LECTURE 10
Machines that Store and Transfer Energy
Thermodynamics and Energy Conversion
2.000 Thermodynamics

Topics of today’s lecture:

- Marty: Project I questions/answers
- Joe: Thermodynamics and machinery
Simple energy concepts

Energy is stored in separate boxes

Thermal energy can only go to a colder system by heat transfer
Energy stored in system boundary

- Mechanical Energy
  - Mechanical energy in as work
  - Mechanical energy loss

- Gravity Energy
  - Mechanical energy loss

- Elastic Energy
  - Mechanical energy loss

- Thermal Energy
  - Thermal energy in as heat
  - Mechanical energy loss
  - Thermal energy out as heat

Mechanical energy out as work
Thermodynamic energy concepts

Energy in by heat transfer is stored in same box as energy in by:

- $F \, dx = p \, A \, dx = p \, dv$

No separate thermal energy storage
Energy transfers

Work is energy or power transferred by:

\[ F \, dx = p \, A \, dx = p \, dv \]

Heat is energy transferred as the result of a temperature difference
Energy storage

Non-thermodynamic systems have separate energy storage -- Uncoupled system.

Thermodynamic systems have coupled energy storage -- Internal energy in thermodynamics.

Thermal expansion is evidence of coupled storage:

- Solids have small thermal expansion - small coupling
- Gases have large expansion - strong coupling
- Boiling liquids have very large expansion - very large coupling
Energy for a gas

As a result of the coupling energy and thus temperature of a gas can be increased or decreased by both work and heat.

Work out can decrease the temperature of a gas without a heat. This is not possible with uncoupled energy storage.

Energy can go in as heat and come out as work -- Energy conversion. This is not possible with uncoupled energy storage.

With work in, heat can go in at a low temperature and come out at a high temperature -- Heat pumping.
Piston cylinder live demo

Demonstrate heat transfer as result of work into and work out of a gas
A simple thermodynamic energy converter

A heat engine operating in a cycle of a piston in a cylinder containing an ideal gas

The engine lifts weights one after the other from a low platform to a high platform
**Step 1:**

- Weight to platform
- Heat cylinder
- Pressure increases while piston rests on stops
- Pressure force just supports the weight
STEP 2:
- Continue heating
- Gas expands, lifts piston and weight
- Piston assembly rests against top stop
**STEP 3:**
- Weight off platform
- Pressure decreases while piston is against top stop
- Cool cylinder until gas pressure just supports weight
STEP 4:
- Continue cooling
- Gas contracts, piston lowers
- Piston assembly rests on lower stop
Energy conversion - heat pumping

Heat going from a high temperature to a low temperature can produce work or power. Some of the heat is converted into work.

Heat can be made to go from $T_{\text{low}}$ to $T_{\text{high}}$ by a work input to a cycle of a system with coupled energy storage. This is a heat pump or refrigerator.

Heat transfer from $T_{\text{high}}$ to $T_{\text{low}}$ without producing work has a loss (of potential work).

This loss is measured by an entropy balance. Entropy is generated by this loss. Entropy generation is a generalization of heat generation in an uncoupled system.
Steady flow energy balance for control volume

Flow of an uncoupled incompressible fluid

\[ \dot{m}_{in} \cdot \left( \frac{p_{in}}{\rho_{in}} \right) \]

\[ \dot{m}_{in} \cdot (c_{in} \cdot T_{in}) \]

\[ \text{Control volume} \]

\[ \text{Heat in} = \text{mass}_{\text{flow}} c \left[ T_{out} - T_{in} \right] \]

\[ \text{Power in} = \text{mass}_{\text{flow}} \left( \frac{1}{\rho} \right) \left[ P_{out} - P_{in} \right] \]

\[ \dot{m}_{out} \cdot \left( \frac{p_{out}}{\rho_{out}} \right) \]

\[ \dot{m}_{out} \cdot (c_{out} \cdot T_{out}) \]
Steady flow energy balance for control volume

Flow of coupled fluid

\[ \dot{m}_{in} \cdot \left( \frac{p_{in}}{\rho_{in}} + c_{in} \cdot T_{in} \right) = \dot{m}_{out} \cdot \left( \frac{p_{out}}{\rho_{out}} + c_{out} \cdot T_{out} \right) \]

\[ \dot{m}_{in} \cdot h_{in} = \dot{m}_{out} \cdot h_{out} \]

\[ Power_{in} - Heat_{in} = mass_{flow} \left[ \left( \frac{P}{\rho} + cT \right)_{out} - \left( \frac{P}{\rho} + cT \right)_{in} \right] \]

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Steady flow energy balance for ideal gas

Definition of enthalpy:
\[ h = \frac{P}{\rho} + cT \]

For an ideal gas:
\[ \frac{P}{\rho} = P_v = RT \]
\[ h = RT + cT = c_p T \]

\[ \text{Power}_{in} - \text{Heat}_{in} = \text{mass}_{flow} \left[ \left( c_p T \right)_{out} - \left( c_p T \right)_{in} \right] \]
Gas turbine engine

In a steady flow machine without heat transfer or friction to or in the fluid

\[ power_{in} = \text{mass}_{flow} \int_{in}^{out} vdP = \text{mass}_{flow} v_{avg} (P_{out} - P_{in}) \]

A gas turbine engine has three basic steady flow components

- Compressor to increase pressure of stream of air
- Burner to heat air by burning fuel
- Turbine to decrease pressure of air

\[ Power_{net} = power_{turbine} - power_{comp} \]
Gas turbine engines

- Air in, low pressure $p_1$
- Compressor power in: $\dot{m} \cdot v_{avg} \cdot (p_2 - p_1)$
- Air, high pressure $p_2$
- Burn fuel to heat air
- Air, @ high T $p_2$
- Turbine power out: $\dot{m} \cdot v_{avg} \cdot (p_2 - p_1)$
- Air out $p_1$

- Average $T$ in Turbine is greater than in Compressor
- Average $v$ in turbine is greater than in compressor
- Turbine power out $>$ Compressor power in
- Power net $> 0$

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Group exercise

You have two minutes to determine the work done by this system as a function of pressure and volume.