Lecture 34 – Rankine cycle improvements

Purdue ME 200, Thermodynamics I

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Outline

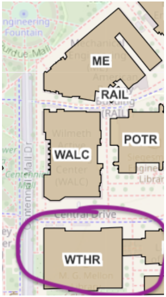
Exam 3 reminders

Inefficiencies in the Rankine cycle

Improving the Rankine cycle

When and where is exam #3?

- 6:30-7:30 PM in WTHR 200 this Thursday, April 13



- no class Friday, April 14
- homework 33-35 due 11:59 PM Monday, April 17

What does exam #3 cover?

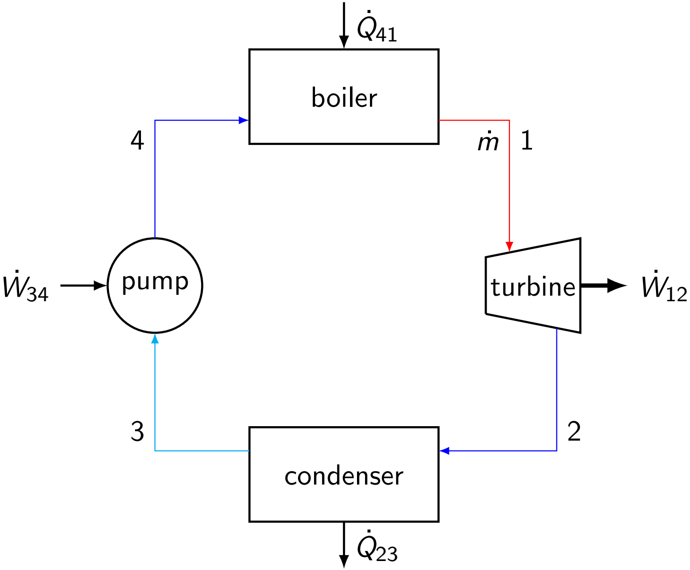
- technically, lectures 1-32 and homework 1-32
- but mostly lectures 20-32 and homework 20-32
- 1 conceptual problem, 2 homework-style problems
- closed book, closed notes
- we'll provide equation sheet and any necessary tables
- don't interpolate tables; just use closest data point

Other exam #3 logistics

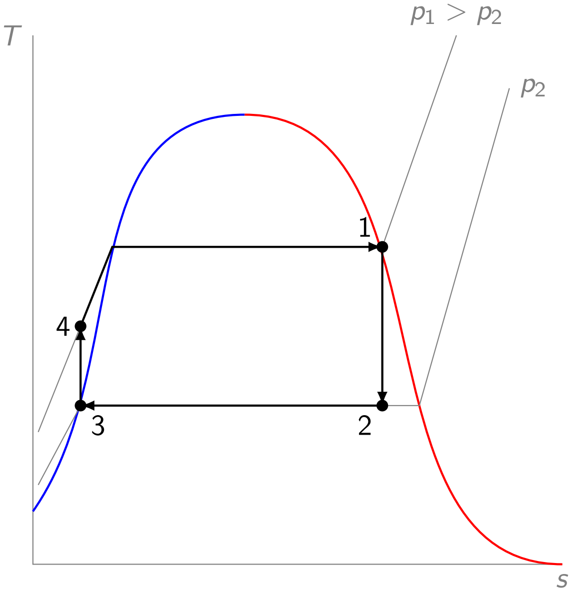
- practice problems and exam are on Brightspace
- arrive 10-15 minutes early
- bring pencils, eraser, scientific calculator
  - ◇ Texas Instruments: TI-30X, TI-36X
  - ◇ Casio: fx-115 or fx-991
- exams 1, 2 and 3 are each 20% of course grade
- final exam is 25%

Outline

Reminder: the Rankine cycle



Reminder: the ideal Rankine cycle



Reminder: ideal Rankine cycle assumptions

- no stray heat transfer
- no pressure drops due to friction in the condenser or boiler
- no friction or heat transfer within the turbine or pump

Deviations of real plants from the ideal Rankine cycle

- stray heat transfer
- fluid friction (hence pressure drops) in boiler or condenser
- internal irreversibilities in turbine or pump
- input power to boiler fan, cooling tower fan, ...

Irreversible turbine and pump

- real turbines and pumps have isentropic efficiencies

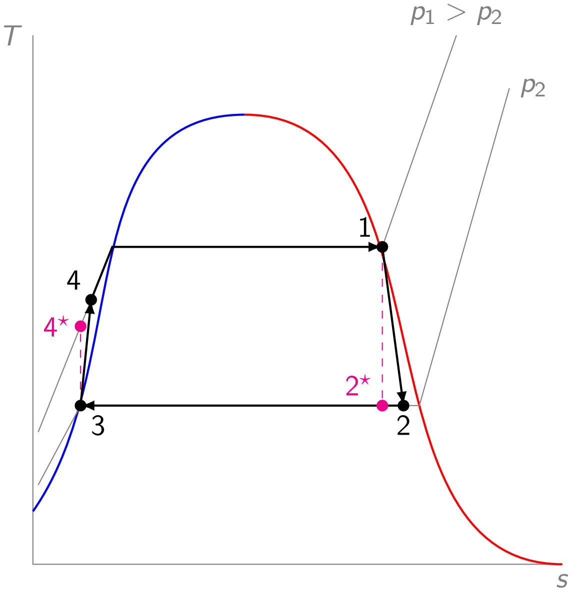
$$\eta_t = \frac{\dot{W}_{12}}{\dot{W}_{12}^\star} = \frac{h_1 - h_2}{h_1 - h_2^\star} < 1$$
$$\eta_p = \frac{\dot{W}_{34}^\star}{\dot{W}_{34}} = \frac{h_4^\star - h_3}{h_4 - h_3} < 1$$

- alternatively, the ideal pump calculation can use

$$\frac{\dot{W}_{34}^\star}{\dot{m}} = \int_{p_3}^{p_4} v \mathrm{d}p \approx v_3(p_4 - p_3),$$

since v is typically $\sim$constant over process $3 \rightarrow 4$

Rankine cycle with irreversible turbine and pump



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Inefficiencies in the Rankine cycle

Improving the Rankine cycle

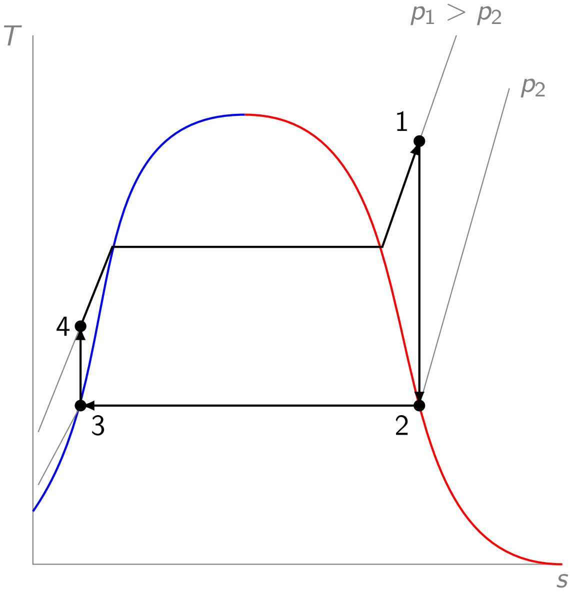
Directions for Rankine cycle improvements

- last lecture: ideal Rankine cycle efficiency is $1 - T_2/\tilde{T}$
- $\tilde{T} \approx T_1$ is an 'effective' temperature over boiler process $4 \to 1$
- to increase efficiency,
  - ◇ increase the effective boiler temperature $\tilde{T}$
    (to do this, increase the boiler outlet temperature T_1)
  - ◇ decrease the condenser temperature T_2
- T_2 is largely determined by the ambient environment
- so most improvements focus on raising $\tilde{T}$

Superheating the working fluid

- one way to raise the effective boiler temperature:
  - ◇ continue heating beyond the saturated vapor point
  - ◇ this is done in a 'superheater' (another heat exchanger)
  - ◇ boiler + superheater = 'steam generator'
- superheat can also increase SLVM quality at turbine outlet
- this can reduce turbine wear and tear

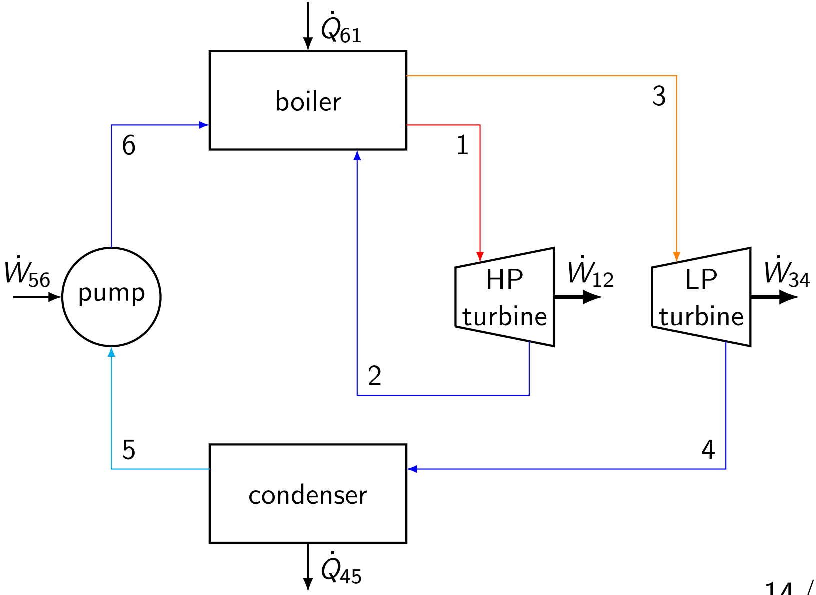
Ideal Rankine cycle with superheat



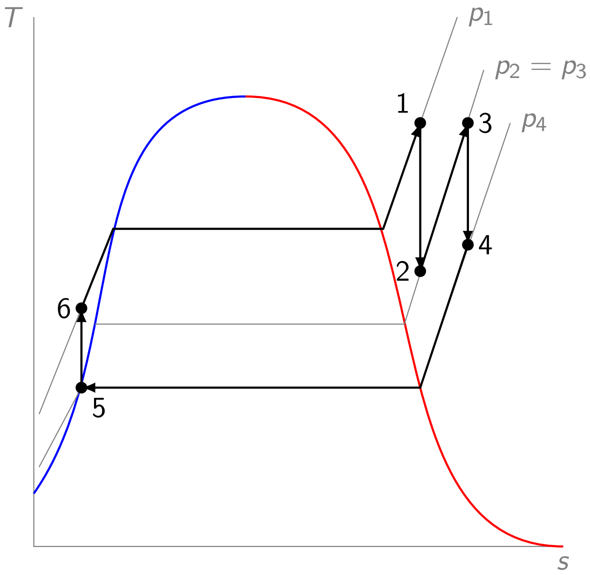
Using two turbines and reheating in between

- another way to raise the effective boiler temperature:
  - ◇ extract work in two stages
  - ◇ first, use a turbine with a high inlet pressure
  - ◇ after this turbine, send the working fluid back to the boiler
  - ◇ then send it to a second turbine with a lower inlet pressure

Rankine cycle with reheat



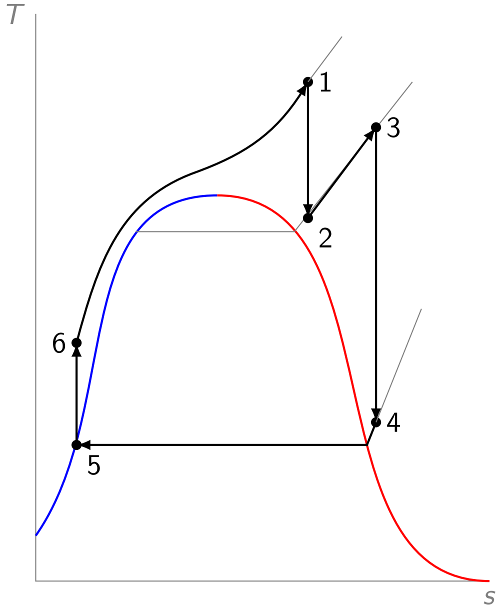
Ideal Rankine cycle with superheat and reheat



Using supercritical temperatures and pressures

- materials limit boiler temperatures and pressure
- over time, engineers have gradually improved materials
- materials can now endure conditions above the critical point
  - ◇ pressures around 30 MPa
  - ◇ temperatures around 600 $^\circ$C
- this raises boiler temperatures and plant efficiencies

Supercritical ideal Rankine cycle with reheat



Typical efficiency numbers for real vapor power plants

- ‘vanilla’ Rankine cycle with superheat: $\sim$25%
- Rankine cycle with one stage of reheat: $\sim$30%
- supercritical Rankine cycle: $\sim$35% for nuclear, $\sim$40% for coal
- US nuclear and coal fleet averages: $\sim$33%