THERMODYNAMIC CYCLES

Problem 1

What are the four processes that are used to model an ideal, simple Rankine cycle? Draw these processes on T-s and P-v diagrams.

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Problem 2 (ME436s14h5)

A solar-pond power plant operates on an ideal, simple Rankine cycle with R-134a as the working fluid. The refrigerant enters the turbine as saturated vapor at 1.3 MPa and exits at 0.6 MPa. The mass flow rate is 5 kg/s. Draw the cycle on a T-s diagram with the saturation line and determine:

(a) The thermal efficiency of the cycle, and

(b) The power output of the plant.

Answer: (a) η_{th} = 7.86 %

(b) $\dot{W}$ = 75.8 kW

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Problem 3 (ME436s14m1-3 / ME405s23m-4)

A small power plant operates on an ideal, simple Rankine cycle with R-134a as the working fluid. The refrigerant enters the turbine as saturated vapor at 1.4 MPa and exits at 0.6 MPa. The mass flow rate is 5 kg/s.

(a) Draw a schematic diagram of the power plant and identify devices on the diagram.

(b) Draw the cycle on a T-s diagram with the saturation line and identify the states of the fluid.

(c) Find the thermal efficiency of the cycle.

(d) Find the power output of the plant.

Hint: Pump work: $w_P \approx v\,\Delta P$

Answer: (c) η_{th} = 8.47 %

(d) $\dot{W}$ = 82.22 kW

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Problem 4 (ME436s16h3)

A Rankine-cycle steam power plant has a 5-MPa, 450 °C turbine entrance and 10 kPa condenser pressure. What are

a) The pump work;
b) Steam generator heat addition;
c) Turbine exit quality;
d) The turbine work;
e) Thermal efficiency; and
f) Carnot efficiency of the cycle corresponding to the temperature extremes.

Note. Assume that it is an ideal Rankine cycle

Answer: (a) w_P = - 5.04 kJ/kg

(b) q_{in} = 3120.4 kJ/kg

(c) x_4 = 0.823

(d) w_T = 1156.8 kJ/kg

(e) η_{th} = 36.9 %

(f) η_{Carnot} = 55.9 %

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Problem 5

Solve Pr. 3 for the cases of (a) an 85 % efficient turbine, (b) an 85 % efficient pump, and (c) both together. What conclusions may be inferred from your results?

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Problem 6 (ME436s15h4)

To reduce the volume flow rate and hence the physical size of the turbine, power plants that operate with low initial temperature water as a heat source, such as some types of geothermal and ocean temperature energy conversion (OTEC), use working fluids other than steam. Examples include Freon-12, ammonia, and propane. Compare the mass flow rates [kg/h], volume flow rates [m^3/s], and boiler and condenser pressures of (a) Freon-12, (b) propane, and (c) steam, if all cycles operate with ideal turbines that receive saturated vapor at 100 °C and condense at 20 °C, each producing 100 kW_m.

Answer:

	Mass flow rate kg/s	Volume flow rate m^3/s (turine exit)	Boiler pressure kPa	Condenser pressure kPa
Freon	7.04	0.028	3340	566.4
Propane	3.03	0.36	3133	833.24
Water	0.723	41.76	1014.2	2.3393

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Problem 7

A superheated non-ideal steam cycle operates with inlet steam at 2400 psia and 1000 F and condenses at 1 psia. It has five feed water heaters, all optimally placed. Assume the isentropic efficiencies of the turbine sections before, between, and after the bleed points to be all the same and equal to 0.90.

(a) Calculate the specific enthalpies of the extracted steam to each feed water heater, in Btu/lbm.

(b) Calculate the overall isentropic efficiency of the turbine.

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Problem 8

An 850-MW Rankine cycle operates with turbine inlet steam at 1200 psia and 1000 F and condenses at 1 psia. There are three feed water heaters place optimally as follows: (a) the high-pressure heater is of the closed type with drains cascaded backward; (b) the intermediate- pressure heater is of the open type; (c) the low-pressure heater is of the closed type with drains pumped forward. Each of the turbine sections have the same isentropic efficiency of 90 %. The pumps have isentropic efficiencies of 80 %. The high-pressure heater has a TTD = -3 F. The low pressure heater has a TTD = +5 F.

(a) Sketch the cycle and T-s diagrams.

(b) Calculate the mass flow rate at the turbine inlet in pounds mass per hour.

(c) Calculate the mass flow rate to the condenser.

(d) Calculate the mass flow rate of the condenser cooling water, in pounds mass per hour, if it undergoes a 25 F temperature rise.

(e) Calculate the cycle efficiency.

(f) Calculate the cycle heat rate, in Btu per kilowatt hour.

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Problem 9

Compare the net work [kJ/kg] and efficiency of two ideal, saturated Rankine cycles using Freon-12 (R12) as a working fluid operating between 100 °C and 20 °C. One cycle has no feed water heaters and the other has one open feed water heater optimally placed. Explain why feed water heating is not usually used in such cycles.

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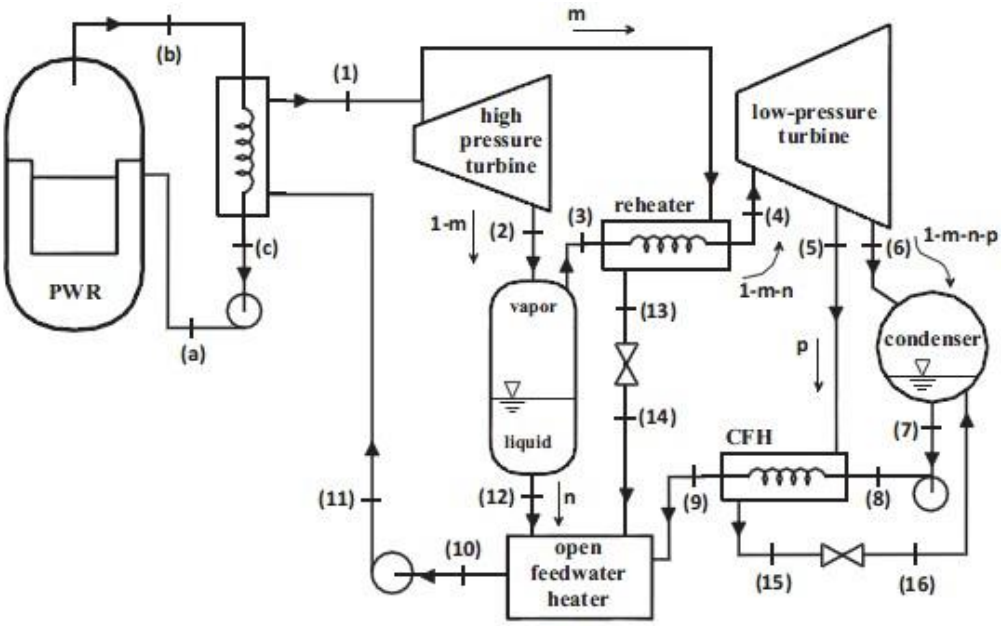
Problem 10

A 3800-MWth PWR is cooled with 15.3-MPa water that enters the core at 300 °C and leaves at 332 °C. In the once-through steam generator, high pressure water is used to produce steam at 8.0 MPa and 315 °C. The steam expands to 0.68 MPa in the high-pressure turbine. Moisture is separated and the saturated steam is reheated with live steam to 288 °C before it enters the low-pressure turbine. The steam expands to 110 kPa, where a fraction is bled to a closed feed water heater. Expansion continues to the condenser pressure of 10 kPa. The separated moisture is drained to an open feed water heater and the reheater condensate is `trapped' to the same heater. The closed feed water heater has a terminal temperature difference of 3 °C. Each segment of the turbine expansion is 85% efficient and the pumps are 65 % efficient.

1. Sketch the cycle on a T-s diagram.
2. Find the cooling water flow rate in the core, in L/min.
3. Find the steam generation rate, in kg/hr.
4. Determine the power output of the system, MWe, if the turbine drives a generator with an efficiency of 94 %.
5. What is the thermal efficiency of the cycle?



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Problem 11

Compare the inlet steam mass and volume flow rates in kg/s and m^3/s of

(a) a fossil-fuel power plant turbine with an isentropic efficiency of 0.9 receiving steam at 15 MPa and 540 °C, and

(b) a nuclear power plant turbine with an isentropic efficiency of 0.88 and receiving saturated steam at 540 °C.

Each turbine produces 1000 MW$_m$, and exhausts to 10 KPa.

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Problem 12

Determine the thermal efficiency, the required steam flow rate, and the moisture at the turbine exhaust for a reheat, regenerative cycle which is to produce 200 MW at the turbine coupling if the throttle conditions are 15.5 MPa and 540 °C; reheat is at 8.0 MPa and 590 °C; one closed feed water heater is at 3.4 MPa; an open feed water heater is at 170 kPa; and the condenser pressure is 13 kPa. The turbine and pump efficiencies are 84 %. The terminal temperature difference for both feed water heaters is 3 °C and the drain from the closed feed water heater is pumped into the steam generator. Also sketch the T-s diagram of the cycle.

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Problem 13

An advanced supercritical power plant has a turbine inlet stream at 7000 psia and 1400 F, double reheat at 1600 psia and 400 psia, both to 1200 F, and condenser at 1 psia. The three turbine sections have isentropic efficiencies of 0.93, 0.91, and 0.89 in order of descending pressures. The pump has an isentropic efficiency of 0.75. The plant receives one unit train of coal daily, which is composed of 100 cars carrying 110 short tons each. The coal has a heating value of 11 000 Btu/lbm. The turbine-generator combined mechanical and electrical efficiency is 0.90. The steam generator efficiency is 0.87. Eight percent of the gross output is used to run plant auxiliaries. Ignoring, for simplicity, all steam line pressure drops and all feed water heaters, calculate

(a) the plant gross and net outputs, in MW_e,

(b) the plant cycle gross and net efficiencies, and

(c) the cycle and station gross and net heat rates, in Btu/kWh.

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Problem 14

What four processes make up the simple ideal Brayton cycle?

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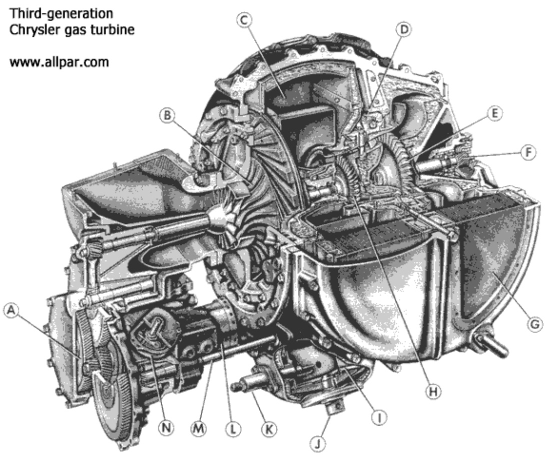
Problem 15

An air-standard Brayton cycle operates with a compressor pressure ratio of 6.0. The actual expansion and compression efficiencies of the gas processes are 0.88 and 0.82, respectively, and the maximum and minimum temperatures are 800 °C and 16 °C, respectively. Compute the compression work, the expansion work, the ratio of compression to expansion work (the back- work ratio), and the actual and theoretical thermal efficiencies. If the power output of the installation is 8 MW, determine the air mass flow rate, kg/min.



MAIN COMPONENTS OF THE TWIN-REGENERATOR GAS TURBINE: (A) accessory drive; (B) compressor; (C) right regenerator rotor; (D) variable nozzle unit; (E) power turbine; (F) reduction gear; (G) left regenerator rotor; (H) gas generator turbine; (I) burner; (J) fuel nozzle; (K) igniter; (L) starter-generator; (M) regenerator drive shaft; (N) ignition unit.

The idea of using gas turbines to power automobiles was conceived in the 1930s, and considerable research was done in the 1940s and 1950s to develop automotive gas turbines by major automobile manufacturers such as the Chrysler and Ford corporations in the US and Rover in the UK. The world's first gas-turbine powered automobile, the 200-hp Rover Jet 1, was built in 1950 in the UK. This was followed by the production of the Plymouth Sport Coupe by Chrysler in 1954 under the leadership of G. J. Huebner. Several hundred gas turbine-powered Plymouth cars were built in the early 1960s for demonstration purposes and were loaned to a select group of people to gather field experience. The users had no complaints other than slow acceleration. But the cars were never mass-produced because of the high production (especially material) costs and the failure to satisfy the provisions of the 1966 Clean Air Act. (See: http://www.allpar.com/mopar/turbine.html)

A gas-turbine-powered Plymouth car built in 1960 had a turbine inlet temperature of 1700 F, a pressure ratio of 4, and a regenerator effectiveness of 0.9. Using isentropic efficiencies of 0.80 for both the compressor and the turbine, determine the thermal efficiency of this car. Also, determine the mass flow rate of air for a net power output of 95 hp. Assume the ambient air to be at 540 R and 14.5 psia.

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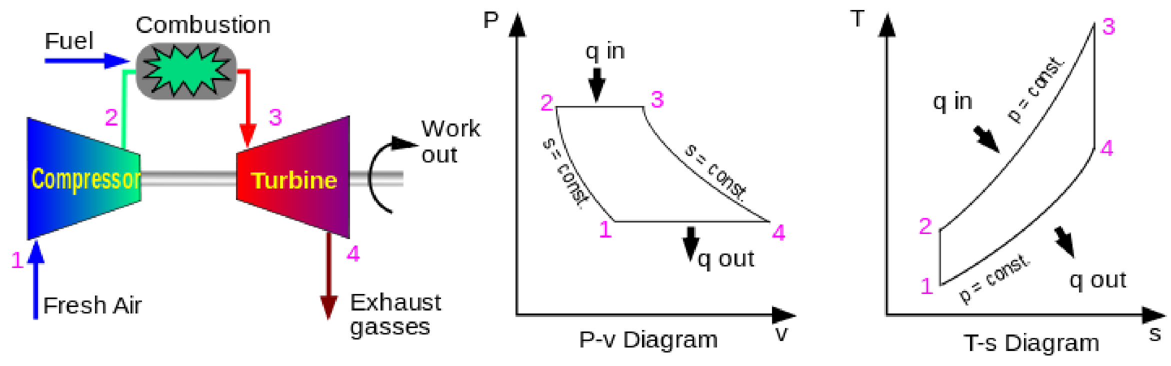
Problem 16 (ME436s17h3 / ME436s19q4 / ME405s19q4)

Compare the optimum pressure ratios and corresponding efficiencies of three ideal Brayton cycles using air, helium, and carbon dioxide as working fluids. The minimum and maximum temperatures are 10 °C and 1115 °C, respectively. Use a constant specific heats at low temperatures.



Answer:

	Air	CO_2	Helium
k	1.40	1.28	1.66
r_p	16	38	7.4
η_{th}	0.55	0.55	0.55

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Problem 17

A two-shaft stationary gas turbine has isentropic efficiencies of 0.85, 0.88, and 0.9 for the compressor, gas generator turbine, and power turbine, respectively, and a compressor pressure ratio of 20.

(a) Determine the compressor work and net work, the gas generator turbine exit temperature, and the thermal efficiency for 80°F ambient and 1900°F compressor-turbine inlet temperatures.

(b) Calculate and discuss the effects of adding reheat to 1900°F ahead of the power turbine.

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Problem 18

A stationary gas turbine used to supply compressed air to a factory operates with zero external shaft load. Derive an equation for the fraction of the inlet air that can be extracted ahead of the combustion chamber for process use in terms of the compressor pressure ratio, the ratio of turbine-to-compressor inlet temperatures, and the turbomachinery efficiencies. What is the extraction mass flow for a machine that has a compressor pressure ratio of 8, turbomachine inlet temperatures of 1000°C and 25°C, turbomachine efficiencies of 90%, and a compressor inlet mass flow rate of 10 kg /s?

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Problem 19

An open-cycle regenerative gas-turbine power plant receives air at 94 kPa and 20 °C. The air is compressed to 550 kPa, heated to 425 °C in the regenerator, and then reaches a maximum temperature of 870 °C in the combustion chamber. Assuming an air-standard cycle, compute the thermal efficiency and the regenerator effectiveness if the mechanical efficiency of the compressor and turbine are 82 and 87 percent, respectively.

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Problem 20

In 1903, Aegidius Elling of Norway designed and built an 11-hp gas turbine that used steam injection between the combustion chamber and the turbine to cool the combustion gases to a safe temperature for the materials available at the time. Currently there are several gas-turbine power plants that use steam injection to augment power and improve thermal efficiency. For example, the thermal efficiency of the General Electric LM5000 gas turbine is reported to increase from 35.8 % in simple-cycle operation to 43 % when steam injection is used. Explain why steam injection increases the power output and the efficiency of gas turbines. Also, explain how you would obtain the steam.

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Problem 21

An open Brayton cycle operates with a compressor-pressure ratio of 5.0, an inlet temperature of 27 °C, and a turbine-inlet temperature of 980 °C, and produces a total of 50 MW of mechanical power. For the following systems, find the thermal efficiency, the air mass flow rate, and the total compressor and turbine powers, in kW, assuming that the compressor and turbine efficiencies are 90%. Find:

(a) A simple Brayton cycle.

(b) A regenerative Brayton cycle with a regenerator effectiveness of 80%.

(c) A reheat Brayton cycle with a reheat at 310 kPa to 955 °C.

(d) A Brayton cycle with 3 stages of compression with 2 intercoolers that cool the gas back to 27 °C.

(e) A system that uses the regenerator of part (b) and the reheater of part (c).

(f) A system that uses the intercoolers of part (d) and the regenerator of (b).

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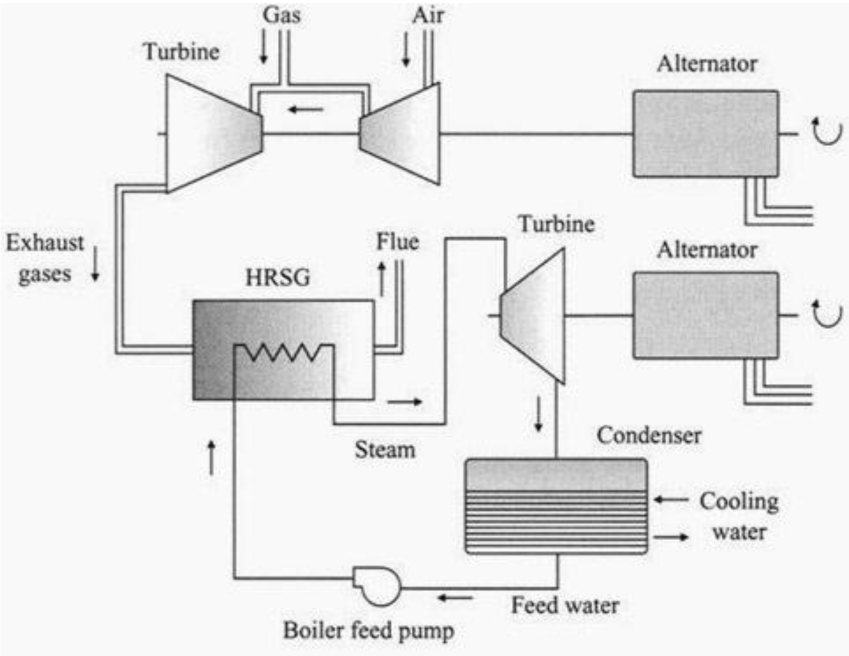
Problem 22 (ME436s20q4 / ME405f22m-2 / ME405f24m-2)

A combined-cycle plant uses a gas-turbine with a thermal efficiency of 38 % and the turbine exhaust is directed into a heat recovery steam generator (HSRG) to generate steam for a Rankine cycle. No supplemental heat is added to the exhaust gas flow. The Rankine cycle has a thermal efficiency of 24 %. Determine the overall thermal efficiency of the combined cycle.



Answer: η_{CC} = 0.53

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Problem 23

A combined Brayton-Rankine cycle, with both cycles ideal, has air entering the compressor of the Brayton cycle at 1 atm and 500 R. The air, treated as an ideal gas, enters the gas turbine at 2400 R. The pressure ratio for both the compressor and turbine is 6.624. No intercooling, reheat, or regeneration is used with the Brayton cycle. The exhaust of the gas turbine is used directly in a heat recovery steam generator (HSRG) without any supplemental firing and leaves the stack at 1000 R. Steam is produced at 1000 psia and 1000 F. The condenser pressure is 1 psia. No feed water heating is used and the pump work may be ignored.

(a) Draw the cycle and T-s diagrams.

(b) Calculate the heat added, per lbm of air.

(c) Calculate the steam flow rate, per lbm of air.

(d) Calculate the combined work in Btu/lbm air.

(e) Calculate the combined cycle thermal efficiency.

(f) Calculate the thermal efficiency if the Rankine cycle is not operating.

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Problem 24

A combined Brayton-Rankine cycle is designed using four 50-MWe gas turbines and one 120-MWe steam turbine. Each gas turbine operates with compressor inlet temperature 505 R, turbine inlet temperature 2450 R, a pressure ratio of 5 for compressor and turbine, and compressor and turbine isentropic and mechanical efficiencies of 0.87 and 0.96, respectively. The exhaust gas leaving the turbines go to a heat recovery steam generator and then to a regenerator with an effectiveness of 0.87. The fuel for the gas turbine is Ohio Natural Gas burned in 200 % theoretical air. The steam turbine has throttle conditions of 1200 psia and 1460 °C, one open-type feed water heater (not optimally placed) with an exit temperature of 920 R, condenser pressure of 1 psia, and turbine isentropic and mechanical efficiencies of 0.87 and 0.96, respectively. All electric generator efficiencies are 0.96. Supplemental firing at rated power raises the combustion product temperature to 2000 °C.

(a) Draw the cycle and T-s diagrams.

(b) Determine the required steam flow rate in lbm/hr.

(c) Determine the air mass flow rate in each gas turbine installation, in lbm/hr.

(d) Determine the ideal heat, mass flow rate of fuel, in lbm/hr, for each gas turbine operating at rated power and for supplemental firing.

(e) Calculate the stack temperature in F.

(f) Calculate the combined cycle efficiency at rated load.

(g) Calculate the combined cycle efficiency at startup when only one gas turbine is used at rated power with no supplementary _ring or regeneration. Ignore the pump work of the Rankine cycle.

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Problem 25 (ME436s14h6)

Find the pressure ratio required by an ideal Bryton cycle to produce a net work of 600 Btu/lbm of (i) helium and (ii) air with constant specific heats. The cycle has initial and maximum temperatures of 500 R and 2500 R, respectively. Also, calculate the optimum pressure ratio for both gases.

Answer:

	Helium	Air
c_p, Btu/lbm.R	1.250	0.240
k	1.659	1.4
r_p for 600 Btu/lbm	2.16 or 26.62	Not Applicable
$r_{p,opt}$	7.58	16.72
w_{net} at $r_{p,opt}$, Btu/lbm.R	954.8	183.3
$r_{p,max}$	57.5	279.6

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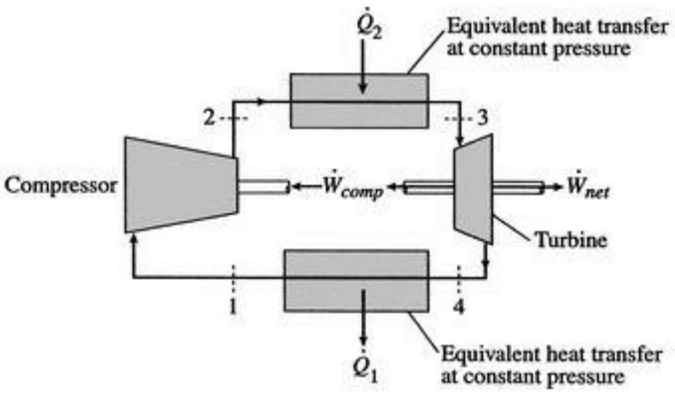
Problem 26 (ME436s14f-3 / ME436s17q3)

In an air-standard Brayton cycle (c_p = 1.005 kJ/kg.K, k = 1.4), the air enters the compressor at 0.1 MPa, 15 °C. The pressure leaving the compressor is 1.0 MPa and the maximum temperature in the cycle is 1100 °C. Determine

(a) The pressure and temperature at each point in the cycle;

(b) The compressor work, turbine work, heat transfer in and out of the cycle, and thermal efficiency of the cycle.

Bryton Cycle:



Prepare a table that looks like this:

	State 1	State 2	State 3	State 4
Pressure, MPa				
Temperature, K				

For an isentropic process, 1 to 2: $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$

For an ideal gas: $\Delta h = c_p \, \Delta T$

Answer:

	State 1	**State 2**	**State 3**	**State 4**
Pressure, MPa	0.1	1	1	0.1
Temperature, K	288	556.8	1373	711

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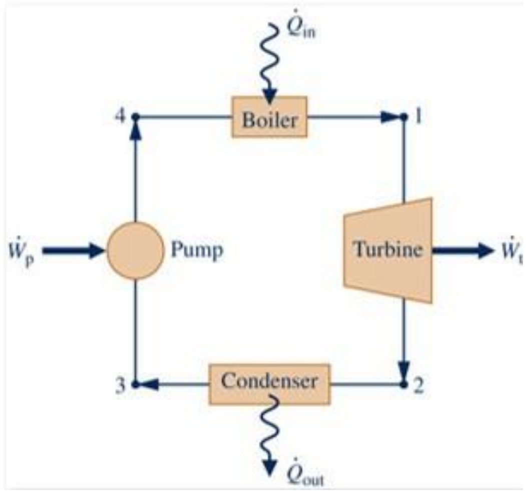
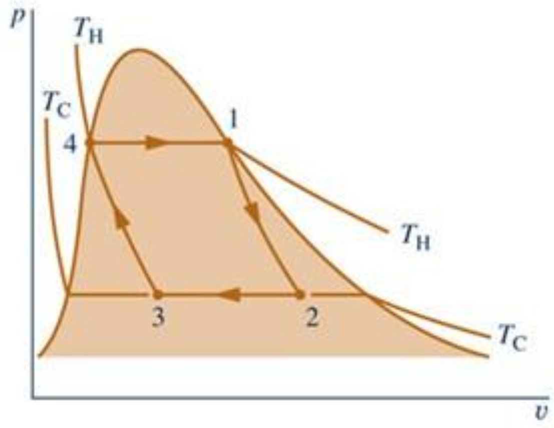
Problem 27 (ME436s15h2)

The figure gives the schematic of a vapor power plant in which water steadily circulates through the four components shown. The water flows through the boiler and condenser at constant pressure, and through the turbine and pump adiabatically. Kinetic and potential energy effects can be ignored.





Process 4-1: Boiler: Constant pressure at 1 MPa from saturated liquid to saturated vapor.

Process 2-3: Condenser: Constant pressure at 20 kPa from x_2 = 88 % to x_3 = 18 %.

(a) Find $\frac{\dot{W}_T}{\dot{m}} = \frac{\dot{W}_{12}}{\dot{m}}$ in kJ/kg

(b) Find $\frac{\dot{Q}_{out}}{\dot{m}} = \frac{\dot{Q}_{23}}{\dot{m}}$ in kJ/kg

(c) Find $\frac{\dot{W}_P}{\dot{m}} = \frac{\dot{W}_{34}}{\dot{m}}$ in kJ/kg

(d) Find $\frac{\dot{Q}_{in}}{\dot{m}} = \frac{\dot{Q}_{41}}{\dot{m}}$ in kJ/kg

(e) Find the thermal efficiency of the cycle and compare with the Carnot efficiency.

From thermodynamic property tables:

State 4: P_4 = 1MPa = 10 bar; sat. liquid; T_4 = 179.9 C v_4 = 0.0011273 m^3/kg u_4=761.68 kJ/kg

State 1: P_1 = 1 MPa = 10 bar; sat. vapor; T_1 = 179.9 C v_1 = 0.1944 m^3/kg u_1 = 2583.6 kJ/kg

State 2: P_2 = 20 kPa = 0.2 bar x_2 = 88 % T_2 = 60.06 C

v_f = 0.0010172 v_g= 7.649 u_f = 251.38 u_g = 2456.7

$v_2 = v_f + x_2 (v_g - v_f)$ = 6.731 m^3/kg $u_2 = u_f + x_2 (u_g - u_f)$ = 2192.1 kJ/kg

State 3: P_3 = 20 kPa = 0.2 bar x_3 = 18% T_3= 60.06 C

v_f = 0.0010172 v_g= 7.649 u_f = 251.38 u_g = 2456.7

$v_3 = v_f + x_3 (v_g - v_f)$ = 1.378 m^3/kg $u_3 = u_f + x_3 (u_g - u_f)$ = 648.3 kJ/kg

Answer: (a) $\frac{W_{12}}{m}$ = - 391.5 kJ/kg

(b) $\frac{Q_{23}}{m}$ = - 1649.9 kJ/kg

(c) $\frac{W_{34}}{m}$ = - 113.38 kJ/kg

(d) $\frac{Q_{41}}{m}$ = 2015.2 kJ/kg

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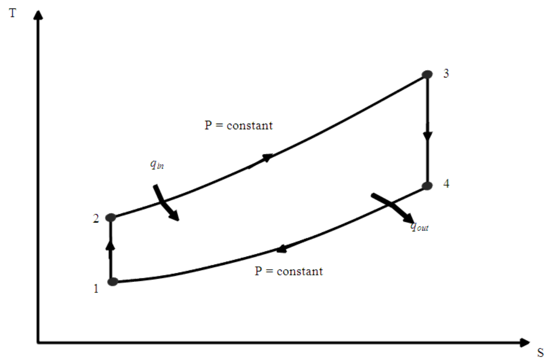
Problem 28 (ME436s15q3)



A Bryton gas cycle operates with isentropic compression and expansion as shown in the T-s diagram. Air enters the compressor at 95 kPa and ambient temperature (295 K). The compressor has a ratio 6:1, and the compressed air is heated to 1100 K. The combustion products are expanded in a turbine. Compute the thermal efficiency of the cycle.

Using air tables and interpolation, the enthalpy of the air at different states can be found as:
h_1 = 295.2 kJ/kg, h_2 = 492.7 kJ/kg, h_3 = 1161.1 kJ/kg, h_4 = 706.5 kJ/kg

Answer: η_{th} = 38.5 %

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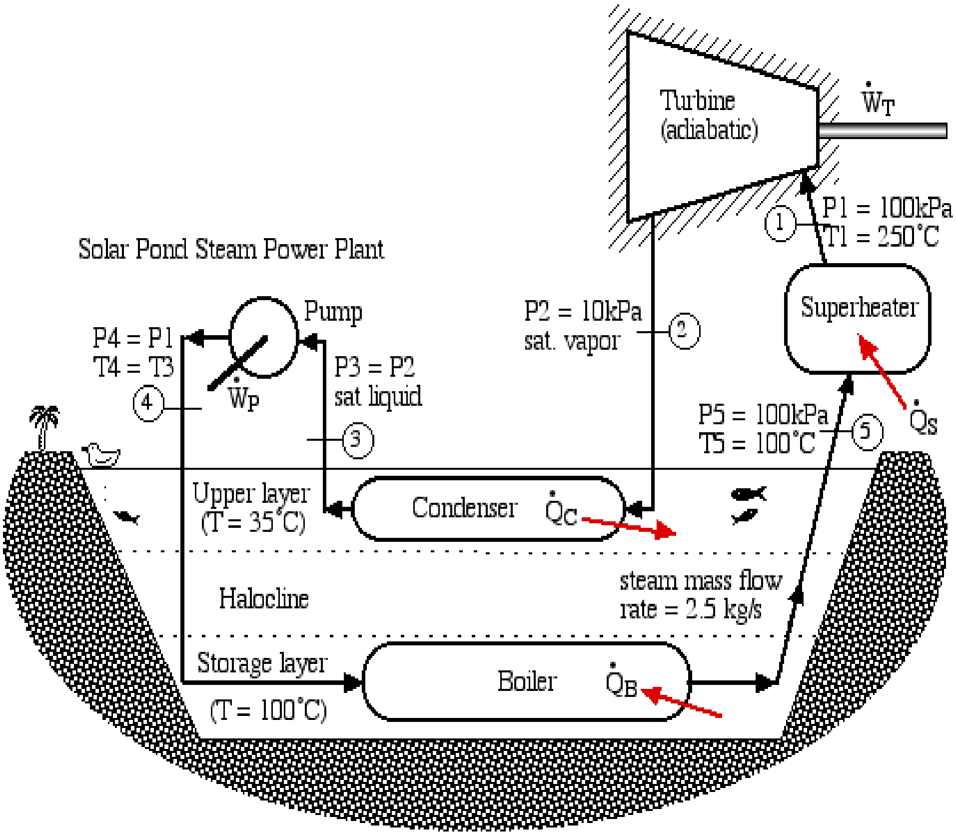
Problem 29 (ME405f15q6)

A solar-pond power plant shown in the Figure operates on an ideal, simple Rankine cycle with R-134a as the working fluid. The refrigerant enters the turbine as saturated vapor at 1.3 MPa and exits at 0.6 MPa. The mass flow rate is 5 kg/s.



(a) The thermal efficiency of the cycle, and

(b) The power output of the plant.

See http://www.ohio.edu/mechanical/thermo/property_tables/R134a/R134a_PresSat.html for the saturated properties of R134a.

$$\eta_{th} = \frac{q_{in} - q_{out}}{q_{in}} \qquad q_{in} = h_3 - h_2 \qquad q_{out} = h_4 - h_1 \qquad \dot{W} = \dot{m}\,(q_{in} - q_{out})$$

R134a - TetraFlouroEthane Saturation Properties - Pressure Table

Pressure	Temp	volume (m^3/kg)		enthalpy (kJ/kg)			entropy (kJ/kg.K)		
kPa	°C	v_f	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
100	-26.4	0.000726	0.1926	17.3	217.2	234.5	0.072	0.8799	0.9519
200	-10.1	0.000753	0.0999	38.5	206	244.5	0.1547	0.7831	0.9378
300	0.7	0.000774	0.0677	52.8	198.1	250.9	0.2077	0.7234	0.9311
400	8.9	0.000791	0.0512	64	191.6	255.6	0.2477	0.6793	0.927
500	15.7	0.000806	0.0411	73.4	186	259.3	0.2803	0.6438	0.9241
600	21.6	0.00082	0.0343	81.5	180.9	262.4	0.3081	0.6138	0.9219
700	26.7	0.000833	0.0294	88.8	176.2	265.1	0.3324	0.5876	0.92
800	31.3	0.000846	0.0256	95.5	171.8	267.3	0.3541	0.5643	0.9184
900	35.5	0.000858	0.0227	101.6	167.7	269.3	0.3739	0.5431	0.917
1000	39.4	0.00087	0.0203	107.4	163.7	271	0.392	0.5237	0.9157
1200	46.3	0.000894	0.0167	117.8	156.1	273.9	0.4245	0.4886	0.9131
1400	52.4	0.000917	0.0141	127.3	148.9	276.2	0.4533	0.4573	0.9106
1600	57.9	0.00094	0.0121	136	141.9	277.9	0.4792	0.4287	0.908
1800	62.9	0.000964	0.0106	144.1	135.1	279.2	0.5031	0.402	0.9051

Answer: (a) η_{th} = 7.86 %

(b) $\dot{W}$ = 75.8 kW

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Problem 30 (ME405f15m1-3)

A Bryton gas cycle operates with isentropic compression and expansion Air enters the compressor at 95 kPa and ambient temperature (295 K). The compressor has a ratio 6:1, and the compressed air is heated to 1100 K. The combustion products are expanded in a turbine.

(a) Draw a schematic diagram of the power plant and identify devices on the diagram.

(b) Draw the cycle on a T-s diagram and identify the states of the fluid.

(c) Find the heat input, turbine work, and compressor work.

(d) Find the thermal efficiency of the cycle.

Kinetic and potential energy effects can be ignored.

Using air tables and interpolation, enthalpy of the air at different states can be found as:

h_1 = 295.2 kJ/kg (at the compressor entrance)

h_2 = 492.7 kJ/kg (at the compressor exit)

h_3 = 1161.1 kJ/kg (at the turbine entrance)

h_4 = 706.5 kJ/kg (at the turbine exit)

Answer: (c) q_{in} = 668.4 kJ/kg ; $w_{turbine}$ = 454.6 kJ/kg ; $w_{compressor}$ = - 197.5 kJ/kg

(d) η_{th} = 38.5 %

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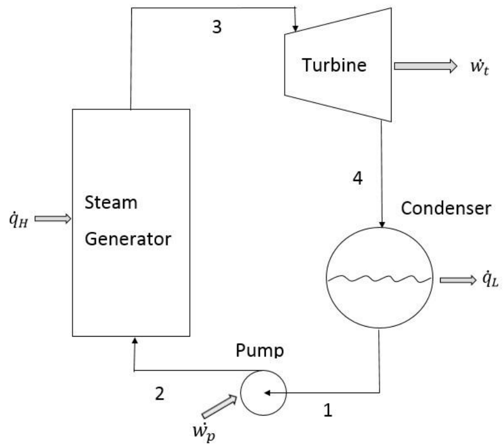
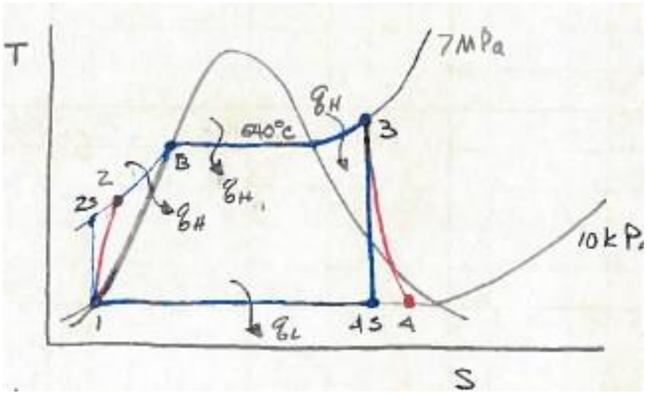
Problem 31 (ME436s16q4)

Find the thermal efficiency and the specific work of a simple Rankine cycle if the maximum temperature and pressure are 540 °C and 7 MPa and the minimum pressure is 10 kPa. The turbine and pump efficiencies are both 85 %.



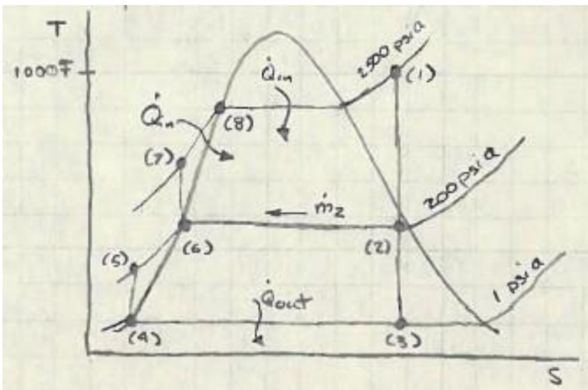


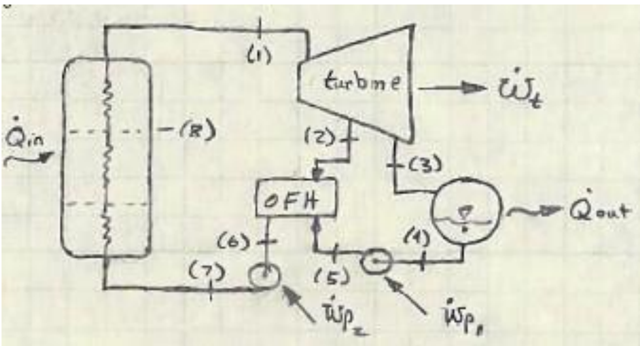
Answer: $w_{net} = w_T + w_P$ = 1117.7 – 8.31 = 1109.7 kJ/kg ; η_{th} = 33.55 %

****

Problem 32

An ideal Rankine cycle operates between 2500 psia and 1000 °F at throttle and 1 psia in the condenser. One open feedwater heater is placed at 200 psia. Calculate the net work and heat input in Btu/lbm.





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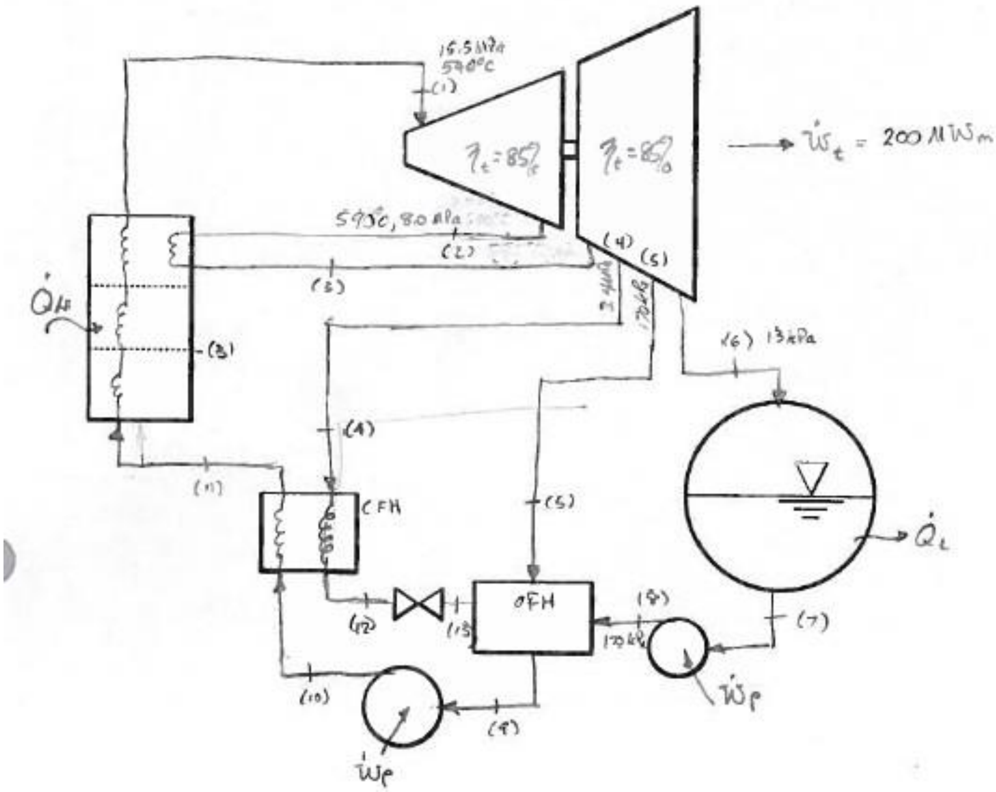
Problem 33

Determine the thermal efficiency, the required steam flow rate, and the moisture at the turbine exhaust for a reheat/regenerative cycle which is to produce 200 MW at the turbine coupling if the turbine throttle conditions are 15.5 MPa and 540 °C; reheat is at 8 MPa and 590 °C; one closed feed water heater is at 3.4 MPa; an open feed water heater is at 170 kPa; and the condenser pressure is 13 kPa.

The adiabatic turbine and pump efficiencies are 84 %. The temperature difference in the closed feed water heater is 3 °C and the drain for the closed feed water heater is trapped to the open feed water heater. Sketch the cycle on a T-s diagram.



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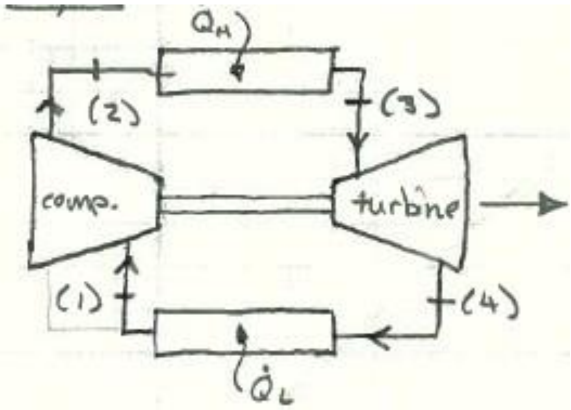
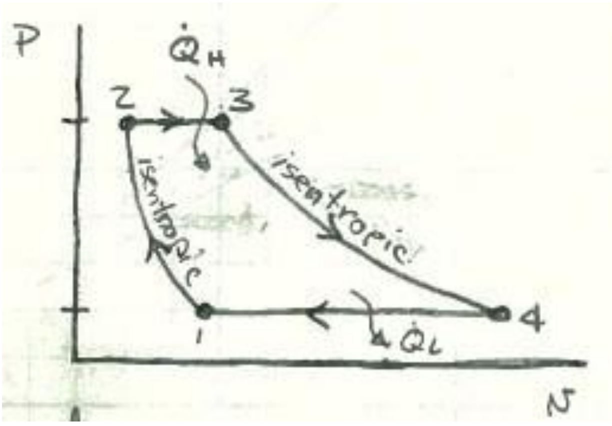
Problem 34

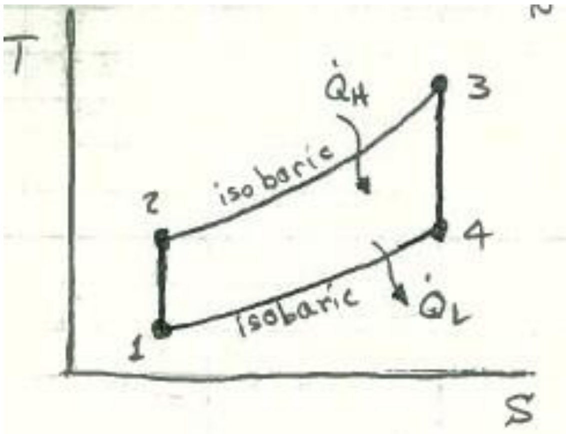
In an air-standard Brayton cycle, the air enters the compressor at 0.1 MPa, 15 °C. The pressure leaving the compressor is 1.0 MPa and the maximum temperature in the cycle is 1100 °C. Determine



(a) The pressure and temperature at each point in the cycle

(b) The compressor work, turbine work, and cycle efficiency





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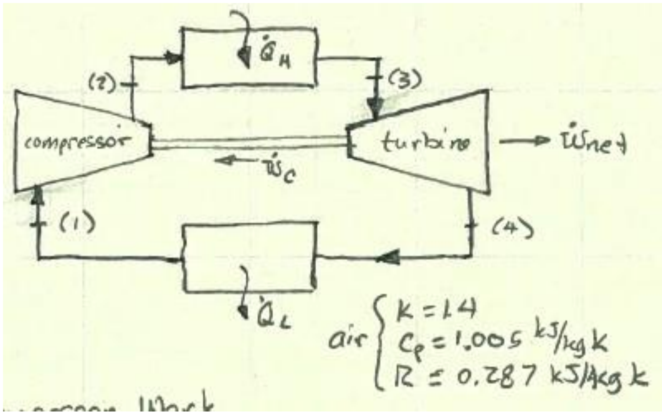
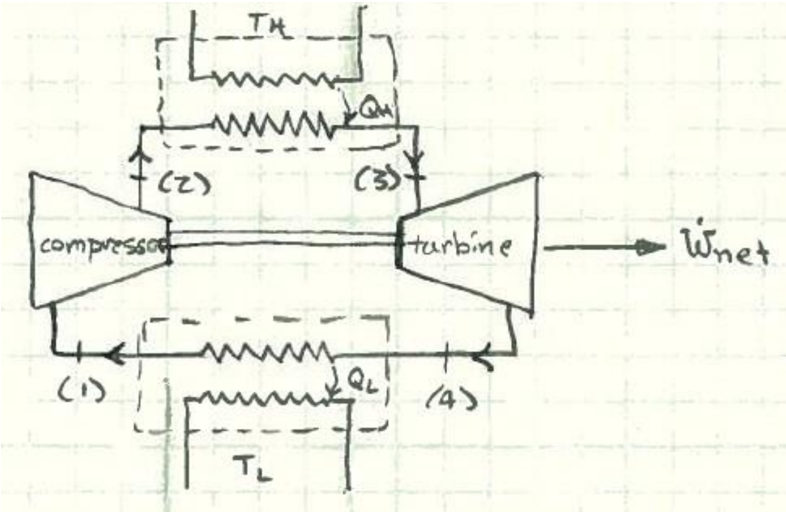
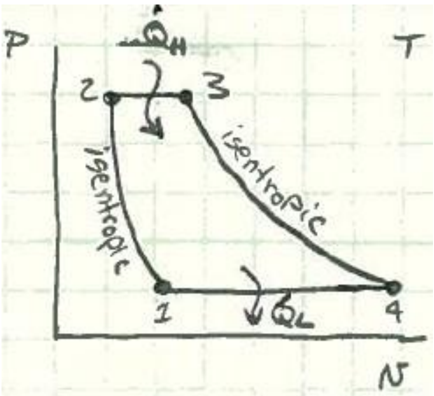
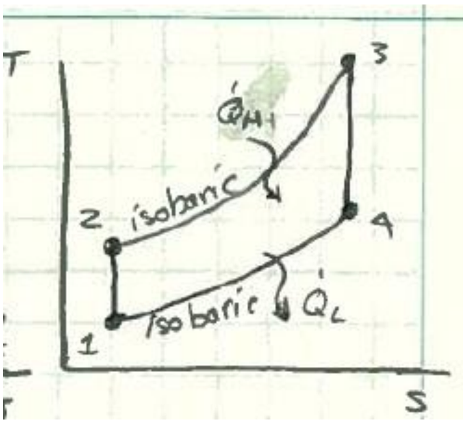
Problem 35



An air-standard Brayton cycle operates with a compression ratio of 5.0. The actual expansion & compression efficiencies of the gas processes are 88 % and 82 %, respectively, and the maximum and minimum temperatures are 750 °C and 16 °C, respectively. Compute the compression work, the expansion work, the ratio of compression work to expansion work (back-work ratio), and the actual and theoretical thermal efficiencies. If the power output of the installation is 8 MW, determine the mass flow rate, kg/min.







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Problem 36

Find the pressure ratio required by an ideal Bryton cycle to produce a net work of 600 Btu/lbm of (i) helium and (ii) air with constant specific heats. The cycle has initial and maximum temperatures of 500 R and 2500 R, respectively. Also, calculate the optimum pressure ratio for both gases.

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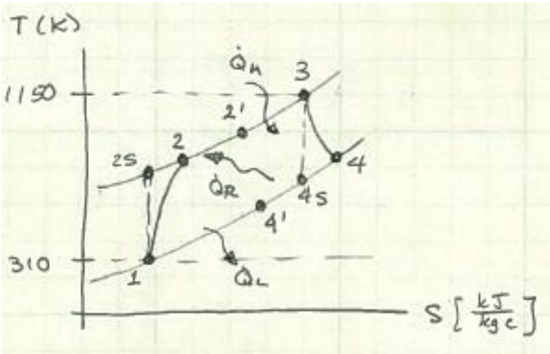
Problem 37 (ME436s22m-2 / ME405s22m-2)



A simple Bryton cycle using air as the working fluid has a pressure ratio of 7. The minimum and maximum temperatures in the cycle are 310 K and 1150 K. Assume that the isentropic efficiencies of the compressor and the turbine are 75 % and 82 %, respectively. The constant specific heat of air is c_p = 1.004 kJ/kg.K. Determine:

a) The air temperatures, T_2 and T_4;
b) The net work output; and
c) The thermal efficiency of the cycle.

Hints:

$$k = 1.4 \qquad \frac{T_{2s}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} \qquad \Delta h = c_p\ \Delta T \qquad \eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}} \qquad \eta = 1 - r_p^{\frac{k-1}{k}}$$

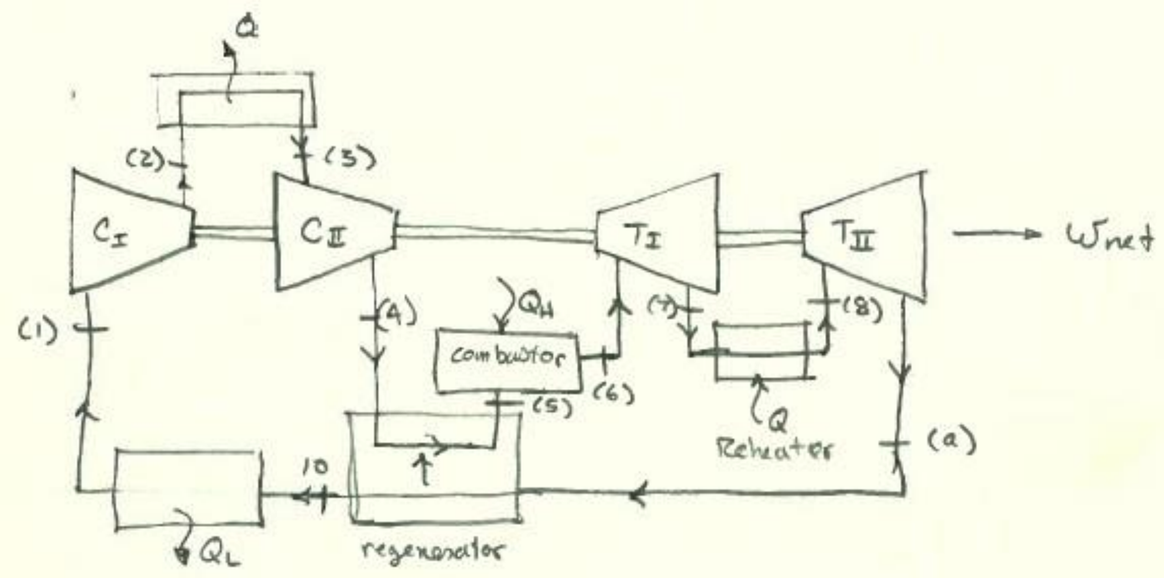
Answers: T_2 = 617.77 K ; T_4 = 747.52 K ; w_{net} = 95.09 kJ/kg ; η = 0.43

****

Problem 38

An ideal gas turbine cycle has 2 stages of compression and 2 stages of expansion. Given data are: $r_{p,total}$ = 8, $T_{c,in}$ = 300 K (both stages), $T_{T,in}$ = 1300 K (both stages). Find

(a) Back work ratio and thermal efficiency when there is no regenerator;
(b) Back work ratio and thermal efficiency when there is an ideal regenerator.



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Problem 39 (ME405f16h2 / ME436s17h2 / ME436s20h3)

An ideal gas cycle is composed of four processes with air as the working fluid:

1 -> 2: Isentropic compression from 100 kPa and 27 °C to 1 MPa.

2 -> 3: Isobaric heat addition of 2800 kJ/kg.

3 -> 4: Isochoric heat rejection to 100 kPa.

4 -> 1: Isobaric heat rejection to state (1).

(a) Show the cycle on a P-v and T-s diagrams.

(b) Calculate the maximum temperature in the cycle.

(c) Calculate the thermal efficiency.

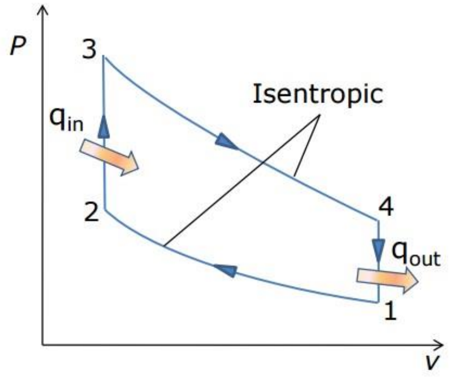
Assume that the specific heats are constant at the room temperature value.

Answer: (b) T_3 = 3360 K

****

Problem 40 (ME405f16m1-2 / ME436s17m1-2 / ME436s18m1-2 / ME405s18m1-2)

An air standard Otto cycle is shown in the figure.



T_1 = 35 °C = 308 K

P_1 = 0.1 MPa

T_3 = 1100 °C = 1373 K

$r = \frac{v_1}{v_2} = 7$

For air: k = 1.4 and c_v = 0.718 kJ/kg.K

Find:

(a) the temperature and pressure at other states in the cycle;

(b) heat supplied per kg of air;

(c) work done per kg of air;

(d) thermal efficiency of the cycle.

For an isentropic process: $\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^k$ and $\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1}$

For an isochoric process in an ideal gas: $Q = c_v \Delta T$

Answer: (a) P_2 = 1524 kPa ; T_2 = 670.8 K ; P_3 = 3119.34 kPa ; T_4 = 630.39 K

(b) q_{in} = 504.18 kJ/kg

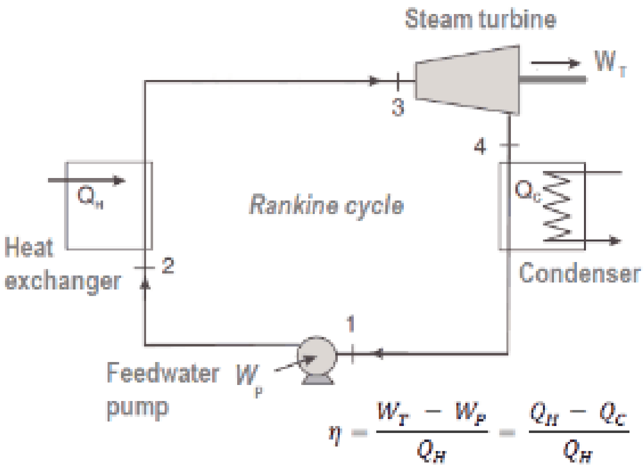
(c) w_{net} = 272.74 kJ/kg

(d) η_{th} = 0.54

****

Problem 41 (ME436s18q4 / ME405s18q4)

An ideal Rankine cycle is shown in the figure. The turbine operates at steady state with inlet conditions of P_3 = 6 MPa, T_3 = 275.6 °C, x = 1 (point 3). Steam leaves this stage of turbine at a pressure of P_4 = 0.008 MPa, T_4 = 41.5 °C and (point 4).



Calculate:

a) The vapor quality of the outlet steam, x_4.

b) The enthalpy difference between these two states (3 → 4), which corresponds to the work done by the steam, W_T.

c) The enthalpy difference between these two states (1 → 2), which corresponds to the work done by feed water pump, W_P.

d) The enthalpy difference between these two states (2 → 3), which corresponds to the net heat added in the steam generator.

e) The thermodynamic efficiency of this cycle and compare this value with the Carnot's efficiency.

Answer: (a) x_4 = 0.694; (b) w_T = 945 kJ/kg; (c) w_P = - 5.7 kJ/kg; (d) q_{in} = 2605.3 kJ/kg;
(e) η_C = 0.426 η_{th} = 0.361

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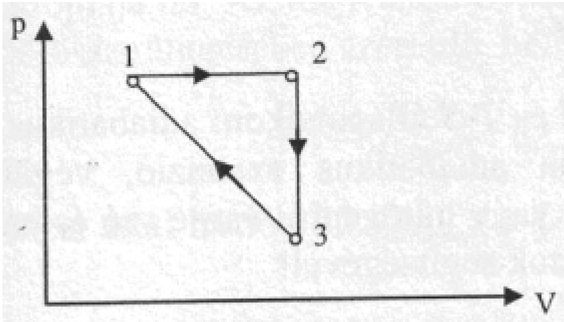
Problem 42 (ME436s18h2 / ME405s18h2)

The working gas is helium (He) in a thermodynamic cycle given in the Figure.



The known parameters are: P_1 = 300 kPa, P_3 = 100 kPa, V_1 = 0.5 m3, V_2 = 0.8 m3.

Calculate the following:

a) Heat flow, work done, and internal energy change during the process 1 -> 2.
b) Heat flow, work done, and internal energy change during the process 2 -> 3.
c) Heat flow, work done, and internal energy change during the process 3 -> 1.
d) Heat flow, work done, and internal energy change in the cycle
e) Thermodynamic efficiency of the cycle?

Answer:

a) ${}_1Q_2$ = 225 kJ ${}_1W_2$ = 90 kJ ${}_1\Delta U_2$ = 135 kJ

b) ${}_2Q_3$ = - 240 kJ ${}_2W_3$ = 0 ${}_2\Delta U_3$ = - 240 kJ

c) ${}_3W_1$ = - 60 kJ ${}_3\Delta U_1$ = 105 kJ ${}_3Q_1$ = 45 KJ

d) Q = 30 kJ W = - 30 kJ ΔU = 0 kJ

e) η = 0.111

****

Problem 43

A heat engine works by Carnot thermodynamic cycle between temperature limits of 500 °C and 100 °C. During every single thermodynamic cycle the heat absorbed by the system is 250 J. What is the heat absorbed by an outer cold heat container (or in other words the heat dissipated from the heat engine to the medium)? At least how many thermodynamic cycles have to be made if the engine has to raise up a piece of stone from the surface (0^{th} level) to 100 meters height? Mass of the stone is given by 500 kg.

Answer: $Q_{dissipated}$ =120.634 J, 3865 thermodynamic cycles

****

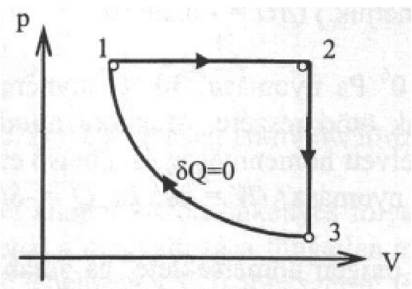
Problem 44

A thermodynamic cycle is made with the working gas air. Pressure and temperature of the air is 1 bar and 27 °C, respectively in the original status. The mentioned thermodynamic cycle can be described as follows: Step (1) first, the air is expanded isothermally to a new volume which is 4-times greater than the original volume. Step (2) as next, the volume is compressed to the original volume keeping the pressure constant. Step (3) finally, the gas is gone back to its original status. What is the thermodynamic efficiency of the given cycle?

Answer: η = 19.51 %

****

Problem 45

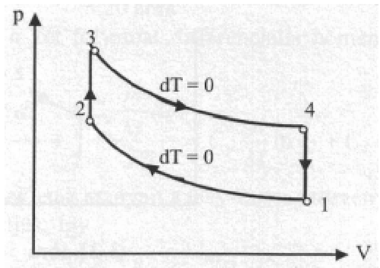


What is the efficiency of the thermodynamic cycle given by the Figure? The cycle is made by double atomic gas (gas molecules with double atoms, for example N_2) and $V_2 / V_1 = 2$

Answer: η = 11.28 %

****

Problem 46



A thermodynamic cycle is given by the Figure. The working gas is oxygen (O_2). What is the thermal efficiency of the cycle, if the followings are given: $P_3 = 4 P_2$, ratio of compression is 6? What is the thermal efficiency of a special Carnot-cycle works in between the same temperature limits?

Answer: η = 36.65 %, η_{Carnot} = 75 %

****

Problem 47

The working gas of a thermodynamic cycle is oxygen. In the original status the gas is given by the following status indicators: $P_1 = 10^5$ Pa, V_1 = 10 liters, T_1 = 10 °C. As first step of the cycle the gas is warmed up to the pressure of $P_2 = 4\ 10^5$ Pa keeping the volume fixed. After it the volume of the gas is extended to its double value keeping the pressure constant. Next step is: the gas is cooled down to the original pressure during the volume of the gas is fixed. Finally, the gas is gone back to the original status holding the pressure constant. What is the thermodynamic efficiency of the cycle and what is the work done during the whole thermal cycle?

Answer: $\eta = 14$ %, W = 300 J

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Problem 48

Original volume of an ideal gas is $2\ 10^{-3}$ m^3 at pressure value of $1.2\ 10^5$ N/m^2 and at temperature of 0 °C. The gas takes part in the thermodynamic cycle given here: As first step the pressure of the gas is increased to $1.5\ 10^5$ Pa keeping the volume constant. Next step is to expand the gas isothermally to the original pressure value. After it, as last process is made: the gas is gone back to its original status keeping the pressure fixed. What is the temperature during the isothermal process? What is the volume reached at the end of the isothermal process? What is the work done by the gas during its whole cycle?

Answer: $T_2 = 341.25$, $V_3 = 2.5\ 10^{-3}$ m^3, W = 6.9415 J

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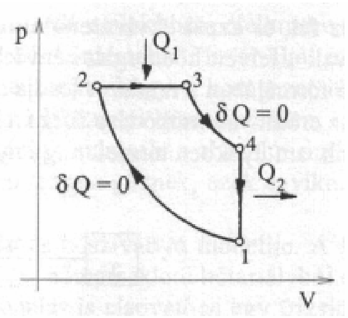
Problem 49



What is the thermodynamic efficiency of a Diesel-engine cycle? The cycle is shown on the Figure. Give us the thermodynamic efficiency by only temperatures!

Answer: $\eta = 1 + \frac{1}{k} \frac{T_1 - T_4}{T_3 - T_2}$

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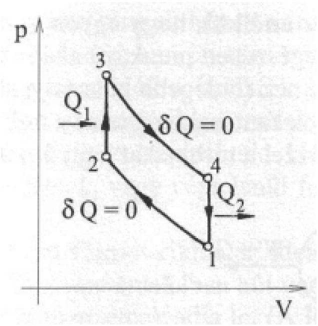
Problem 50

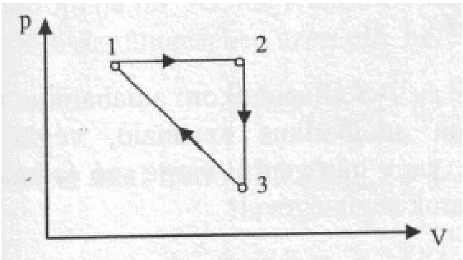


What is the theoretical thermodynamic efficiency of an Otto-engine if k = 1.4 and the ratio of the compression is 9.5 (see the Figure)? What is the heat dissipated to the surrounding medium if the heat absorbed by the cycle is $Q_{absorbed}$ = 10 000 J?

Answer: η = 59.36 %, $Q_{dissipated}$ = 4063.6 J

****

Problem 51



The working gas is helium (He) in a thermodynamic cycle given by the Figure. All known parameters are the followings: $P_1 = 3\ 10^5$ Pa, $P_2 = 10^5$ Pa, $V_1 = 0.5$ m^3, $V_2 = 0.8$ m^3. What are the heats during all the given processes (separately)? What are the works done during the processes (calculate the work for all given processes separately)? What is the change of the internal energy during the processes (separately)? What are these values for the whole cycle? What is the thermodynamic efficiency of the cycle?

Answer: $Q_1 = 2.25\ 10^5$ J, $Q_2 = 2.4\ 10^5$ J, $Q_3 = 0.45\ 10^5$ J,

$W_1 = 0.9\ 10^5$ J, $W_2 = 0$, $W_3 = 0.6\ 10^5$ J,

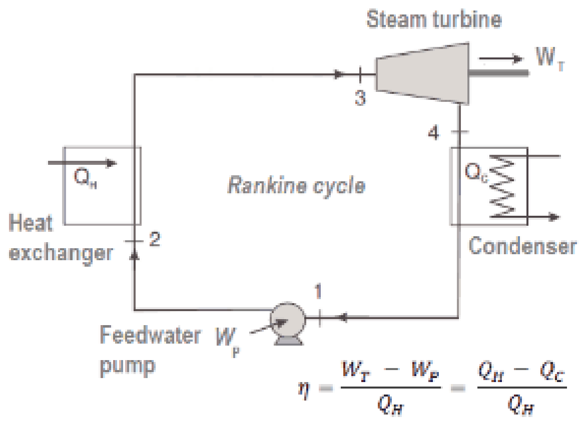
$\Delta U_1 = 1.35\ 10^5$ J, $\Delta U_2 = Q_2$, $\Delta U_3 = 1.05\ 10^5$ J,

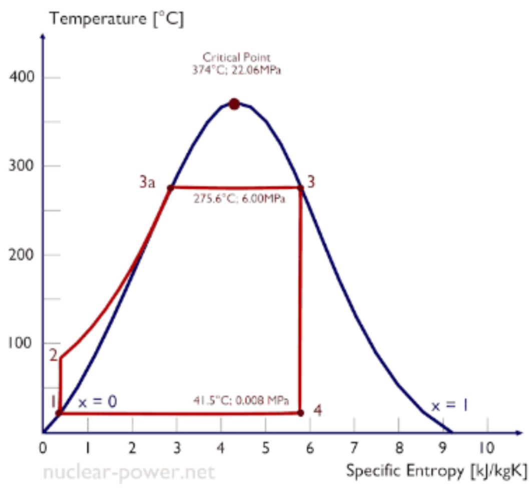
$Q = 0.3\ 10^5$ J, $W = 0.3\ 10^5$ J, $\Delta U = 0$, η = 11.1 %

****

Problem 52 (ME436s19h4 / ME405s19h4)

A Rankine cycle of a power plant is shown in the figure. The turbine operates at steady state with inlet conditions of P_3 = 6 MPa, T_3 = 275.6 °C, x_3 = 1. Steam leaves the turbine at a pressure of P_4 = 0.008 MPa, and T_4 = 41 °C (state 4).





Calculate:

a) The vapor quality of the outlet steam, x_4;

b) Turbine work, W_T;

c) Pump work, W_P;

d) Heat added at the steam generator, Q_H;

e) The thermal efficiency of this cycle and compare this value with the Carnot's efficiency.

Answers:

(a) $x_4 = 0.694$

(b) $w_T = 945$kJ/kg

(c) $w_P = -5.7$ kJ/kg

(d) $q_H = 2605.3$ kJ/kg

(e) $\eta_C = 0.426$

****

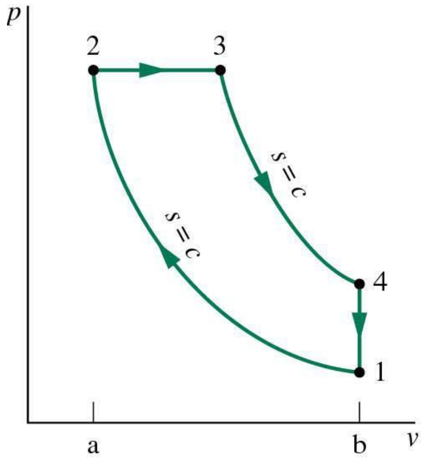
Problem 53 (ME436s19m1-4 / ME405s19m1-4)

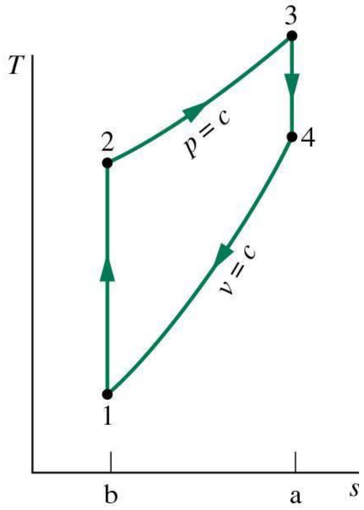
In a Diesel cycle, the compression ratio, i.e., the ratio of volumes, v_1/v_2, is 15. Compression begins at 0.1 MPa, 40 ^oC. The heat added is 1675 kJ/kg. Find

(a) Properties at states 2, 3, and 4 (pressure, temperature, specific volume);

(b) Work done per kg of air;

(c) Thermal efficiency;





Ideal gas: P v = R T

For air:

R = 0.287 kJ/kg.K

k = 1.4

c_p = 1.005 kJ/kg.K

c_v = 0.718 kJ/kg.K

Isentropic process: $\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1}$ $\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^{k}$

Answers:

(a)

State	P, kPa	T, K	v, m^3/kg
2	4431	924.6	0.06
3	4431	2591.3	0.168
4	424	1325.4	0.898

(b) w = 948.12 kJ/kg

(c) η_{th} = 56.6 %

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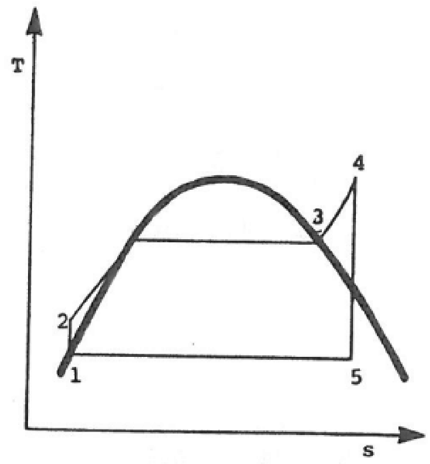
Problem 54 (ME436s21q5 / ME405s21q5 / ME436s22q4 / ME405s22q4)



Steam leaves the boiler in a steam turbine plant at P_4 = 2 MPa, T_4 = 300 °C and is expanded to P_5 = 3.5 kPa before entering the condensor. Find the efficiency of the cycle.

$$\eta = \frac{w_{net}}{q_{42}} = \frac{w_T + w_P}{q_{42}} = \frac{w_{45} + w_{12}}{q_{42}}$$

$w_{45} = h_4 - h_5$

$w_{12} = h_1 - h_2 = v_{1,f} (P_1 - P_2)$

$q_{42} = h_4 - h_2$

Using thermodynamic tables:

State 4: h_4 = 3025 kJ/kg s_4 = 6768 KJ/kg.K

State 5: $s_{5,g}$ = 8521 kJ/kg $h_{5,f}$ = 112 kJ/kg

$s_{5,f}$ = 0.391 kJ/kg.K $h_{5,fg}$ = 2438 kJ/kg

State 1: $v_{1,f}$ = 0.0010 m^3/kg $h_1 = h_{5,f}$ = 112 kJ/kg

Answer: η = 0.344

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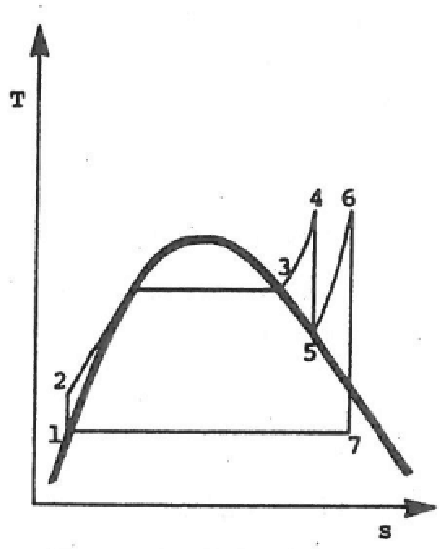
Problem 55 (ME436s21h5 / ME405s21h5 / ME436s22h5 / ME405s22h4)



Steam leaves the boiler in a steam turbine plant at P_4 = 2 MPa, T_4 = 300 °C, is expanded to P_5 until saturation, reheated back to 300 °C, then expanded to P_7 = 3.5 kPa before entering the condensor as shown in the figure. Find the efficiency of the cycle.

$$\eta = \frac{w_{net}}{q_{42} + q_{65}} = \frac{w_{45} + w_{67} + w_{12}}{q_{42} + q_{65}}$$

$w_{45} = h_4 - h_5$ $w_{67} = h_6 - h_7$

$w_{12} = h_1 - h_2 = v_{1,f} (P_1 - P_2)$

$q_{42} = h_4 - h_2$

$q_{65} = h_6 - h_5$

Answer: η = 0.35

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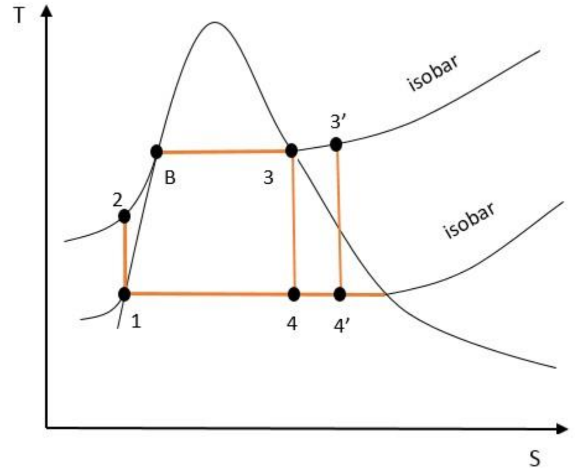
Problem 56 (ME436s21m-4 / ME405s21m-4)



A small power plant uses R-134A as the working fluid and works on an *ideal* Rankine cycle. The turbine receives saturated vapor at 50 °C (state 3) and produces 80 kW mechanical power. The fluid exits the turbine at 20 °C (state 4). The T-s diagram of the cycle (states 1, 2, 3, 4) is shown in the figure.

Kinetic and potential energy effects can be ignored. Properties at different states are given in the table below

Properties							
	P, kPa	**T, °C**	**h_f, kJ/kg**	**h_g, kJ/kg**	**v, m³/kg**	s_f, kJ/kg.K	s_g, kJ/kg.K
State 1	571.7	20	79.32		0.0008161		
State 3	1319.15	50		275.28			0.91165
State 4	571.7	20	79.32	261.6		0.3006	0.9224

(a) Find the thermal efficiency of the cycle.

(b) What will be the effect of superheating to State 3'? Explain in words.

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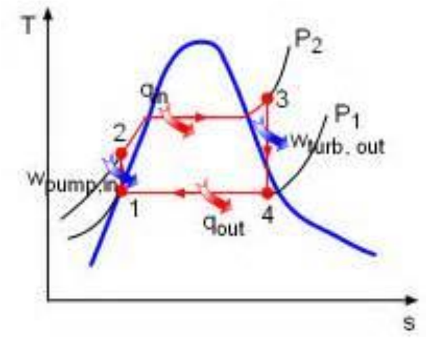
Problem 57 (ME436s22f-2 / ME405s22f2)

To reduce the volume flow rate and hence the physical size of the turbine, power plants that operate with low initial temperature water as a heat source, such as some types of geothermal and ocean temperature energy conversion (OTEC), use working fluids other than steam. Assume that there is such a power plant using propane as the working fluid; the turbine is isentropic receiving saturated vapor at 100 °C; the condenser temperature is 20 °C; and the cycle is producing 100 kW_m power. Find

(a) the missing four properties in the table below; and

(b) the mass and volume flow rate of the propane.



Number the states of the working fluid as shown in the figure.

State 1: Saturated liquid with quality x = 0.

State 2: Compressed liquid.

State 3: Assume saturated vapor (almost).

State 4: Actually liquid-vapor mixture. But, assume saturated liquid with quality, x = 1.

Properties of the propane:

	P, kPa	T, C	h, kJ/kg.K	v, m^3/kg
State 1 Saturated liquid	833.24	20	251.82	0.002
State2 Compressed liquid	?		?	?
State 3 Saturated vapor	3133	100 (assume 80)	629.3	
State 4 Saturated vapor	?	20	596.3	0.0118

Answer: $\dot{m}$ = 3.03 kg/s = 10909 kg/h = 0.36 m^3/s

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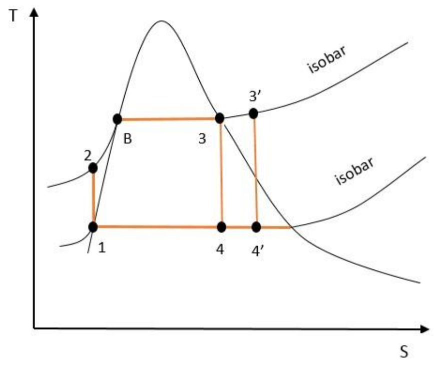

Problem 58 (ME405f22q5)

Steam generated in a power plant at a pressure of 8 MPa and a temperature of 500 C (state 3) is fed to a turbine. Exhaust for the turbine enters a condenser at 10 kPa (state 4), where it is condensed to saturated liquid (state 1), which is then pumped to the boiler (state 2)

If it is an ideal Rankine cycle, find the enthalpy of the steam at state 4 (exit of the turbine) and the turbine work.

Properties:

State	T, C	P, kPa	h, kJ/kg	s, kJ/kg.K
3	500	8000	3398.3	6.724

4	45.81	10	?	6.724
1	45.81	10	191.83	

At state 4: s_f = 0.6493 kJ/kg.K , s_g = 8.1502 kJ/kg.K
h_f = 191.83 kJ/kg , h_g = 2584.7 kJ/kg

Answer: h_4 = 2130.1 kJ/kg w_T = 1268.2 kJ/kg

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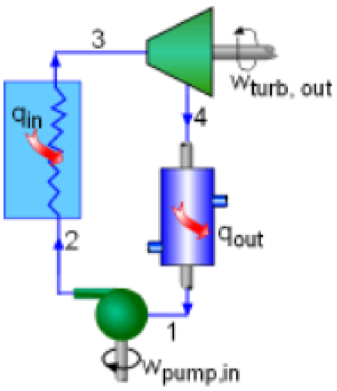
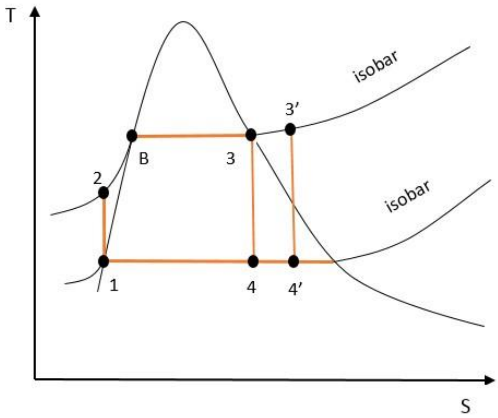
Problem 59 (ME405f22h5)

Steam generated in a power plant at a pressure of 8 MPa and a temperature of 500 °C (state 3) is fed to a turbine. Exhaust for the turbine enters a condenser at 10 kPa (state 4), where it is condensed to saturated liquid (state 1), which is then pumped to the boiler (state 2).



Schematic of the Rankine Cycle



a) What is the thermal efficiency of the ideal cycle?
b) What is the thermal efficiency of a real cycle operating at these conditions if the isentropic turbine and pump efficiencies are both 75 %?
c) If the rating of the power cycle of part (b) is 80 MW, what is the steam mass flow rate and what are the heat transfer rates in the boiler and the condenser?

Properties:

State	T, °C	P, kPa	h, kJ/kg	s, kJ/kg.K
3	500	8000	3398.3	6.724
4	45.81	10		6.724
1	45.81	10	191.83	
2		8000		

At state 4: s_f = 0.6493 kJ/kg.K , s_g = 8.1502 kJ/kg.K

h_f = 191.83 kJ/kg , h_g = 2584.7 kJ/kg

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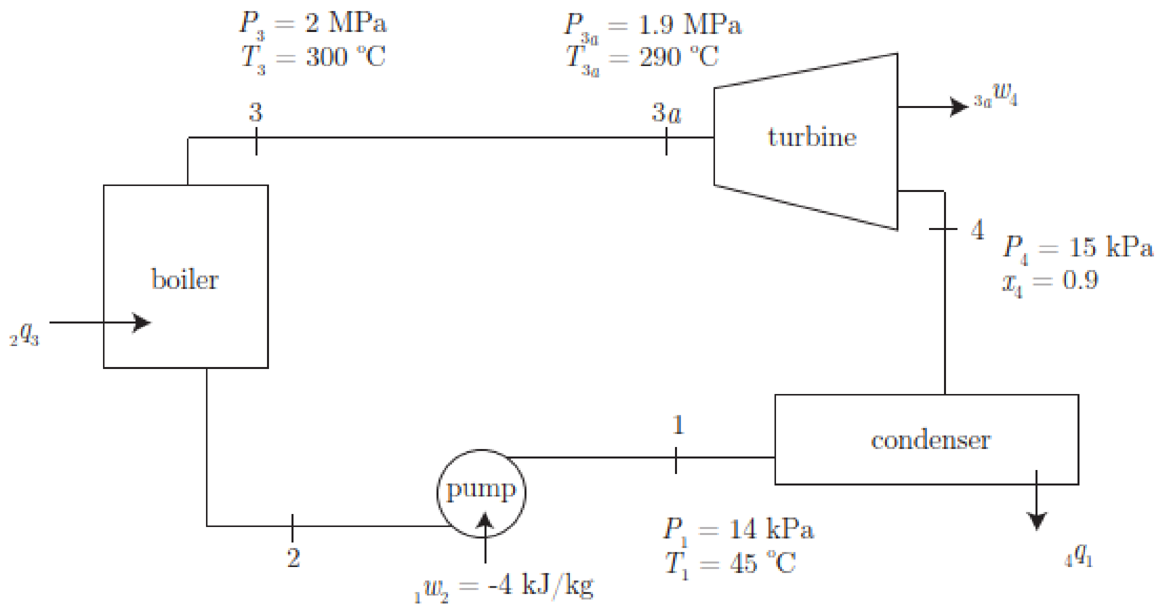
Problem 60 (ME405f23h4)

Consider the Rankine cycle sketched in the Figure for generation of power.



The cycle includes some of the effect of losses; thus, it is not an ideal Rankine cycle. But it is close. The actual plant is more complex than indicated in the Figure. It contains additional elements for cooling, heating with gas and oil, and pollution removal.

Find, on a per unit mass basis,

(a) the heat transfer in the boiler;

(b) the heat transfer in the line between the boiler and the turbine;

(c) the turbine work;

(d) the heat transfer in the condenser; and

(e) the thermal efficiency.

Use the steam tables for the properties. This is a steady state system composed of devices with one inlet and one exit. Neglect changes in KE and PE.

Answer: (a) ${}_2q_3$ = 2831.1 kJ/kg (b) ${}_3q_{3a}$ = - 21 kJ/kg (c) ${}_{3a}w_4$ = 640.8 kJ/kg

(d) ${}_4q_1$ = - 2173.25 (e) η = 0.225

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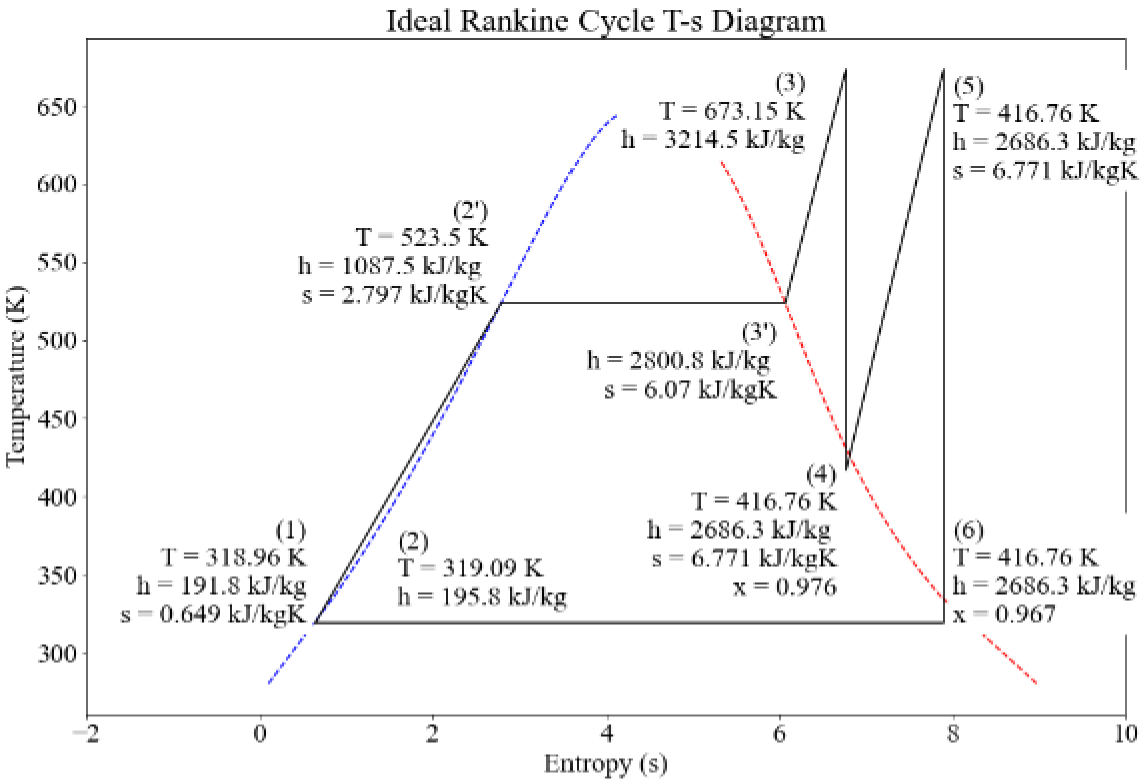
Problem 61 (ME405f24q4)

Consider a reheat cycle utilizing steam. Steam leaves the boiler and enters the turbine at 4 MPa, 400 ◦C. After expansion in the turbine to 400 kPa, the steam is reheated to 400 ◦C and then expanded in the low-pressure turbine to 10 kPa.



(a) Draw a schematic diagram of the cycle;

(b) Determine the cycle efficiency.

Corrections: P_5 = 400 kPa T_5 = 673 K h_5 = 3867 kJ/kg

P_6 = 10 kPa T_6 = 318.96 K h_6 = 2580 kJ/kg

Answer: η_{th} = 0.43

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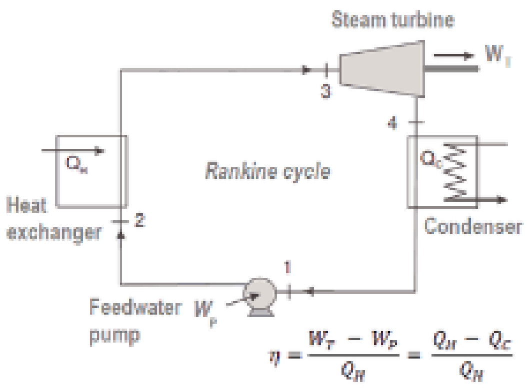
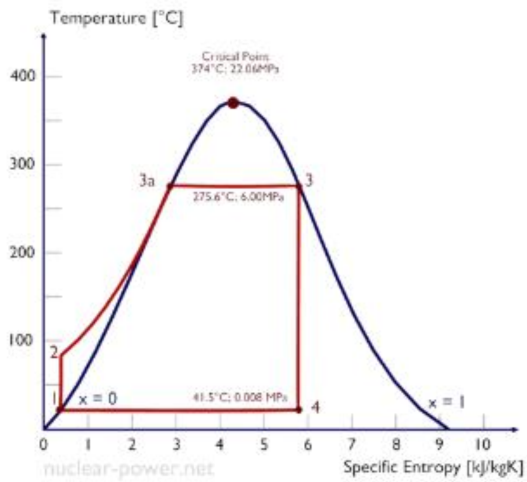
Problem 62 (ME405f24h4)

Consider the Rankine cycle sketched in the Figure for generation of power.





This is a simple cycle without reheat and condensing steam turbine running on saturated steam (dry steam). The turbine operates at a steady state with inlet conditions of 6 MPa, T = 275.6 °C. Steam leaves this turbine stage at a pressure of 0.008 MPa, 41.5 °C.

Calculate:

a) The vapor quality of the outlet steam.

b) The enthalpy difference between these two states (3 → 4) corresponds to the work done by the steam, w_T.

c) The enthalpy difference between these two states (1 → 2) corresponds to the work done by pumps, w_P.

d) The enthalpy difference between these two states (2 → 3) corresponds to the net heat added to the steam generator.

e) The thermodynamic efficiency of this cycle and compare this value with the Carnot's efficiency.

Answers: (a) x_4 = 0.69.4 %; (b) w_T = 945 kJ/kg; (c) w_P = - 5.7 kJ/kg;
(d) $Q_{in} = h_3 – h_2$ = 2605.3 kJ/kg; (e) η_{th} = 36.1 % η_C = 42.6 %

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