

## Chapter 2

### Work and Heat

{	•EL 2.1-2.4	Work, Reversibility
	•EL 2.5	Path Properties
	•EL 2.6	Heat Flow
	•EL 2.7	Closed System
	(FR 7.0-7.3)	Energy Balance
	•EL 2.8	Open, Steady-State
	(FR 7.4)	Balance
	•EL 2.10	Enthalpy, Heat Capacities
(FR 8.1-8.3b)	Latent Heats	
(FR 8.4a,c)		
•EL 2.11, 2.12	Process Equipment	
•EL 2.13 (FR 7.6)	Strategies	

*A theory is the more impressive the greater the simplicity of its premises is, the more different kinds of things it relates, and the more extended is its area of applicability. Therefore the deep impression which classical thermodynamics made upon me.*

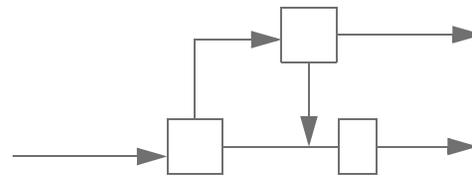
*Albert Einstein*

**The first law of thermodynamics** - energy is conserved. Relates heat, work, mass flow *across boundaries* to  $U$ ,  $KE$ ,  $PE$  of the system.

## *The Mass Balance*

$$\left[ \begin{array}{c} \text{rate of mass} \\ \text{accumulation within} \\ \text{system boundaries} \end{array} \right] = \left[ \begin{array}{c} \text{rate of mass flow} \\ \text{into system} \end{array} \right] -$$

$$\left[ \begin{array}{c} \text{rate of mass flow} \\ \text{out of system} \end{array} \right]$$



$$\dot{m} = \sum_{\text{inlets}} \dot{m}^{\text{in}} - \sum_{\text{outlets}} \dot{m}^{\text{out}}$$

where  $\dot{m} = \frac{dm}{dt}$

$\dot{m}^{in}, \dot{m}^{out}$  = absolute value of mass flow rate entering and leaving, respectively

We may also write

$$dm = \sum_{inlets} dm^{in} - \sum_{outlets} dm^{out}$$

$dm^{in}$  and  $dm^{out} > 0$ .

## ***Work***

- Expansion/Contraction Work
- Shaft Work
- Flow work

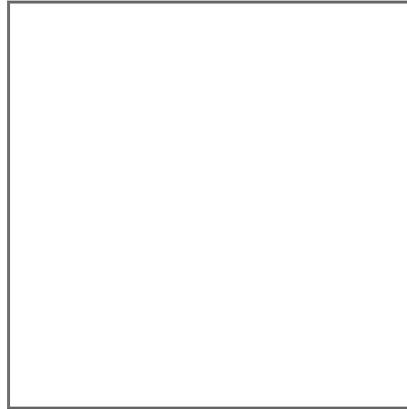
***Expansion/Contraction Work (System must change size)***

$$d\underline{W} = F_{applied}dx = -F_{system}dx$$

$$P = F/A \Rightarrow F = P \cdot A$$

$$\underline{W}_{EC} = -\int P A dx = -\int P d\underline{V}$$

rigid



if lower  $T$ ,  
 $P$  drops

## 2.2 Shaft Work

Work done in pushing and or stirring system.

- Usually involves a pump, turbine, or stirring shaft

The essential feature of shaft work is that work is being added or removed without a change in volume of the *system*. (Fluid may change molar volume as it passes through the system).

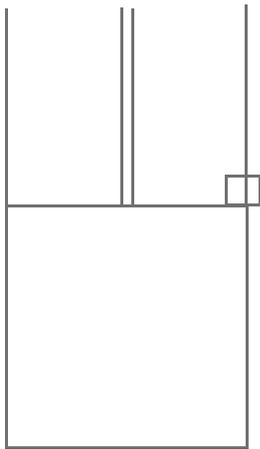
## 2.3 Flow Work

$$\dot{W}_{flow}^{in} = F\dot{x} = PA\dot{x} = P\dot{V} = PV\dot{m}^{in}$$

## *Reversibility*

*Friction* decreases the work available from a process. Frequently we neglect friction to perform a calculation of maximum work.

- perpetual motion?
- velocity gradients,

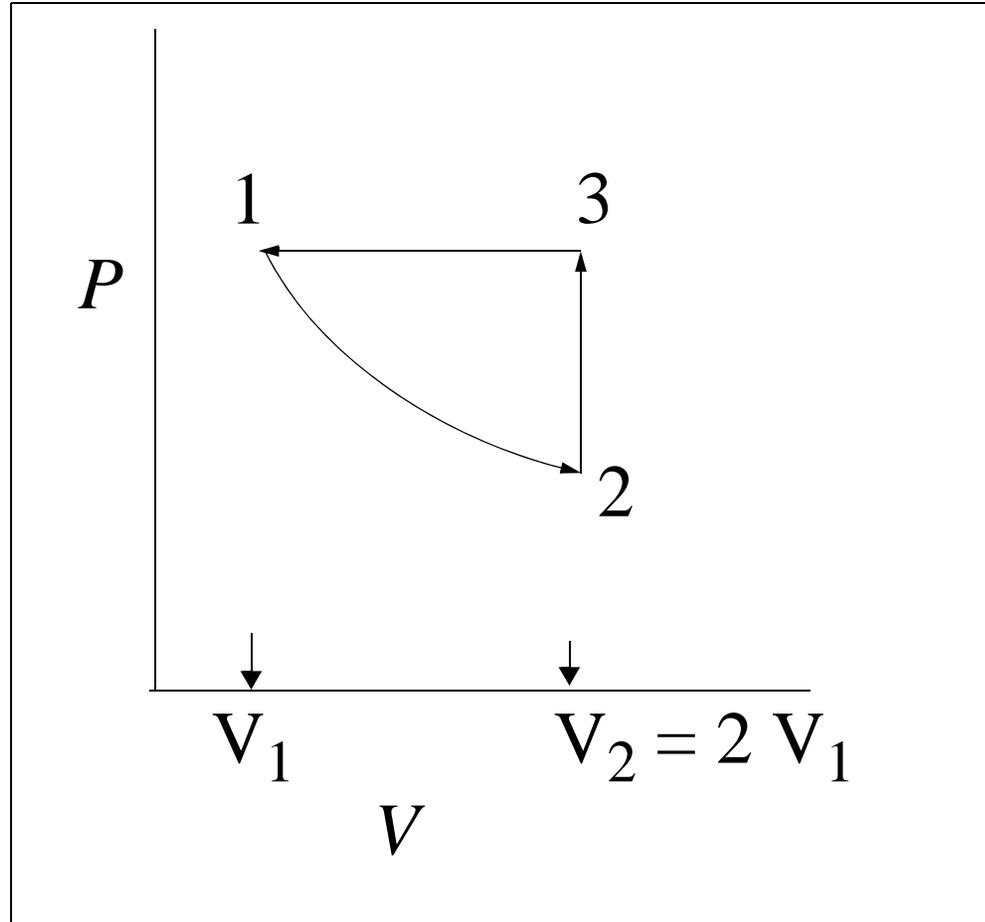


Reversibility by series of equilibrium states

Reversibility by neglecting friction and viscosity

## *Work as a Path Function (Example EL 2.2)*

Find  $\underline{W}_{EC}$  around path:



$$\underline{V}_1 = nRT/P = \frac{1.2 \text{ moles} \mid 8.314 \text{ cm}^3\text{MPa}}{\text{moleK}} \mid \frac{298 \text{ K}}{0.2 \text{ MPa}} =$$

$$14,865 \text{ cm}^3$$

step A) isothermally expand that gas

$$\Rightarrow \underline{W}_{EC} = -\int P d\underline{V} = -nRT_1 \ln(V_2 / V_1) = -2060 \text{ J } (ig)$$

step B) heat at constant volume back to  $P_1$

$$\Rightarrow \underline{W}_{EC} = 0 \text{ (because } d\underline{V} = 0 \text{ for step)}$$

step C) cool isobarically down to  $V_1$

$$\underline{W} = - \int_{V_3}^{V_1} P_1 d\underline{V} = -P_1(\underline{V}_1 - \underline{V}_3)$$

$$= -0.2 \text{ MPa}(-14865 \text{ cm}^3) = 2973 \text{ J}$$

Back to original state.

All state properties returned to their initial values.

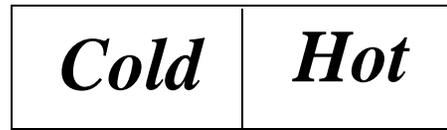
What is the total work done on the system?

$$W_{total} = 2060 + 2973 = 913 \text{ J} \quad (ig)$$

Exercise: Textbook path.  $\underline{W} = -573.6 \text{ J}$

Heat has not been accounted for above.

## *Heat Flow*



$$\underline{Q}_{block1} = -\underline{Q}_{block2}$$

## Chapter 2

### The energy balance and hand calcs

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## ***THE CLOSED-SYSTEM ENERGY BALANCE***

*A closed system is one in which no mass flows in or out of the system.*

*There are only two ways a closed system can interact with the surroundings, via heat and work interactions.*

- By performing enough experiments, we would decide that in fact the sum of heat and work interactions for a *closed* system *is* the energy change of the system!

Differential

$$md \left[ U + \frac{u^2}{2g_c} + \frac{g}{g_c} z \right] = d\underline{Q} + d\underline{W}_S + d\underline{W}_{EC}$$

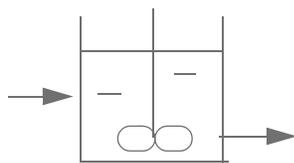
$$\int d \left[ U + \frac{u^2}{2g_c} + \frac{g}{g_c} z \right] = \int dQ + \int dW_S + \int dW_{EC}$$

Integral

$$\Delta(U + KE + PE) = Q + W_S + W_{EC}$$

*See example 2.3 (transfer of heat between blocks)  
several important point about boundaries,  
assumptions.*

## *Open Steady-State System Balance*

$$0 = \sum_{inlets} \left[ U + \frac{u^2}{2g_c} + \frac{gz}{g_c} \right]^{in} \dot{m}^{in} - \sum_{outlets} \left[ U + \frac{u^2}{2g_c} + \frac{gz}{g_c} \right]^{out} \dot{m}^{out} + \underline{\dot{Q}} + \underline{\dot{W}}_S + \underline{\dot{W}}_{flow}$$


$$0 = \sum_{inlets} \left[ U + PV + \frac{u^2}{2g_c} + \frac{gz}{g_c} \right]^{in} \dot{m}^{in} - \sum_{outlets} \left[ U + PV + \frac{u^2}{2g_c} + \frac{gz}{g_c} \right]^{out} \dot{m}^{out} + \underline{\dot{Q}} + \underline{\dot{W}}_S$$

**Enthalpy**

$$H \equiv U + PV$$

$$0 = \sum_{inlets} \left[ H + \frac{u^2}{2g_c} + \frac{gz}{g_c} \right]^{in} \dot{m}^{in} - \sum_{outlets} \left[ H + \frac{u^2}{2g_c} + \frac{gz}{g_c} \right]^{out} \dot{m}^{out} + \underline{\dot{Q}} + \underline{\dot{W}}_S$$

*Single stream, KE and PE changes small*

$$0 = -\Delta H\dot{m} + \underline{\dot{Q}} + \underline{\dot{W}}_S$$

$$0 = -\Delta H + Q + W_S$$

Need to relate  $U$ ,  $H$  to  $T$ ,  $P$ ,  $V$  --- *Heat capacities*

Constant volume heat capacity:

$$C_v \equiv \left( \frac{\partial U}{\partial T} \right)_V$$

Constant pressure heat capacity:

$$C_p \equiv \left( \frac{\partial H}{\partial T} \right)_P$$

## Relations between $C_P$ and $C_V$

$$C_P = C_V + R \quad \text{Ideal gases.} \quad (ig)$$

Nonideal gases - defer relation. (Use tables/charts rather than heat capacities for  $H$ ,  $U$ ).

$\Delta U = \int_{T_1}^{T_2} C_V(T) dT$	Ideal gas: exact. Real gas: valid only if $V = \text{constant}$ .
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$$\Delta H = \int_{T_1}^{T_2} C_P(T) dT$$

Ideal gas: exact.

Real gas: valid only  
if  $P = \text{constant}$ .

$$\Delta H = \int_{T_1}^{T_2} C_P(T) dT + V\Delta P$$

Liquid below  $T_r = 0.75$  or solid: reasonable approximation.

$C_P^L$  not equal to  $C_P^V$ ,

\* in text (EL)

## *Latent Heat*

- Enthalpy change associated with phase change at constant T, P is *heat of vaporization*.
- For melting -- *heat of fusion*.
- see appx FR or EL

Heat liquid propanol (25°C) (1) to 150°C at 1 bar (2).  
(boils at 98°C at 1 bar)

## Summary of Expansion Contraction Work for *ig*.

### Isothermal

$$W_{EC} = -\int_{V_1}^{V_2} P dV = RT \ln(V_2/V_1) \quad (ig)$$

### Isobaric

$$W_{EC} = -\int_{V_1}^{V_2} P dV = -P(V_2 - V_1)$$

### Adiabatic

$$W_{EC} = -\int_{V_1}^{V_2} P dV = -Q = C_V(T_1 - T_2) \quad (*ig)$$

where

$$(T_2/T_1) = (P_2/P_1)^{R/C_p} = (V_1/V_2)^{R/C_v} \quad (*ig)$$

Isochoric  $W_{EC} = 0$

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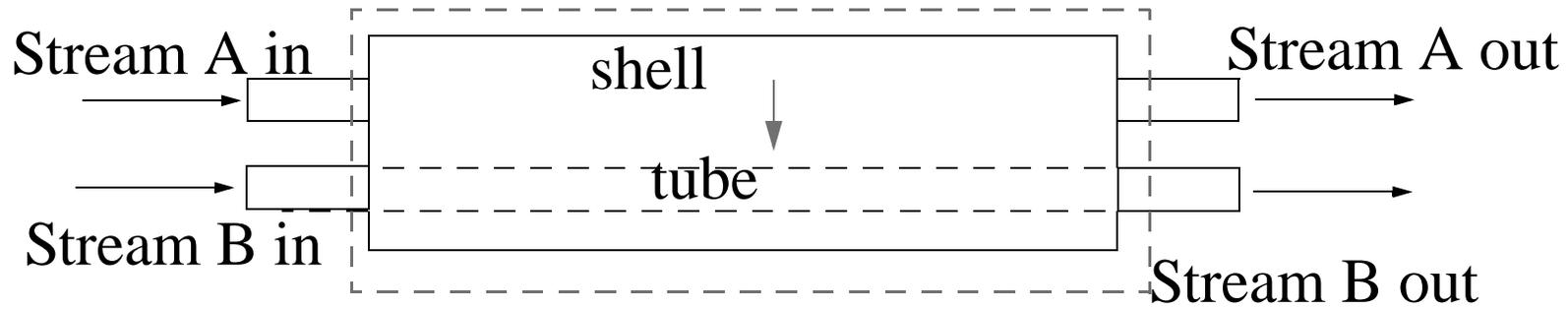
## ***Throttles (Joule-Thomson expansion)***

$$0 = \left[ H + \frac{u^2}{2g_c} + \frac{gz}{g_c} \right]^{in} \dot{m}^{in} - \left[ H + \frac{u^2}{2g_c} + \frac{gz}{g_c} \right]^{out} \dot{m}^{out} +$$
$$\cancel{\dot{Q}} + \cancel{\dot{W}_{EC}} + \cancel{\dot{W}_S}$$

## ***Nozzles***

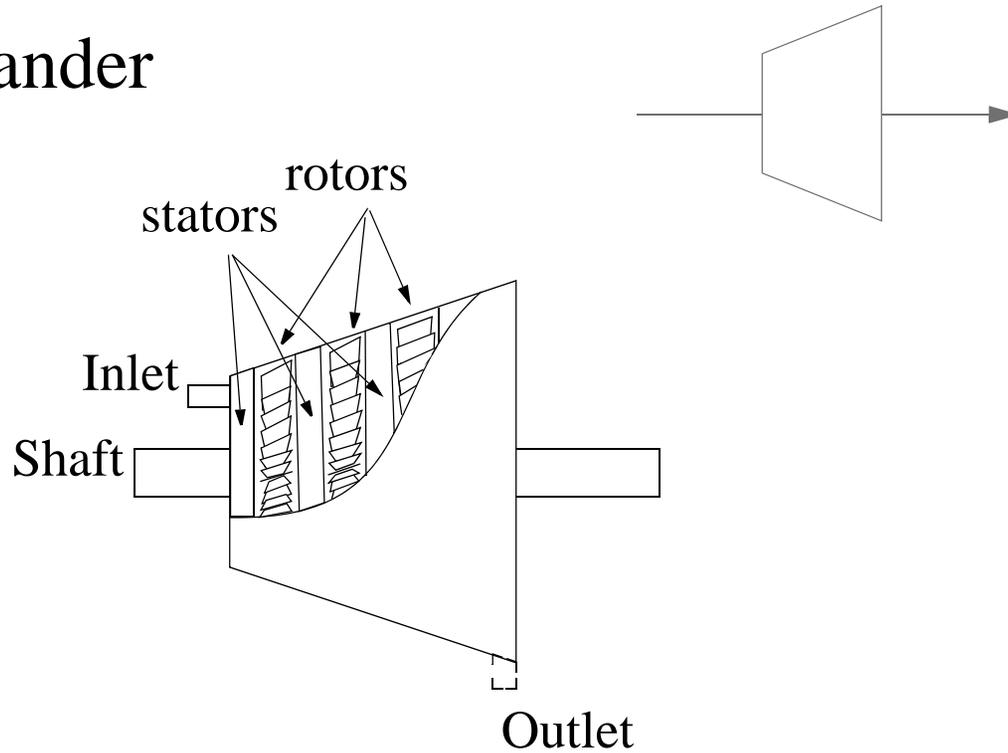
$$0 = \left[ H + \frac{u^2}{2g_c} + \frac{gz}{g_c} \right]^{in} \dot{m}^{in} - \left[ H + \frac{u^2}{2g_c} + \frac{gz}{g_c} \right]^{out} \dot{m}^{out} +$$
$$\cancel{\dot{Q}} + \cancel{\dot{W}_{EC}} + \cancel{\dot{W}_S}$$

# Heat Exchanger



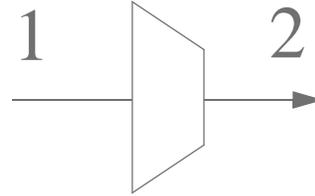
*Illustration of a generic heat exchanger with a cocurrent flow pattern.*

# Turbine or Expander



$$0 = \left[ H + \frac{u^2}{2g_c} + \frac{gz}{g_c} \right]^{in} \dot{m}^{in} - \left[ H + \frac{u^2}{2g_c} + \frac{gz}{g_c} \right]^{out} \dot{m}^{out} + \dot{Q} + \dot{W}_{EC} + \dot{W}_S$$

## *Pumps/Compressors*



Similar to turbines/expanders

Pump (liquid) (adiabatic)

$$0 = \dot{m}H_1 - \dot{m}H_2 + \underline{\dot{W}}_S$$

$$\dot{m}\Delta H = \underline{\dot{W}}_S \quad \Delta H = W_S$$

## Chapter 2 Strategies

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## *Strategies*

1. Choose boundaries; decide **open or closed**.

2. **steady or unsteady-state?**

• For open, steady-state systems, solve mass balance and **if possible**.

3. How many state variables are needed?

#### **4.Simplify energy balance.**

For unsteady-state problems:

Closed system-- integrate the accumulation of energy directly without combining with other energy balance terms.

5.Look for *key words*:

**adiabatic, isolated, throttling, nozzle, reversible, irreversible.**

6. Introduce the thermodynamic properties of the fluid (the equation of state). **This provides all equations relating  $P, V, T, U, H, C_P, C_V$ .** Either 1) the ideal gas approximation; 2) a thermodynamic chart or table; or 3) a volumetric equation of state (which will be introduced in Chapter 6). Try to avoid using more than one model.

Combine with energy balance.

7. Move boundary if necessary. Try overall balance.

8. Verify assumptions when done.