ES 202
Fluid and Thermal Systems

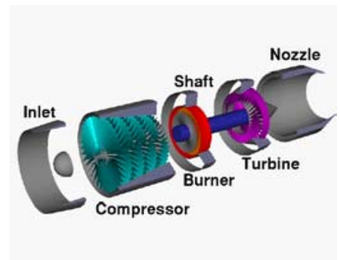
Lecture 23:
Power Cycles
(2/4/2003)

Road Map of Lecture 23

- Power cycle
  - use Rankine cycle as an example
  - the ideal Rankine cycle
  - representation on a *T-s* diagram
  - divergence of constant pressure lines
  - analysis of individual components (energy balance)
  - effects of irreversibility in turbine and compressor
- Comments on Quiz 4

Power Cycles

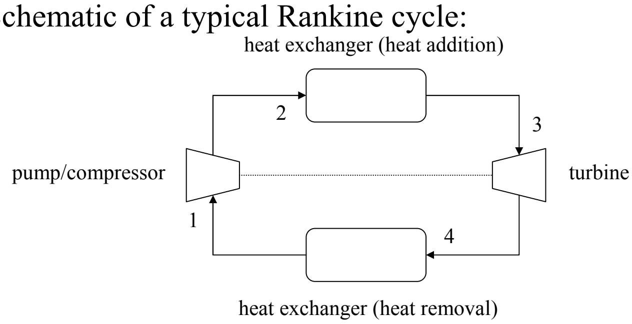
- The integration of turbines, compressors, heat exchangers and combustors can generate power.
- For example, the gas turbine engine:
  - identify the different components



- The process path of any thermodynamic cycles form a closed loop on any phase/property diagram.
- The direction of process path determines what kind of cycle it is (extracting power versus refrigeration, *etc*.)

Rankine Cycle

- Schematic of a typical Rankine cycle:



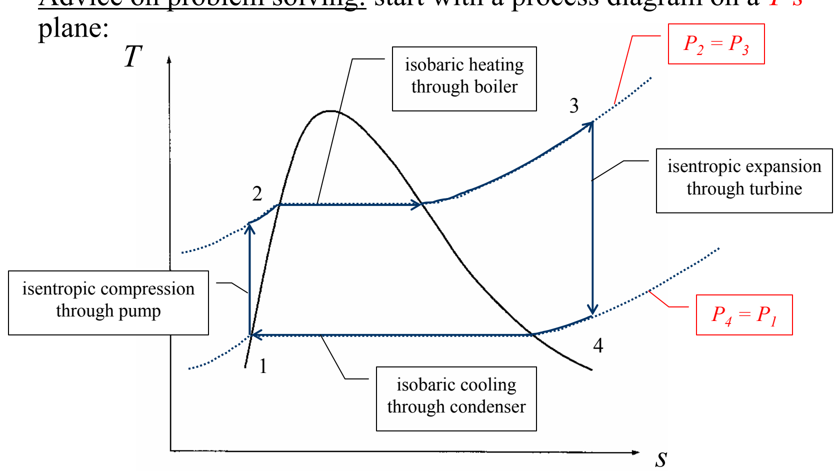
- For an ideal Rankine cycle:
  - from State 1 to State 2: isentropic compression (pump)
  - from State 2 to State 3: isobaric heating (boiler)
  - from State 3 to State 4: isentropic expansion (turbine)
  - from State 4 to State 1: isobaric cooling (condenser)

Questions of Interests

- Representation on a *T-s* diagram
- How do we get a net work output from the cycle?
- Effects of irreversibilities on cycle performance (graphical representation)
- Analysis of individual components
  - definition of thermal efficiency
  - back work ratio

The *T-s* Diagram

- Advice on problem solving: start with a process diagram on a *T-s* plane:



Energy Conversion

- With reference to the *T-s* diagram on previous slide, a few observations are noteworthy:
  - the divergence of constant pressure lines at high temperatures implies that the mechanical power extracted from the turbine outweighs that required by the pump
  - in most situations, a fraction of the turbine work output is used to drive the pump and this fraction is called the back work ratio:

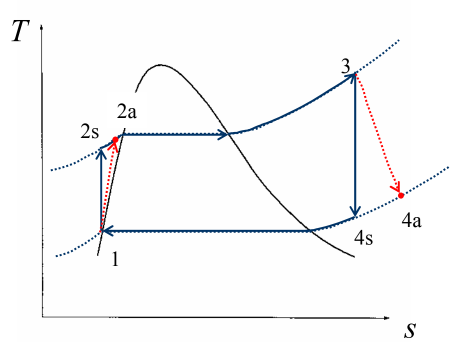
$$BWR = \frac{\dot{W}_{\text{pump}}}{\dot{W}_{\text{turbine}}}$$

  - the Rankine cycle can be viewed as an energy conversion process from thermal energy to mechanical energy
  - the ratio between the net power output (turbine power – pump power) and the heat addition at the boiler is termed the thermal efficiency:

$$\eta_{\text{thermal}} = \frac{\dot{W}_{\text{turbine}} - \dot{W}_{\text{pump}}}{\dot{Q}_{\text{boiler}}}$$

Effects of Irreversibilities

- Irreversibilities in the pump and turbine for non-ideal processes result in higher entropy at the exit of pump *(2a)* and turbine *(4a)*.



  - higher temperature at pump exit implies more pump work
  - higher temperature at turbine exit implies less turbine work

Energy Analysis

- Adopt a "divide and conquer" approach to analyze the Rankine cycle.
- Apply energy balance to the four individual components in the cycle.
- Depending on the particular component, different terms in the energy balance are active while others are suppressed.
- Typical assumptions common to all four components are:
  - steady state operation
  - negligible changes in kinetic and potential energy
  - <u>Caution:</u> changes in kinetic energy are not negligible for nozzle and diffusers
- For these components, the energy balance can be reduced to a simple form:

$$\underbrace{\cancel{\frac{dE}{dt}}}_{\text{steady state}} = \dot{Q}_{\text{in}} + \dot{W}_{\text{in}} + \dot{m}_{\text{in}}\left(h + \cancel{\frac{v^2}{2}} + \cancel{gz}\right)_{\text{in}} - \underbrace{\dot{m}_{\text{out}}}_{=\dot{m}_{\text{in}}\ \text{(due to mass conservation)}}\left(h + \cancel{\frac{v^2}{2}} + \cancel{gz}\right)_{\text{out}}$$

Summary of Energy Analysis

	$\dot{Q}_{\text{in}}$	$\dot{W}_{\text{in}}$	reduced energy balance
pump	0	> 0	$\dot{W}_{\text{pump,in}} = \dot{m}\left(h_2 - h_1\right)$
boiler	> 0	0	$\dot{Q}_{\text{boiler,in}} = \dot{m}\left(h_3 - h_2\right)$
turbine	0	< 0	$\dot{W}_{\text{turbine,out}} = \dot{m}\left(h_3 - h_4\right)$
condenser	< 0	0	$\dot{Q}_{\text{condenser,out}} = \dot{m}\left(h_4 - h_1\right)$