Physics 115
General Physics II

Session 12

Thermodynamic processes

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# Lecture Schedule
(up to exam 2)

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Announcements

• Exam 1 scores just came back from scan shop – grades will be posted on WebAssign gradebook later today
  – I will post on Catalyst Gradebook tomorrow, along with statistics (avg, standard deviation)

Solutions: see ex1-14-solns.pdf posted in class website

Slides directory
Next topic: Laws of Thermodynamics

(Each of these 4 “laws” has many alternative versions)

We’ll see what all these words mean later...

- **0th Law**: if objects are in thermal equilibrium, they have the same T, and no heat flows between them
  - Already discussed
- **1st Law**: Conservation of energy, including heat:
  
  Change in internal energy of system = Heat added – Work done

- **2nd Law**: when objects of different T are in contact, *spontaneous* heat flow is from higher T to lower T
- **3rd Law**: It is impossible to bring an object to T=0K in any finite sequence of processes
Internal energy and 1st Law

- **1st Law of Thermodynamics**: The change in internal energy of a system equals the heat transfer into the system\(^*\) minus the work done by the system.

(Essentially: conservation of energy).

\[ \Delta U = Q_{in} - W \]

\( \text{System} \) could be \( n \) moles of ideal gas, for example...

Sign convention:
- \( W > 0 \) \( \rightarrow \) work done by the system
- \( W < 0 \) \( \rightarrow \) work done on the system

Minus sign in equation means:
- \( U \) decreases if \( W \) is by system
- \( U \) increases if \( W \) is on system

Work done by the system
Example: expanding gas pushes a piston some distance
Work done on the system
Example: piston pushed by external force compresses gas
Example of sign convention

- Ideal gas in insulated container: no Q in or out: $Q=0$
- Gas expands, pushing piston up ($F=mg$, so $W=mgd$)
  - Work is done by system, so $W$ is a positive number
  - So $U$ is decreased

- If instead: we add more weights to compress gas
  - Work done on gas $\rightarrow$ now $W$ is a negative number
  - $U$ is increased

\[ \Delta U = -W \]

\[ U_f = U_i - W \]

\[ \Delta U = -(-W) = +W \]
State of system, and state variables

• U is another thermodynamic property, like P, V, and T, used to describe the state of the system.
  – They are connected by equations describing system behavior: for ideal gas, PV=NkT, and U=(3/2)NkT
    “equation of state”

• Q and W are not state variables: they describe changes to the state of the system.
  – Adding or subtracting Q or W moves the system from one state to another: points in a {P,V,T} coordinate system.
  – The system can be moved from one point to another via different sequences of intermediate states.
    = different paths in PVT space
    = different sequences of adding/subtracting W and Q
    = different thermodynamic processes
3D model of PVT surface

- Ideal gas law $PV = NkT$ constrains state variables $P, V, T$ to lie on the curved surface shown here.
- Every point on the surface is a possible state of the system.
- Points off the surface cannot be valid combinations of $P, V, T$, for an ideal gas.

hyperphysics.phy-astr.gsu.edu
Thermodynamic processes

- For ideal gas, we can describe processes that are:
  - Isothermal (T=const)
  - Constant P
  - Constant V
  - Adiabatic (Q=0)

- Quasi-static processes: very slow changes
  - System is approximately in equilibrium throughout
  - Example: push a piston in very small steps
  - At each step, wait to let system regain equilibrium
  - “Neglect friction”

Such processes are reversible
  - Could run process backwards, and return to initial (P,V,T) state

Real processes are irreversible
  (due to friction, etc)
Quasi-static compression: reversible

- Ideal gas in piston, within heat reservoir
  - Compress gas slowly; heat must go out to keep $T=\text{const}$
  - Temperature reservoir can absorb heat without changing its $T$
- Reverse the process: expansion
  - Let gas pressure push piston up slowly; reservoir must supply $Q$ to keep $T=\text{const}$
  - System (gas) and reservoir ("surroundings") are back to their original states
  - Reversible process for ideal gas, ideal reservoir, no friction
- But: No real process is truly reversible (friction in piston, etc)
Process diagrams

- **Example:** constant P expansion of ideal gas
  - Ideal gas with \( P = P_0 \), at \( x_i \)
  - Frictionless piston moves to \( x_f \)
  - Volume increases from \( V_i \) to \( V_f \)

- Gas has done work on piston
  \[ W = F \Delta x = (P_0 A) \Delta x = P_0 \Delta V \]

Plot process on \( P \) vs \( V \) axes:
Notice: \( W = P_0 \Delta V = \text{area under path} \) of process in the \( P-V \) plot

This applies to any path, not just for constant-\( P \):
Work done = area under path on a \( P \) vs \( V \) plot

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\( \Delta V \)

\( P_0 \)

\( \Delta V \)

\( O \)

\( V_i \)

\( V_f \)

\( V \) (m\(^3\))

\( P \) (kPa)

\( 4/21/14 \)

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Example

• Ideal gas expands from $V_{\text{initial}} = 0.40 \text{ m}^3$ to $V_{\text{final}} = 0.62 \text{ m}^3$ while its pressure increases linearly from $P_i = 110\text{kPa}$ to $P_f = 230\text{kPa}$

• Work done = area under path

Without calculus, we can calculate as Pythagoras would have done:

Area = rectangle + triangle = $(110\text{kPa})(0.22\text{m}^3) + \frac{1}{2}(120\text{kPa})(0.22\text{m}^3)$

Area = $W = 3.7 \times 10^4 \text{ J}$

This work was done BY the expanding gas, so its internal energy is reduced
Constant volume processes

- For $V =$ constant, $P = \left(\frac{nR}{V}\right) T$
- No work done (area=0)
- $T$ must increase to change $P$
- $1^{\text{st}}$ Law: $\Delta U = Q - W \Rightarrow \Delta U = Q$
Process paths in P,V plots

- Many possible paths on a P vs V diagram, for a gas moved from state \((P_i, V_i)\) to \((P_f, V_f)\).
- Suppose the final state has unchanged T, then
  \[ P_iV_i = nRT = P_fV_f \]
- \(U\) depends only on T, so the initial and final internal energies \(U\) also must be equal
  Note: To keep constant T (\(\Delta U=0\)), heat transfer must occur, with \(Q = W\)
- Therefore, since area under \(\{P,V\}\) path = work done,
  \[ W_{\text{Path A}} > W_{\text{Path C}} > W_{\text{Path B}} \]
  (Is work by or on the gas?)
Isothermal process

- If ideal gas expands but $T$ remains constant, $P$ must drop: $P = \frac{nRT}{V}$
  - Family of curves for each $T$
  - Shape is always $\sim \frac{1}{V}$
  - $W$ by gas= area under plot
    - Add up slices of width $\Delta V$
      \[ W \approx \sum_{V_i}^{V_f} \left( \frac{nRT}{V} \right) \Delta V \]
    - Use calculus, integrate to find area:
      \[ \Rightarrow \int_{V_i}^{V_f} \frac{nRT}{V} dV = nRT \ln \left( \frac{V_f}{V_i} \right) \]
      "\ln" = natural (base $e$) logarithm
      \[ e = \frac{1}{1} + \frac{1}{2!} + \frac{1}{3!} + \cdots = 2.72\ldots \]
Isothermal example

- **For** $T = \text{constant}$, $U$ **must be constant**: $U = (3/2) nRT$
  
  So $Q - W = 0$; $W$ **is done by gas**, so $Q=W$
  
  +$Q$ **means into system**

  **We must add heat** $Q=W$ **to keep** $T$ **constant**

  **Example**: $n = 0.5\, \text{mol}, T = 310\, \text{K}, V_{i} = 0.31\, \text{m}^3, V_{f} = 0.50\, \text{m}^3$

  
  $$W = nRT \ln \left( \frac{V_{f}}{V_{i}} \right) = (0.5\, \text{mol}) (8.31\, \text{J/mol/K}) (310\, \text{K}) \ln \left( \frac{0.45\, \text{m}^3}{0.31\, \text{m}^3} \right)$$

  $$\ln (1.45) = 0.373 \implies W = 480\, \text{J} = Q_{IN}$$

  

  **For reverse direction**: Compress gas
  
  **Now work is done on gas**, so $W$ **is negative**: must have $Q$ **out of gas**
Adiabatic (Q=0) processes

- If ideal gas expands but no heat flows, work is done by gas \((W>0)\) so \(U\) must drop: \(\Delta U = Q - W \Rightarrow \Delta U = -W\)

\(U \sim T\), so \(T\) must drop also

Adiabatic compression

Adiabatic expansion

Adiabatic expansion path on \(P\) vs \(V\) must be steeper than isotherm path:
Temperature must drop \(\rightarrow\)
State must move to a lower isotherm