

THERMO MIDTERM I STUDY GUIDE

WORK

the work W done by, or on, a system evaluated in terms of macroscopically observable forces and displacements is

$$W = \int_{s_1}^{s_2} F \cdot d\mathbf{z}$$

- compression/expansion of gas/liquid
- extension of solid bar
- stretching of liquid film

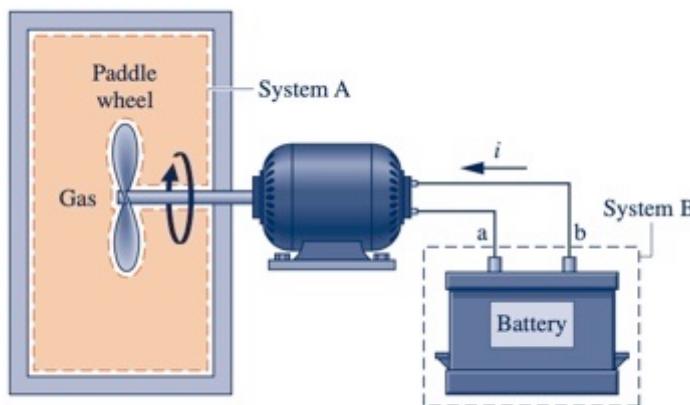
* THERMODYNAMIC DEFINITION OF WORK *

work is done by a system on its surroundings if the sole effect on everything external to the system could have been the raising of a weight. The raising of a weight is a force acting through a distance so the concept of work in thermodynamics is a natural extension of the concept of work in mechanics.

↳ the test of whether a work interaction has taken place is not that the elevation of a weight has actually taken place, or that a force has actually acted through a distance, but that the sole effect could have been an increase in the elevation of a weight.

SYSTEM A

- paddle wheel does work on gas (bc work could be evaluated in terms of forces & motions at boundary between paddle wheel and gas, which is consistent with force & displacement)



SYSTEM B:

- only battery
- at boundary, no forces/motion
- but! electric current driven by electrical potential difference existing across terminals a & b
- we can imagine current supplied by a hypothetical motor that lifts weight in the surroundings

WORK is a means of transferring energy.

- work doesn't refer to what is being transferred between systems or to what is stored within systems.
- energy is transferred and stored when work is done.

$W > 0$... work done by the system

$W < 0$... work done on the system

The value of **WORK** depends on the details of the interactions taking place between the system and surroundings during a process and not just the initial and final states of the system.

- ∴ work is not a property of the system or surroundings
- while the limits on the integration mean from state 1 to state 2 they cannot be interpreted as the values of work at these states
- the notion of work at a state has no meaning, so can't say $W_2 - W_1$ for example

δW : THE DIFFERENTIAL OF WORK is inexact because $\int \delta W = W$ can't be evaluated without specifying details of the process

↳ however, the differential of a property is exact because the change in a property between 2 particular states depends in no way on the details of the process linking the two states

→ ex. change in θ between 2 states can be determined by integrating the differential $d\theta$ without regard for details of the process

$$\int_{t_1}^{t_2} dt = t_2 - t_1$$

→ the differential of every property is exact
 δ = inexact d = exact ... differentials

POWER

rate of energy transfer by work, denoted as \dot{W}

→ when a work interaction involves a macroscopically observable force, rate of energy transfer by work is equal to product of force and velocity at point of application of force

$$\dot{W} = \underbrace{F}_{\sim} \cdot \underbrace{V}_{\sim}$$

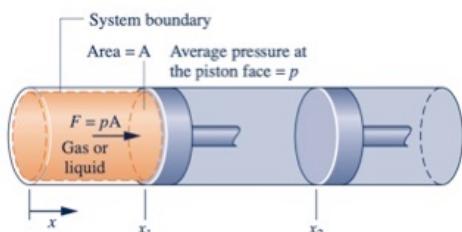
$$W = \int_{t_1}^{t_2} \dot{W} dt = \int_{t_1}^{t_2} F \cdot V dt$$

→ same sign convention as work

$$SI: \frac{\text{J}}{\text{s}} = \text{Watt} \quad \text{English: } \frac{\text{ft} \cdot \text{lbf}}{\text{s}}, \frac{\text{Btu}}{\text{hr}}, \text{hp}$$

Modeling Expansion or Compression Work

1. gas (or liquid) contained in piston-cylinder assembly as gas expands



During the process, the gas pressure exerts a normal force on the piston
 p = pressure acting at interface between gas & piston

Work done by system as piston displaced a distance dx $\rightarrow \delta W = pAdx$

$$\text{Since } Adx = dV \Rightarrow \delta W = pdV$$

Since $dV \oplus$ when $V \uparrow$, work at moving boundary is \oplus when gas expands

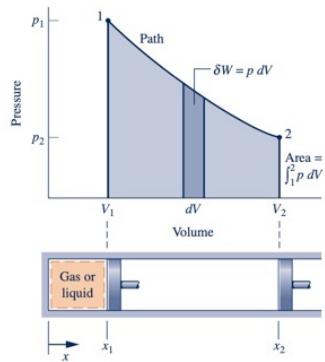
For compression, $dV \ominus$ and work \ominus

$$W = \int_{x_1}^{x_2} pdV$$

← this is applicable to systems of any shape provided pressure is uniform w/position over moving boundary

There's no requirement that a system undergoing a process be in equilibrium during the process. Some or all of the intervening states may be nonequilibrium states. For many processes, we are limited to knowing the state before the process occurs and the state after the process is completed.

Processes are sometimes modeled as an idealized type of process called a **Quasiequilibrium** (or **quasistatic**) process, which is one in which the departure from thermodynamic equilibrium is at most infinitesimal. All states through which the system passes in a quasiequilibrium process may be considered equilibrium states.



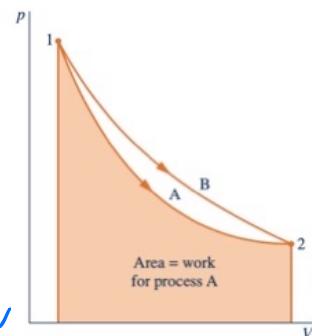
Initially piston face at position x_1 and pressure p_1 . At the conclusion of a quasiequilibrium expansion process the piston face is at position x_2 and pressure reduced to p_2 . At each intervening piston position, the uniform pressure throughout the gas is shown as a point. The path connecting states 1 and 2 represents the equilibrium states through which the system has passed during the process. Work done by gas on piston during the expansion is $\int p dt$, which is the area under the curve of pressure vs. volume.

*Had the gas been compressed from 2 to 1 along the same path, the magnitude of the work would be the same but the sign would be \ominus , indicating that for compression the energy xfer was from the piston \rightarrow the gas.

WORK DEPENDS ON THE PROCESS

Suppose gas in piston-cylinder assembly goes from an initial equilibrium state 1 to a final equilibrium state 2 along two different paths A and B. Since area beneath each path represents work for that process, work depends on the details of the process as defined by the particular curve and not just on the end states.

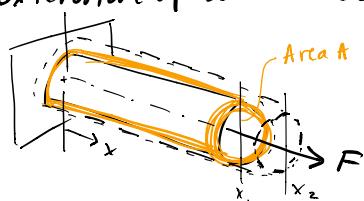
∴ WORK IS NOT A PROPERTY. THE VALUE OF WORK DEPENDS ON THE NATURE OF THE PROCESS BETWEEN THE END STATES



Polytropic Process

a quasiequilibrium process described by $pV^n = C$ or $pr^n = C$

2. Extension of a Solid Bar



The work done as the end of the bar moves a distance dx is given by $\Delta W = -\sigma A dx$. The \ominus sign is required bc work is done on the bar when dx is \oplus

$$W = - \int_{x_1}^{x_2} \sigma A dx$$

3. Stretching of a liquid film

$$\Delta W = -2/\tau dx \text{ where } \tau \text{ is surface tension}$$

⊖ sign required bc work done on system when $dx \oplus$

$$W = - \int_{A_1}^{A_2} \tau dA$$

↗ increase in
surface area

4. Power Transferred By a Shaft

$$\dot{W} = F_t V = (\tau/R)(R\omega) = \tau\omega$$

F_t = tangential force R = radius τ = torque

$$\tau = F_t R$$

V = velocity = $R\omega$ where ω in rad/sec (angular velocity)

5. Electric Power

$$\dot{W} = -Ei$$

$$\Delta W = -Edz$$

E = potential diff across terminals i = current = $\frac{dz}{dt}$

dz = amount of electrical charge that flows into system

⊖ required

Broadening Understanding of Energy

- when work is done to compress a spring, energy is stored w/in the spring
- when battery is charged, energy stored w/in it is increased
- when a gas (or liquid) initially at an equilibrium state in a closed, insulated vessel is stirred vigorously and allowed to come to a final equilibrium state, the energy of the gas is increased in the process

* in each of these examples the change in system energy cannot be attributed to changes in the system's overall KE or PE. The change in energy can be accounted for in terms of internal energy

INTERNAL ENERGY

all other energy changes besides PE & KE lumped together; internal energy is an extensive property of the system, as is the total energy

The change in total energy of a system is

$$E_2 - E_1 = (U_2 - U_1) + (KE_2 - KE_1) + (PE_2 - PE_1)$$

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

Ex. Gas inside a tank: microscopic interpretation of internal energy

- gas molecules move about, encountering other molecules or the walls of the container
- part of the internal energy of the gas is the translational KE of the molecules
- KE due to rotation of molecules relative to their centers of mass and KE associated w/vibrational motions w/in molecules also contribute to U
- energy stored in chemical bonds between atoms that make up the molecules
- energy storage on the atomic level (nuclear spin, electron orbital states)

Energy transfer by Heat

→ closed systems can also interact w/their surroundings in a way that can't be categorized as work... when a gas in a rigid container interacts w/a hot plate, energy of gas is increased even though no work is done

$\dot{Q} > 0$: heat transfer into the system
 $\dot{Q} < 0$: heat transfer from the system

→ value of **heat transfer** depends on the details of a process and not just the end states

$$Q = \int_{S_1}^{S_2} \dot{Q}$$

the limits mean from state 1 to state 2, but not values of heat like work, notion of "heat" at a state has no meaning and the integral should never be evaluated as $Q_2 - Q_1$.

HEAT IS NOT A PROPERTY

NET RATE OF HEAT TRANSFER, \dot{Q} — amount of energy xfer by heat during a period of time

$$\dot{Q} = \int_{t_1}^{t_2} \dot{\dot{Q}} dt$$

in some cases it's convenient to use heat flux, \dot{q} which is heat transfer rate per unit of system surface area, so the net rate of heat transfer \dot{Q} related to heat flux \dot{q}

$$\dot{Q} = \int_A \dot{q} dA$$

units for **heat transfer** Q and **heat transfer rate** \dot{Q} as same as for **work** W and **Power** \dot{W}

units for heat flux are those of heat transfer rate per unit area (kw/m^2 or Btu/hr.ft^2)

ADIABATIC

means w/out heat transfer, so if a system undergoes a process involving no heat transfer w/its surroundings, this process is called an **adiabatic process**.

Heat Transfer Modes

1. Conduction
2. Radiation
3. Convection

CONDUCTION

- energy xfer by conduction can take place in solids, liquids, and gases
- xfer of energy from the more energetic particles of a substance to adjacent particles that are less energetic due to interactions between particles
- **Fourier's Law** - time rate of energy transfer by conduction is quantified macroscopically by F's Law
- ex. plane wall of thickness L at steady-state (ss) where temperature $T(x)$ varies linearly w/position x
↳ rate of heat transfer across any plane normal to the x direction, \dot{Q}_x is proportional to the wall area, A , and the temperature gradient in the x direction dT/dx :

$$\dot{Q}_x = -KA \frac{dT}{dx} \quad K = \text{proportionality constant, property called thermal conductivity}$$

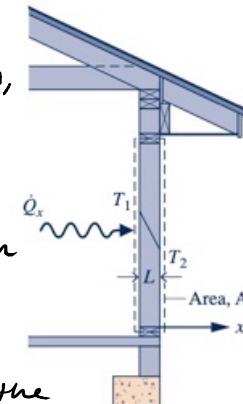
② sign consequence of energy transfer in direction of decreasing temperature

- in the picture, temp varies linearly so the temperature gradient is $\frac{dT}{dx} = \frac{T_2 - T_1}{L} (< 0)$

and the rate of heat transfer in x direction is then

$$\dot{Q}_x = -KA \left[\frac{T_2 - T_1}{L} \right]$$

- substances w/large values of thermal conductivity such as copper are GOOD CONDUCTORS, those w/small conductivities (cork, polystyrene foam) are GOOD INSULATORS

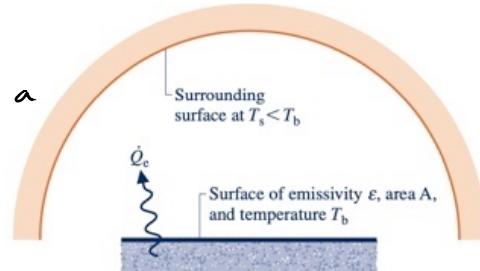


RADIATION

- thermal radiation is emitted by matter as a result of changes in the electronic configurations of the atoms or molecules w/in it
- energy is transported by electromagnetic waves (or photons)
- unlike conduction, thermal radiation requires no intervening medium to propagate and can take place in a vacuum
- solid surfaces, gases, and liquids all emit, absorb, and transmit thermal radiation to varying degrees
- \dot{Q}_e rate at which energy is emitted from a surface of area A is quantified macroscopically by a modified form of the STEFAN-BOLTZMANN LAW

$$\dot{Q}_e = \epsilon \sigma A T_b^4 \quad \sigma = 5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \text{K}^4} = 0.1714 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \text{K}^4 \cdot \text{sr}}$$

$$0 \leq \epsilon \leq 1.0$$



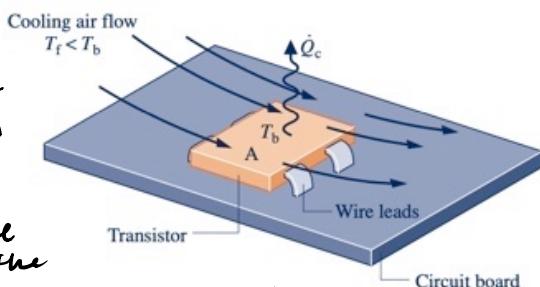
shows that thermal radiation is associated w/4th power of absolute temp of surface T_b . ϵ = emissivity, property of surface indicates how effectively radiates

- in general, net rate of energy xfer by thermal radiation between two surfaces involves relationships among the properties of the surfaces
- Radiation Exchange Between
A Surface at Temp T_b and
larger surrounding surfaces $\Rightarrow \dot{Q}_r = \epsilon \sigma A [T_b^4 - T_s^4]$

CONVECTION

- energy xfer between a solid surface at a temperature T_b and an adjacent gas or liquid at another temp T_f

$T_b > T_f$ and energy is xferred in the direction indicated by the arrow due to the combined effects of conduction within the air and the bulk motion of the air



Rate of energy transfer from the surface to the air $\dot{Q}_c = hA(T_b - T_f)$ [NEWTON'S LAW OF COOLING]

A = surface area h = proportionality factor, heat transfer coefficient

- heat transfer coefficient, h , is NOT a thermodynamic property

REMEMBER

only after system boundary has been specified that possible heat interactions w/ surroundings are considered, for these are always evaluated at a system boundary

REMEMBER

In thermodynamics, heat refers only to a particular means by which energy is xferred... it does not refer to what is being xferred between systems or to what is stored within systems
 \rightarrow Energy is xferred and stored, not heat

FIRST LAW OF THERMODYNAMICS

- energy is conserved
- requires that in any process of a closed system the energy of the system increases or decreases by an amount equal to the net amount of energy xferred across its boundary

$$\left[\begin{array}{l} \text{change in the amount} \\ \text{of energy contained w/in} \\ \text{a system during some} \\ \text{time interval} \end{array} \right] = \left[\begin{array}{l} \text{net amount of energy} \\ \text{xferred in across the} \\ \text{system boundary by} \\ \text{heat xfer during time inter.} \end{array} \right] - \left[\begin{array}{l} \text{net amount energy} \\ \text{xferred out across} \\ \text{system bound. by} \\ \text{work during time interval} \end{array} \right]$$

$$E_2 - E_1 = Q - W$$

$$\Delta KE + \Delta PE + U = Q - W$$

$$dE = \delta Q - \delta W$$

dE = differential of energy (-property)
 $\delta Q, \delta W$ = differentials (not properties)

$$\frac{dE}{dt} = \dot{Q} - \dot{W} \quad \left[\begin{array}{l} \text{time rate form of} \\ \text{the energy balance} \end{array} \right]$$

$$\left[\begin{array}{l} \text{time rate of change} \\ \text{of energy contained} \\ \text{in system at time } t \end{array} \right] = \left[\begin{array}{l} \text{net rate at which} \\ \text{energy being xferred} \\ \text{in by heat xfer at } t \end{array} \right] - \left[\begin{array}{l} \text{net rate at which} \\ \text{energy being xferred} \\ \text{out by work at time } t \end{array} \right]$$

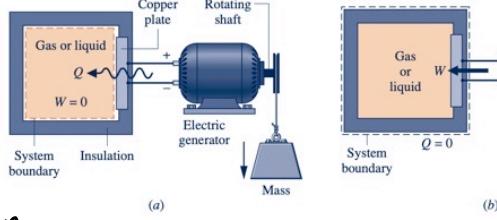
$$\frac{dE}{dt} = \frac{dKE}{dt} + \frac{dPE}{dt} + \frac{dU}{dt}$$

then ...

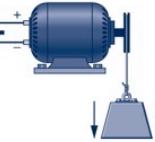
$$\frac{dKE}{dt} + \frac{dPE}{dt} + \frac{dU}{dt} = \dot{Q} - \dot{W}$$

Alternative Choices for System Boundaries

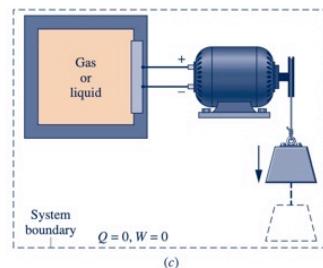
(a) the gas itself is system, as current flows thru Cu plate, there's an energy xfer from Cu plate to gas and since this energy xfer occurs as result of temp diff between the plate and the gas, it's classified as heat xfer



(b) boundary now includes Cu plate and the energy xfer that occurs as current crosses boundary of system must be regarded as work



(c) boundary is located so that no energy is xferred across it by heat or work



Steady-State (SS) — a system is at steady-state if none of its properties change w/time

ENERGY ANALYSIS OF CYCLES

THERMODYNAMIC CYCLE — sequence of processes that begins and ends at the same state

- at conclusion of cycle all properties have same values they had at the beginning
- consequently, over the cycle the system experiences no net change of state

Energy Balance for any system undergoing a TD cycle takes the form

$$\Delta E_{\text{cycle}} = Q_{\text{cycle}} - W_{\text{cycle}}$$

where Q_{cycle} and W_{cycle} mean net amounts of energy rfer by heat/work

Since system is returned to its initial state after the cycle, there's no net change in its energy. Therefore the equation reduces to

$$W_{\text{cycle}} = Q_{\text{cycle}}$$

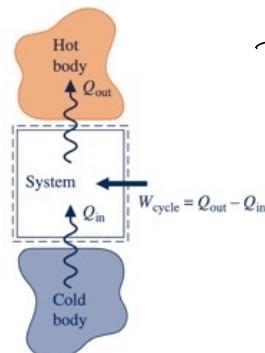
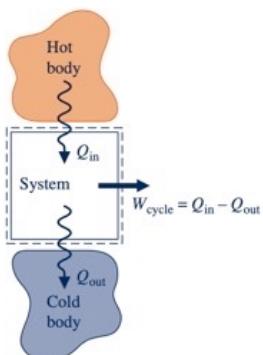
* This conservation of energy principle must be satisfied by every thermodynamic cycle, regardless of sequence of processes followed by system undergoing cycle or nature of substances making up system

POWER CYCLE

- deliver a net work x fer of energy to surroundings

$$W_{\text{cycle}} = Q_{\text{in}} - Q_{\text{out}}$$

heat xfer into system from hot body *heat xfer out of system to cold body*



~ REFRIGERATION AND HEAT PUMP CYCLES

• Q_{in} is energy x ferred by heat into system undergoing cycle from the cold body, and Q_{out} is energy x ferred by heat x fer from system to hot body

here, in each case, a system undergoes a cycle while communicating thermally w/two bodies, one hot and other cold, and these bodies are systems located in the surroundings of the system undergoing the cycle --- during each cycle there's also net amount of energy x changed w/ surroundings by work

For a power cycle: Q_{in} must be $> Q_{\text{out}}$

• performance of system undergoing power cycle can be described in terms of extent to which the energy added by heat (Q_{in}) is converted to a net work output (W_{cycle})

→ extent of energy conversion from heat to work can be expressed by the **THERMAL EFFICIENCY**: $\eta = \frac{W_{\text{cycle}}}{Q_{\text{in}}} \quad (\text{power cycle}) \quad \text{or} \quad \eta = \frac{Q_{\text{in}} - Q_{\text{out}}}{Q_{\text{in}}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}}$

For a refrigeration/heat pump cycle: Q_{out} must be $> Q_{\text{in}}$ because $W_{\text{cycle}} \in \mathbb{R}^+$

• net work input, W_{cycle}

$$W_{\text{cycle}} = Q_{\text{out}} - Q_{\text{in}} \quad (\text{refrigeration + heat pump cycles})$$

• objective of refrigeration: cool a refrigerated space or maintain the temp w/in a dwelling below that of surroundings

• objective of heat pump: maintain temp w/in dwelling above that of the surroundings or to provide heating for certain industrial processes that occur at elevated temps

COEFFICIENTS OF PERFORMANCE: $\beta = \frac{Q_{\text{in}}}{W_{\text{cycle}}} \quad \text{or} \quad \frac{Q_{\text{in}}}{Q_{\text{out}} - Q_{\text{in}}} \quad (\text{refrigeration})$

$$\gamma = \frac{Q_{\text{out}}}{W_{\text{cycle}}} \quad \text{or} \quad \frac{Q_{\text{out}}}{Q_{\text{out}} - Q_{\text{in}}} \quad (\text{heat pump})$$