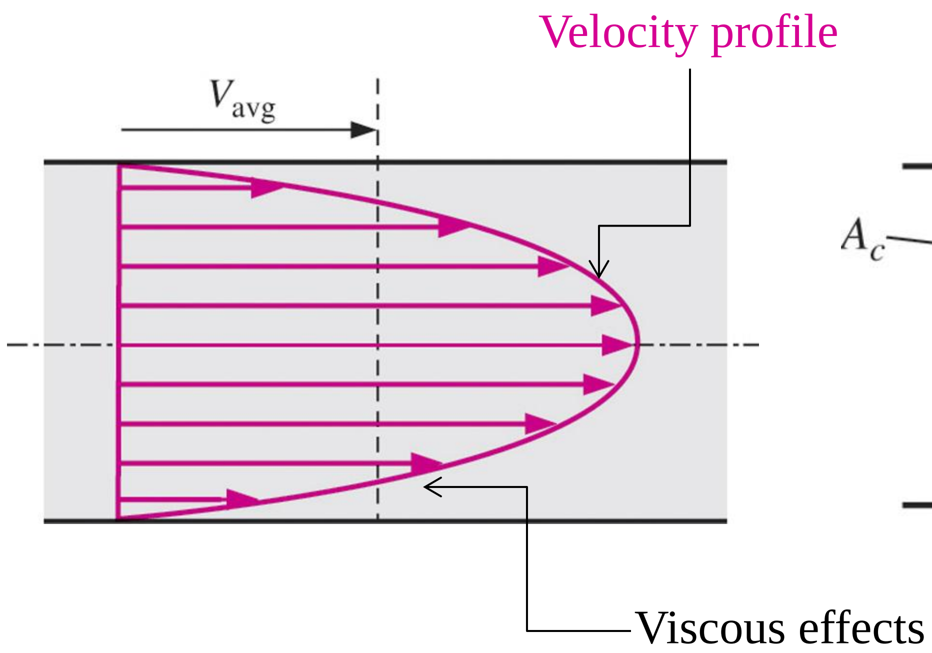
$$\sum m_i - \sum m_e = \Delta m_{\mathrm{CV}}$$

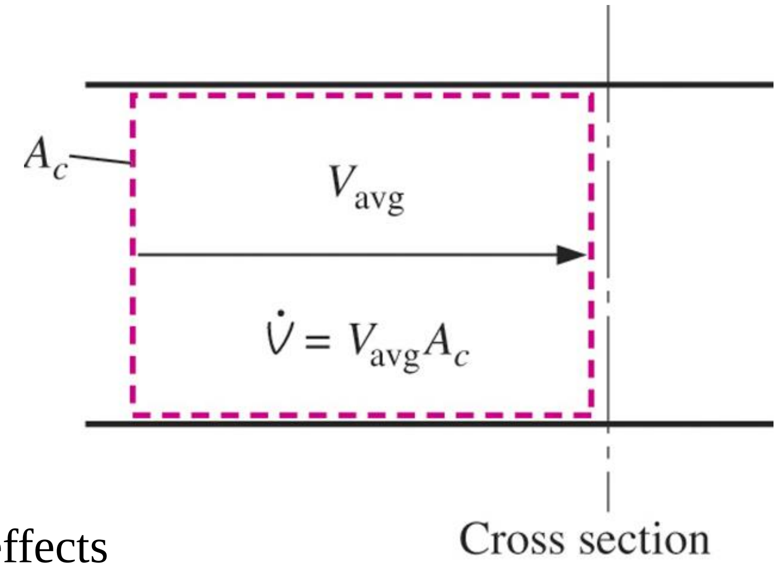
Note: *i*-inlet , *e*-exit , CV-control volume

The rate form $\rightarrow$ $$\sum \dot{m}_i - \sum \dot{m}_e = \Delta \dot{m}_{\mathrm{CV}}$$

where $\dot{m}$ **is mass flow rate, i.e** $\dfrac{dm}{dt}$

Flow through a pipe or duct

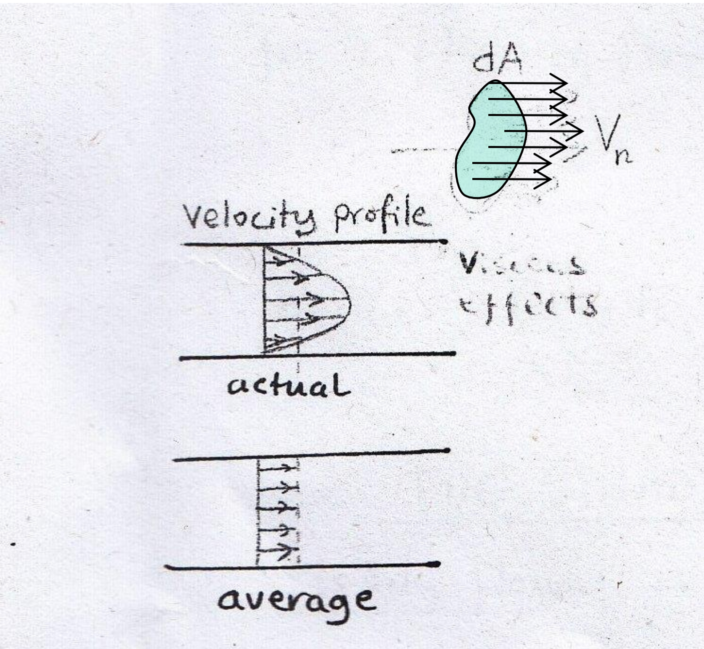




The average velocity V_{avg} is defined as the average speed through a cross section.

The volume flow rate is the volume of fluid flowing through a cross section per unit time.

The **mass flow rate** through a different area *dA* can be expressed as:



$$d\dot{m} = \rho V_n dA$$

Velocity normal to *dA*

$$\dot{m} = \int_A \rho V_n dA \quad (\text{kg/s})$$

$$\dot{m} = \rho V_{avg} A \quad (\text{kg/s})$$

density kg/ m^3 **average fluid velocity normal to *A*,** m/s

The **volume flow rate**:

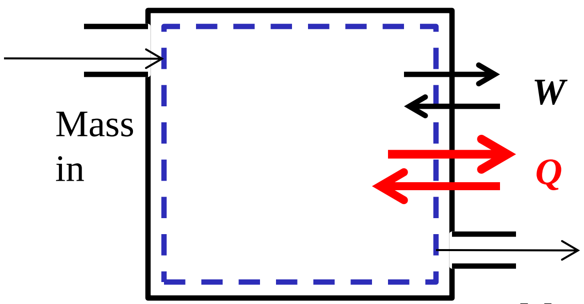
$$\dot{V} = \int_A V_n dA = V_{av} A (m^3/s)$$

The mass and volume flow rates are related by :

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

Conservation of Energy Principle

$$\left\{\begin{array}{l}\textbf{Total energy}\\ \textbf{crossing boundary}\\ \textbf{as heat and work}\end{array}\right\} + \left\{\begin{array}{l}\textbf{Total energy}\\ \textbf{of mass}\\ \textbf{entering CV}\end{array}\right\} - \left\{\begin{array}{l}\textbf{Total energy}\\ \textbf{of mass}\\ \textbf{exiting CV}\end{array}\right\} = \left\{\begin{array}{l}\textbf{Net change}\\ \textbf{in energy}\\ \textbf{of CV}\end{array}\right\}$$



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

This equation can also be expressed in the rate form (i.e. quantities per unit time).

When there is no mass flow in and out of the system, the energy equation reduces to that of a closed system:

$$Q - W = \Delta E$$

Flow work or flow energy

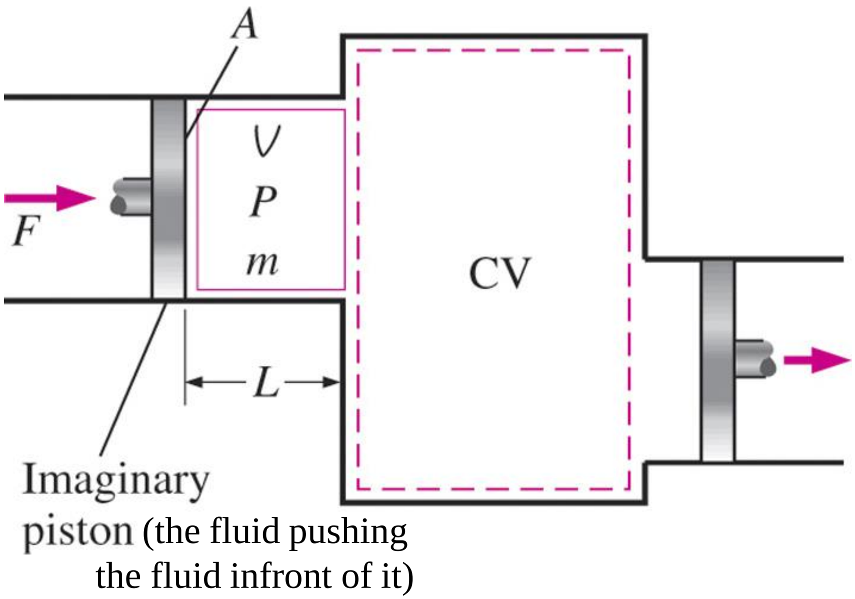
The energy required to push fluid into or out of a control volume.

The force applied on the fluid element : $F = PA$

The work done in pushing the fluid element into the control volume:

i.e. the flow work : $W_{flow} = FL = PAL = PV$ **(kJ)**

On a unit mass basis $w_{flow} = Pv$ **(kJ/kg)**

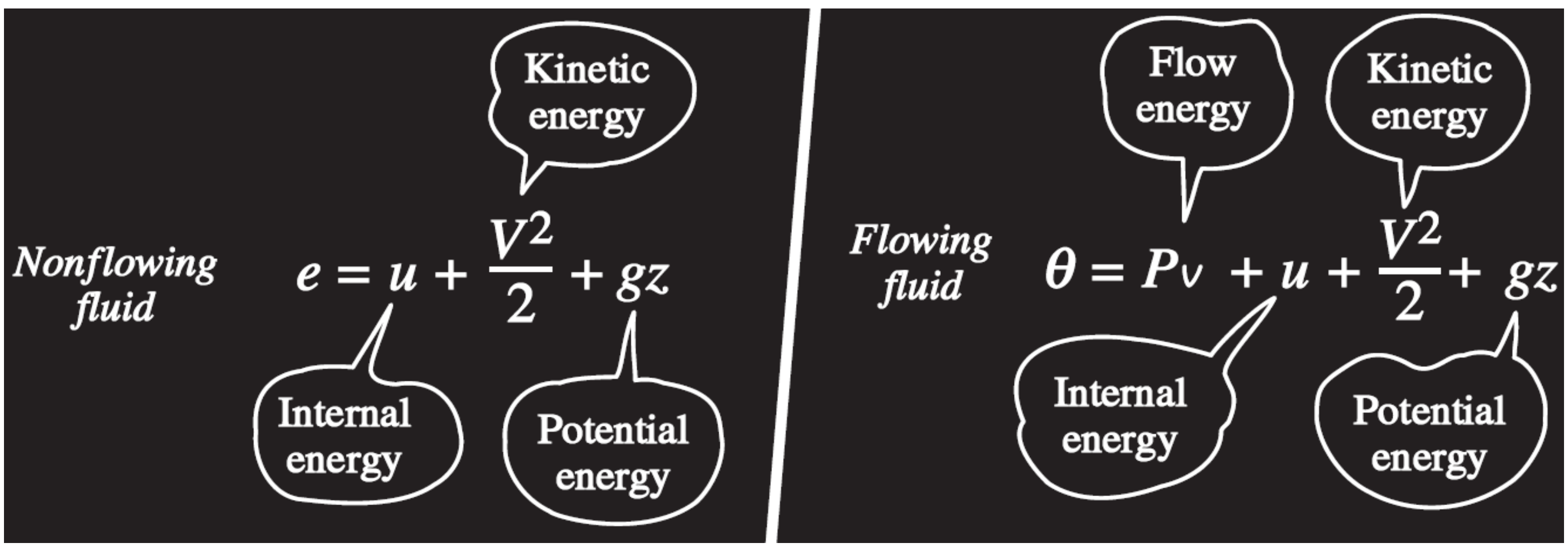


Total Energy of a flowing fluid

For a nonflowing fluid : $e = u + ke + pe = u + \frac{V^2}{2} + gz$ (kJ/kg)

For a flowing fluid the total energy $\theta = Pv + e = \underbrace{Pv + u}_{h} + \frac{V^2}{2} + gz$ (kJ/kg)

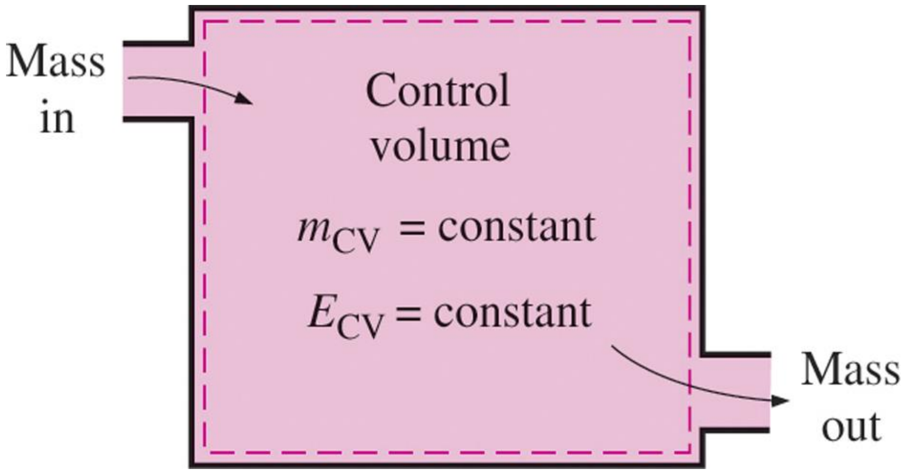
Hence $\theta = h + ke + pe = h + \frac{V^2}{2} + gz$ (kJ/kg)



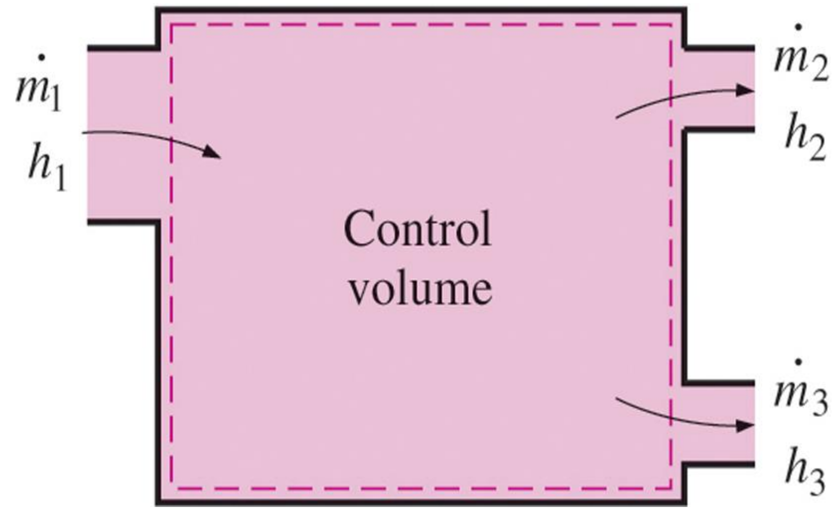
The total energy consists of three parts for a nonflowing fluid and four parts for a flowing fluid.

THE STEADY-FLOW PROCESS

Steady flow is defined such that all properties at each point in a system remain constant with respect to time. (e.g. turbines, compressors, and heat exchangers)

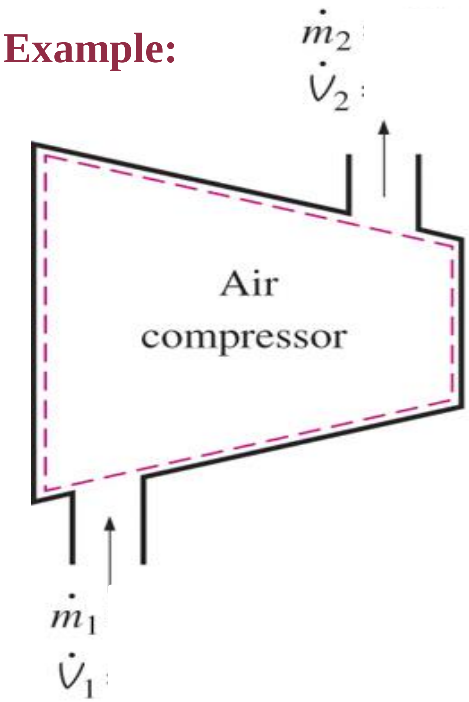


Under steady-flow conditions, the mass and energy contents of a control volume remain constant.



Under steady-flow conditions, the fluid properties at an inlet or exit remain constant (do not change with time).

Example:



Conservation of mass

m_{cv} **= constant for steady-flow process**

$$\sum \dot{m}_i = \sum \dot{m}_e$$

If there is only one inlet and one exit

$$\dot{m}_1 = \dot{m}_2 \text{ (kg/s) or } \rho_1 V_1 A_1 = \rho_2 V_2 A_2 \qquad \textbf{(or } \frac{1}{v_1} V_1 A_1 = \frac{1}{v_2} V_2 A_2 \textbf{)}$$

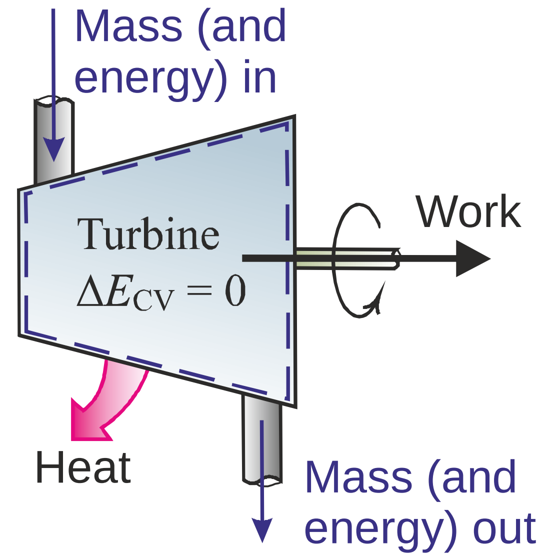
where $\rho = \text{density (kg/m}^3\text{)}$

$v = \text{specific volume (m}^3\text{/kg)}$

$V = \text{average velocity (m/s)}$

$A = \text{cross} - \text{sectional area normal to area (m}^2\text{)}$

Conservation of energy for steady flow



$$E_{CV} = \text{constant} \quad \text{or} \quad \Delta E_{CV} = 0$$

$$\dot{Q} - \dot{W} = \sum \dot{E}_{out} - \sum \dot{E}_{in} + \Delta \dot{E}_{cv}$$

$$\Rightarrow \dot{Q} - \dot{W} = \sum \dot{m}_e \theta_e - \sum \dot{m}_i \theta_i$$

$$\Rightarrow \dot{Q} - \dot{W} = \sum \dot{m}_e \left(h_e + \frac{V_e^2}{2} + g z_e\right) - \sum \dot{m}_i \left(h_i + \frac{V_i^2}{2} + g z_i\right)$$

For one-inlet, one-exit systems(i.e single stream systems):

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

$$\dot{Q} - \dot{W} = \dot{m}\{\underbrace{h_2 - h_1}_{\Delta h} + \underbrace{\frac{V_2 - V_1}{2}}_{\Delta ke} + g(\underbrace{z_2 - z_1}_{\Delta pe})\}$$

In many cases:

$\Delta ke = \Delta pe = 0$

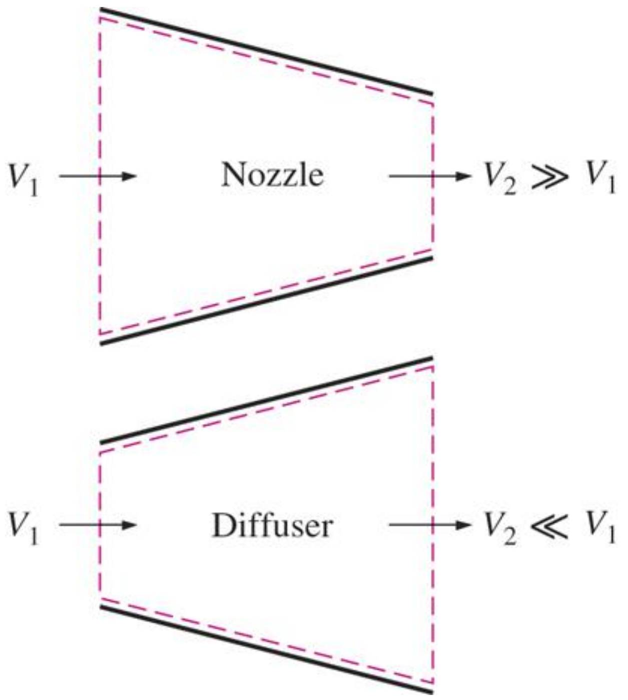
$\Rightarrow q - w = \Delta h$

Some Steady-Flow Engineering Devices

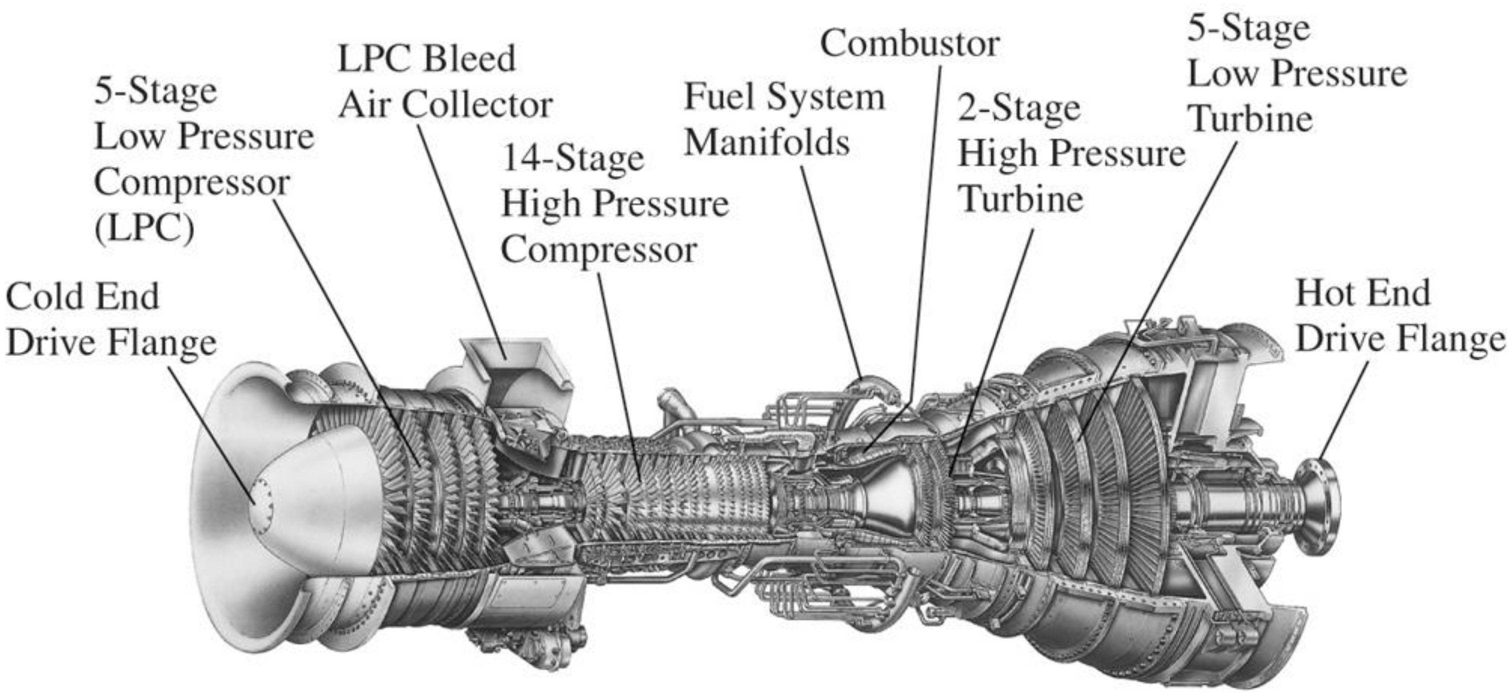
1.Nozzels and Diffusers

$$\cancel{q}^{\,0} - \cancel{w}^{\,0} = \Delta h + \Delta ke + \cancel{\Delta pe}^{\,0}$$

$$0 = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2}$$



2.Turbines and compressors



A modern land-based gas turbine used for electric power production. This is a General Electric LM5000 turbine. It has a length of 6.2 m, it weighs 12.5 tons, and produces 55.2 MW at 3600 rpm with steam injection.

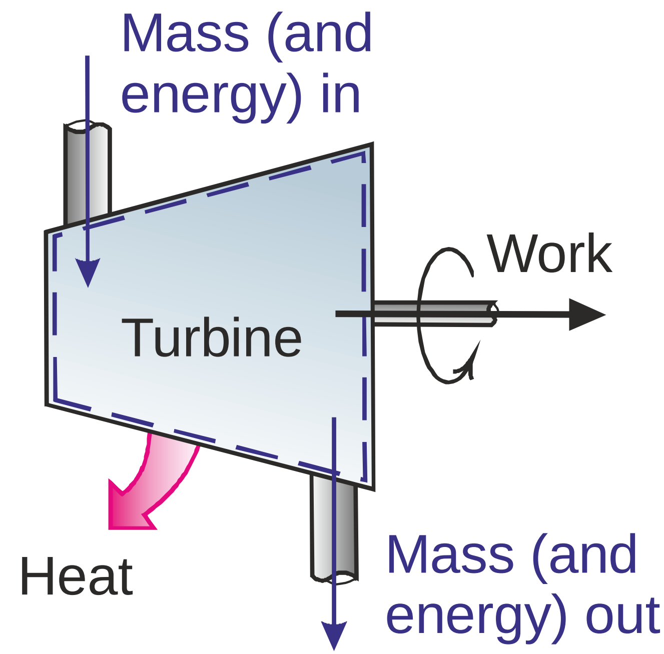
2.Turbines and compressors

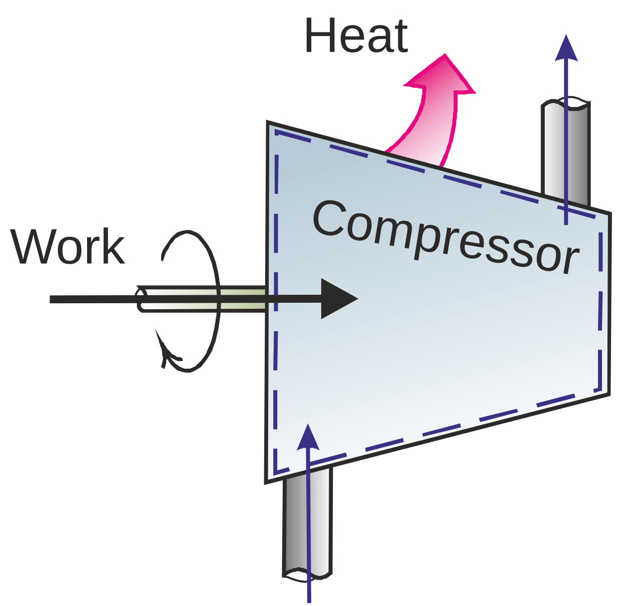
$$q - w = \Delta h + \Delta ke + \Delta pe$$

$$w = -(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2})$$

$$q - w = \Delta h + \cancelto{0}{\Delta ke} + \cancelto{0}{\Delta pe}$$

$$q - w = h_2 - h_1$$





Ex: Steam turbine

For steady flow

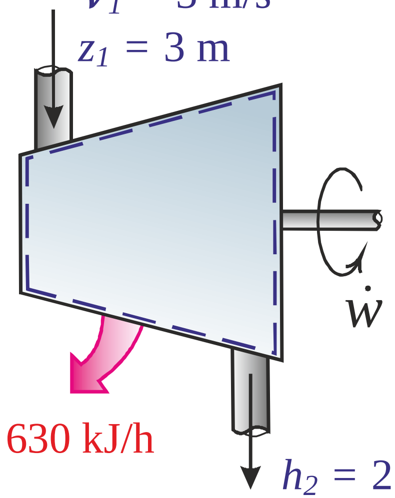
$$\dot m_1 = \dot m_2 = \dot m$$

$$\dot Q - \dot W = \dot m\{h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\}$$

$$\frac{\dot Q}{\dot m} - \frac{\dot W}{\dot m} + (h + \frac{V^2}{2} + gz)_1 - (h + \frac{V^2}{2} + gz)_2 = 0$$

$$\dot m = \frac{600\, {kg}/{hr}}{3600\, \text{sec}/{hr}} = 0.167\, {kg}/\text{sec}$$

$$\dot Q = \frac{630\, {kg}/{hr}}{3600\, \text{sec}/{hr}} = 0.175 kW$$



$$-\frac{0.175\, {kJ}/{s}}{0.167\, {kg}/{s}} - \frac{\dot W}{0.167\, {kg}/{s}} + (3120\, {kJ}/{kg} + \frac{(100\, {m}/{s})^2}{2(1000\, {J}/{kJ})} + \frac{9.81\, {m}/{s^2}}{1000\, {J}/{kJ}}) - (2330\, {kJ}/{kg} + \frac{(130\, {m}/{s})^2}{2(1000\, {J}/{kJ})} + 0) = 0$$

$$\Rightarrow -1.05\, {kJ}/{kg} - \frac{\dot W}{0.167\, {kg}/{s}} + (3120\, {kJ}/{kg} + 5\, {kJ}/{kg} + 0.029\, {kJ}/{kg}) - (2330 + 8.45 + 0) = 0$$

$$\Rightarrow \dot W = +131.183 kW$$

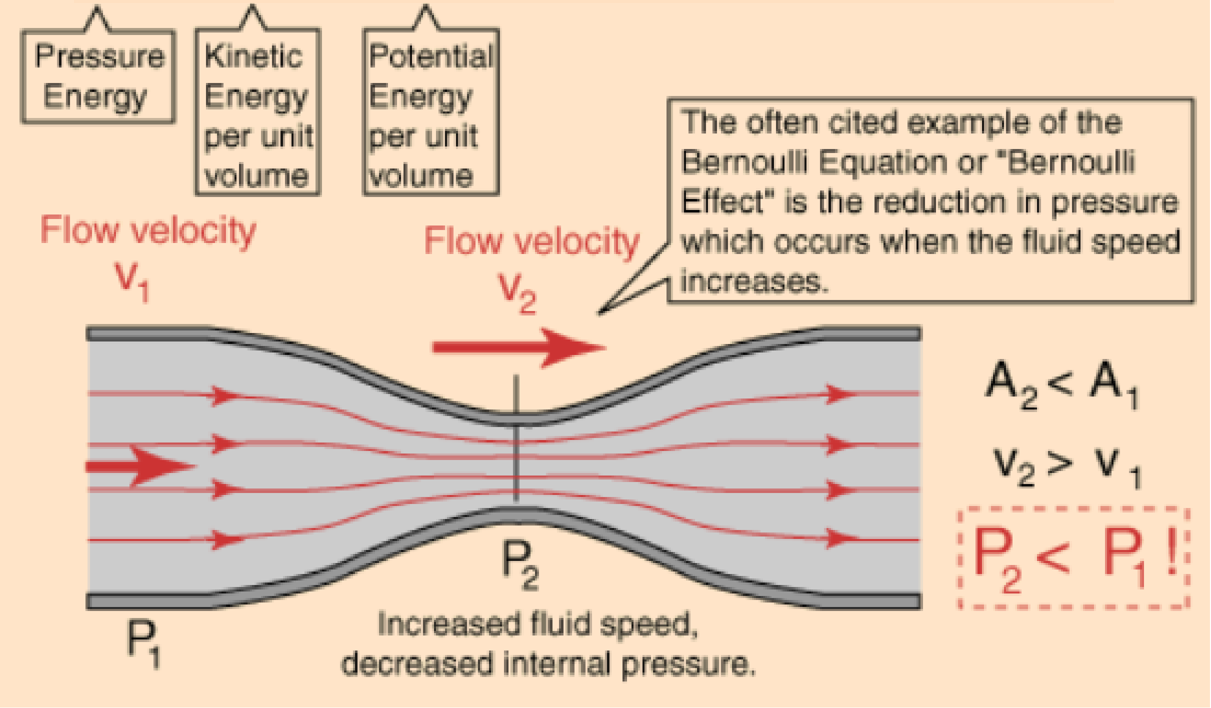
3.Throling Valves

Throttling valves are *any kind of flow-restricting devices* that cause a significant pressure drop in the fluid.

Why there is a pressure drop?

Energy per unit volume before = Energy per unit volume after

$$P_1 + \tfrac{1}{2}\rho v_1^2 + \rho g z_1 = P_2 + \tfrac{1}{2}\rho v_2^2 + \rho g z_2$$



3.Throling Valves

What is the difference between a turbine and a throttling valve?

The pressure drop in the fluid is often accompanied by a *large drop in temperature*, and for that reason throttling devices are commonly used in refrigeration and air-conditioning applications.

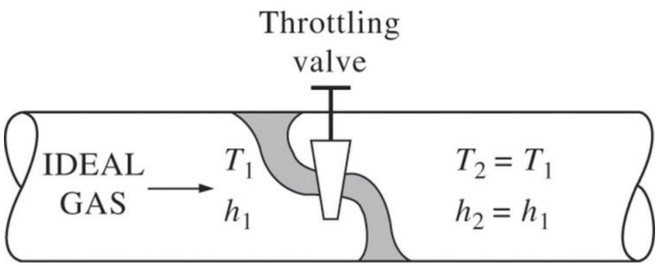
→ Energy balance

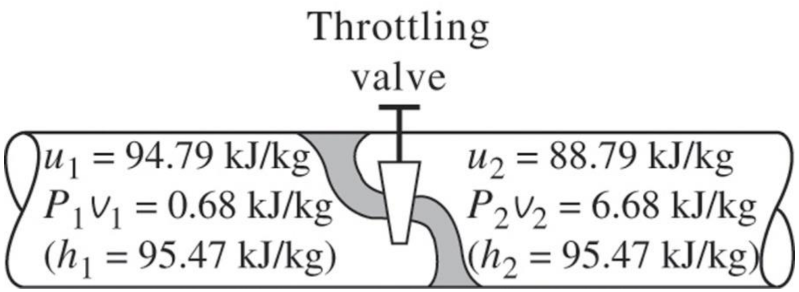
$$\overset{0}{\cancel{q}} - \overset{0}{\cancel{w}} = \Delta h + \Delta \overset{0}{\cancel{ke}} + \Delta \overset{0}{\cancel{pe}}$$

$$\Rightarrow h_2 = h_1$$

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

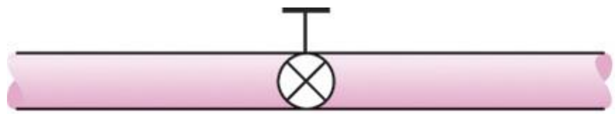
Internal energy + Flow energy = Constant





During a throttling process, the enthalpy of a fluid remains constant. But internal and flow energies may be converted to each other.

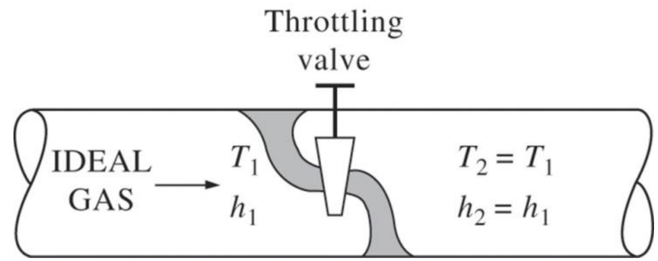
3.Throttling Valves



(*a*) An adjustable valve

(*b*) A porous plug

(*c*) A capillary tube



$$h_2 \cong h_1$$

$$u_1 + P_1v_1 = u_2 + P_2v_2$$

Internal energy +flow =const.

If P_2v_2 increase then u_2 decreases $\longrightarrow$ drop in temperature

If P_1v_1 decrease then u_1 increases $\longrightarrow$ increase in temperature

For an ideal gas, h=h(T) and since $h_1 = h_2$, the temperature does not change $T_1 = T_2$.

4. Heat exchangers

Mass flow rate of fluid A:

Mass flow rate of fluid B:

$$\dot{m}_i = \dot{m}_e = \dot{m}_A$$

$$\dot{m}_i = \dot{m}_e = \dot{m}_B$$

Energy equation for blue CV:

$$\dot{Q} - \dot{W} = \sum \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right) - \sum \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right)$$

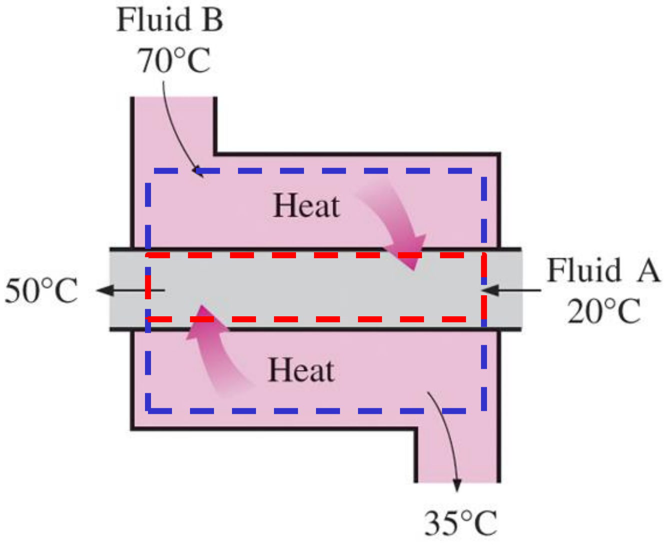
$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$

$$\dot{m}_B h_{Bi} + \dot{m}_A h_{Ai} = \dot{m}_B h_{Be} + \dot{m}_A h_{Ae}$$

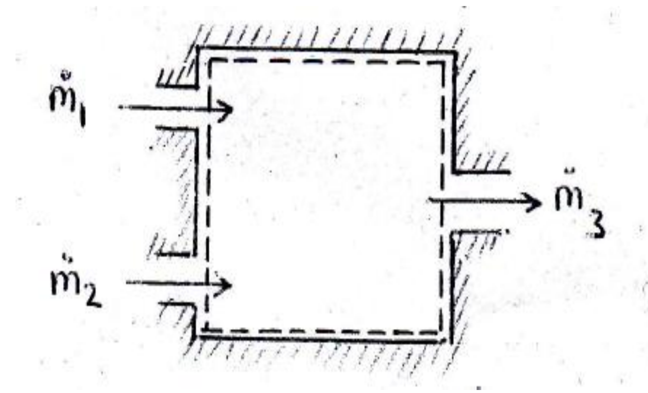
Energy equation for red CV: $\longrightarrow$ **single stream**

$$\dot{Q} - \cancelto{0}{\dot{W}} = \dot{m}_A(\Delta h + \cancelto{0}{\Delta ke} + \cancelto{0}{\Delta pe})$$

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



5.Mixing Chambers



$$\sum \dot{m}_i = \sum \dot{m}_2$$

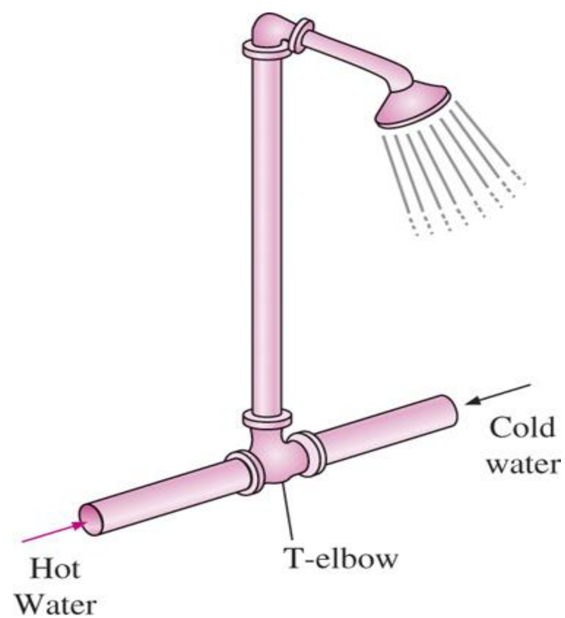
$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \rightarrow \frac{\dot{m}_1}{\dot{m}_2} + 1 = \frac{\dot{m}_3}{\dot{m}_2}$$

$$\cancelto{0}{\dot{Q}} - \cancelto{0}{\dot{W}} = \sum \dot{m}_e \left(h_e + \cancelto{0}{\frac{V_e^2}{2}} + \cancelto{0}{gz_e}\right) - \sum \dot{m}_i \left(h_i + \cancelto{0}{\frac{V_i^2}{2}} + \cancelto{0}{gz_i}\right)$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$

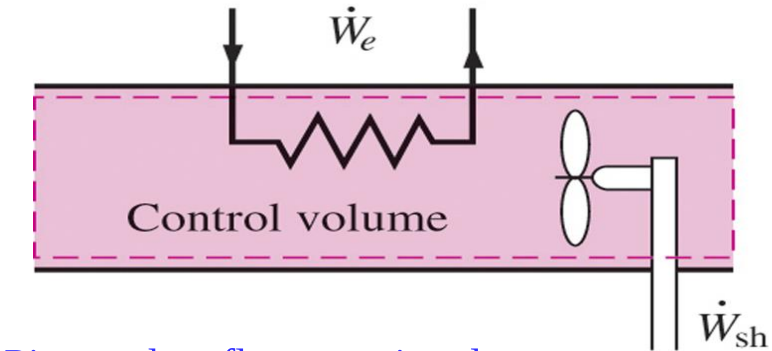
$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$

Divide by $\dot{m}_2$ **and let** $y = \dfrac{\dot{m}_1}{\dot{m}_2} \therefore y\, h_1 + h_2 = (y+1)\, h_3$



The T-elbow of an ordinary shower serves as the mixing chamber for the hot- and the cold-water streams.

6.Pipe and Duct Flow

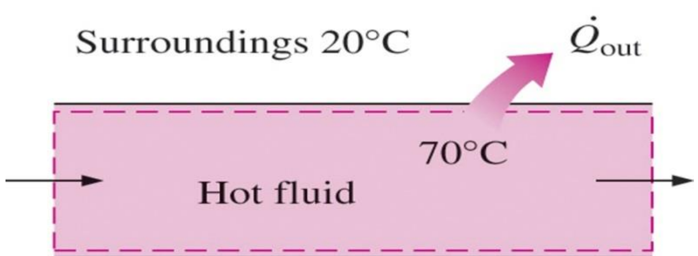


Pipe or duct flow may involve more than one form of work at the same tim

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

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

When air treated as ideal gas

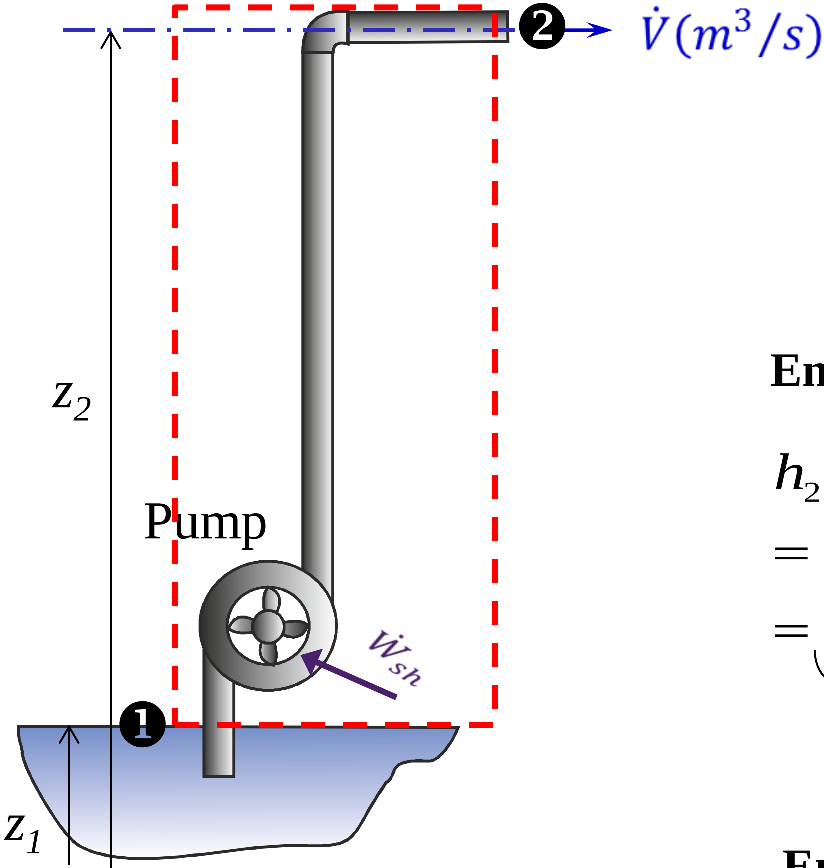


Heat losses from a hot fluid flowing through an uninsulated pipe or duct to the cooler environment may be very significant.

$$v_1 = \frac{RT_1}{P_1}$$

$$\dot{m} = \frac{\dot{V}_1}{v_1}$$

$$\Rightarrow \dot{Q} - \underset{(-\dot{W}_e - W_{sh})}{\underset{\uparrow}{\dot{W}}} = \dot{m}C_p(T_2 - T_1)$$



$$\dot{m} = \rho\dot{V} \qquad \left(\frac{kg}{s}\right)$$

$$V_1 = \frac{\dot{m}}{\rho_1 A_1} \qquad \left(\frac{m}{s}\right)$$

$$V_2 = \frac{\dot{m}}{\rho_2 A_2} \qquad \left(\frac{m}{s}\right)$$

Enthalpy change for incompressible substance:

$$h_2 - h_1 = (u_2 + P_2 v_2) - (u_1 + P_1 v_1)$$

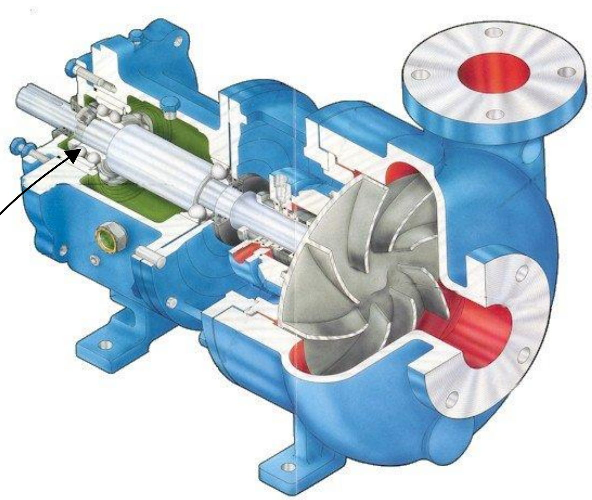
$$= (u_2 - u_1) + v(P_2 - P_1)$$

$$= \underbrace{C(T_2 - T_1)}_{\Delta u} + v(P_2 - P_1)$$

Energy equation becomes:

$$\dot{Q} - \dot{W}_{sh} = \dot{m}\{\, C\,(T_2 - T_1) + v\,(P_2 - P_1) + \frac{\vartheta_2^2 - \vartheta_1^2}{2} + g\,(z_2 - z_1)\}$$

Energy Equation: $\dot{Q} - \dot{W}_{sh} = \dot{m}\left\{C(T_2 - T_1) + v(P_2 - P_1) + \frac{\vartheta_2{}^2 - \vartheta_1{}^2}{2} + g(z_2 - z_1)\right\}$



Electric Pump

When $\dot{Q}$ is neglible and $T_1 = T_2$:

$$\rightarrow \dot{W}_{sh} = \dot{m}\left\{v(P_2 - P_1) + \frac{\vartheta_2{}^2 - \vartheta_1{}^2}{2} + g(z_2 - z_1)\right\}$$

In the case of negligible changes of kinetic and potential energies:

$$\rightarrow \dot{W}_{sh} \approx \dot{V}\{(P_2 - P_1)\}$$

Definition of pump efficiency:

$$\eta_{pump} = \frac{\text{Water (output) Power}}{\text{Shaft (input) Power}} = \frac{\dot{V}(\frac{\text{m}^3}{\text{s}}) \times (P_2 - P_1)\text{kPa}}{\dot{W}_{sh}(\text{kW})}$$

$$\eta_{motor} = \dot{W}_{sh} / \dot{W}_{el}$$

The overall pump efficiency:

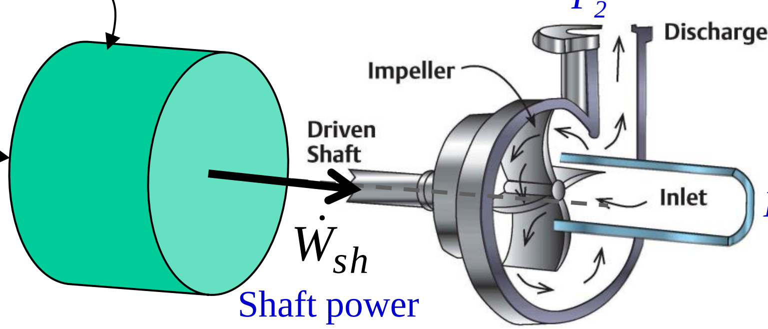
$$\eta_{ov} = \eta_{pump} \times \eta_{motor}$$

Electric motor

$\dot{V}(P_2 - P_1)$ $\left\{\begin{array}{l}\text{Power delivered} \\ \text{to the fluid}\end{array}\right.$

$\dot{W}_{el}$

Electric power



P_2

P_1

$\dot{W}_{sh}$

Shaft power

Electric power consumption:

$$\dot{W}_{el} = \frac{\dot{W}_{sh}}{\eta_{motor}} = \frac{\dot{V} \times (P_2 - P_1)}{\eta_{motor}\eta_{pump}}$$