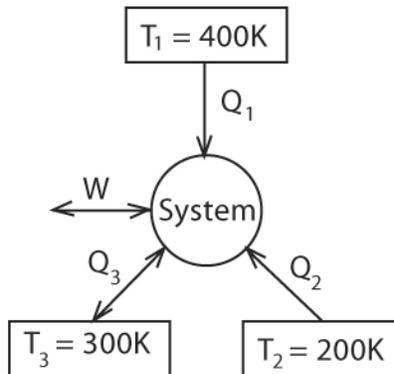# 16.050 Thermal Energy

Do all eight problems. All problems count the same.

1. A system undergoes a reversible cycle while exchanging heat with three thermal reservoirs, as shown below. Compute the magnitude and direction of Q_3 and W.

2. A tank contains 2 kg of nitrogen at 100 K with a quality of 50%. Through a valve, 0.5 kg is now removed while the temperature remains constant. Find the final quality inside the tank and the volume of nitrogen removed if the valve is located at:

    a) the top of the tank,

    b) the bottom of the tank.

    Hint: a table for saturated nitrogen is given on page 5.

3. Saturated water vapor enters a reversible, adiabatic turbine at a pressure of 10 MPa. At exit the pressure is 0.1 MPa. A table for steam properties is given on page 6.

    a) What are the inlet and exit temperatures?

    b) What are the inlet and exit entropy per unit mass?

    c) What are the inlet and exit qualities?

    d) What is the turbine work per unit mass?

    Suppose now that the turbine adiabatic efficiency is 0.8:

    e) Draw both the ideal and non-ideal processes on *T-s* and *h-s* diagrams and sketch isobars and isotherms through the inlet and exit states for the liquid region, inside the vapor dome and for superheated vapor.

    f) What is the turbine work per unit mass for the non-ideal expansion?

   g) What is the exit quality for the non-ideal expansion?

4. Hydrogen and oxygen in gaseous form flow into a combustion chamber and react with each other to produce H_2O, also in gaseous form. The flow rate of oxygen is 1 kmol/second and the proportions of the hydrogen and oxygen are such that all the incoming gas is involved in the reaction. The temperature of the reactants entering the combustion chamber is 298 K.

a) What is the equation that describes the reaction?

b) Assuming that all gases involved in the reaction can be considered perfect, what is the adiabatic flame temperature?

c) If the maximum temperature that can be tolerated in the combustion chamber is 1798 K, what is the rate at which heat would have to be removed from the combustion chamber?

Useful Information:

The enthalpy of formation for H_2O is $\bar{h}^o_{f,H_2O}$ =-242,000 kJ/kmol and the specific heats can be approximated as follows:

c_P for H_2 and O_2 can both be taken as constant and equal to 30 kJ/kmol-K
c_P for H_2O can be taken as constant and equal to 40 kJ/kmol-K

5. The figure below shows a 30-ohm electrical resistor located in an insulated duct carrying a stream of air. At steady state, an electric current of 15 amp passes through the resistor, whose temperature remains constant at 28°C. The air enters the duct at 15°C, 1 atm and exits at 25°C with a negligible change in pressure. Kinetic and potential energy changes can be ignored and the flow in the duct can be considered frictionless. The specific heat of air can be assumed c_P = 1000 J/kg-K.
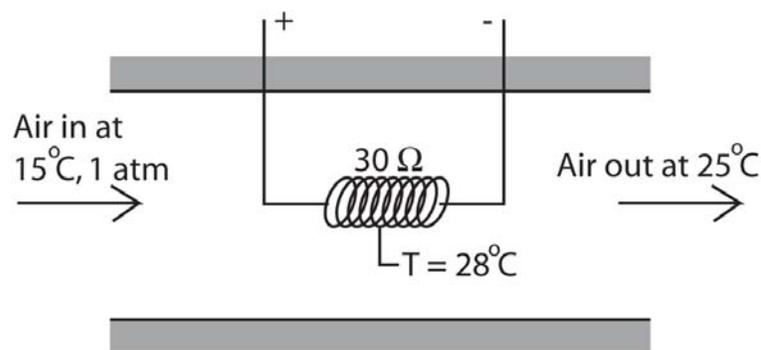

a) For the resistor as the system, determine the rate of entropy production, in kW/K if the electrical power needed to pass a current through a given resistance is $P=I^2R$.

b) For a control volume enclosing the air in the duct and the resistor, determine the mass flow rate of the air, in kg/s.

c) Determine the lost work if the current flows for 10 seconds (the amount of work that is unavailable to us).

6. A turbojet engine can be operated with or without afterburning. The cycle is shown in the figure below. Operated without an afterburner, it consists of reversible, adiabatic compression from 0 to 1, constant pressure burning from 1 to 2, then reversible adiabatic expansion through the turbine and the nozzle from 2 to 4, where the pressure at state 4 is atmospheric. The isentropic temperature ratio (T_1/T_0 where T_1 is the temperature at the compressor exit and T_0 is the atmospheric temperature) is τ_s, which is equal to 2. The ratio of maximum temperature to atmospheric temperature is 10. The kinetic energy changes across the turbine and compressor can be neglected, as can any temperature rise produced in the inlet and diffuser ahead of the compressor. **If necessary, express your answers in terms of T_0 and c_p.**

   a) Sketch the non-afterburning cycle in a T-s diagram and label all states.

   b) What is the thermal efficiency of the non-afterburning cycle?

   c) What is the net mechanical work produced per unit mass flow?

In the afterburning mode, expansion takes place in the turbine from state 2 to state 3, and then the flow is passed through an afterburner where it undergoes constant pressure combustion from state 3 to state 5. The maximum temperature at the afterburner is the same as the maximum temperature at the combustor exit. On leaving the afterburner, the flow expands through a nozzle to atmospheric pressure at state 6.

   d) Sketch states 3, 5 and 6 in the same T-s diagram.

   e) The afterburner entrance is at the turbine exit. What is the afterburner inlet temperature T_3?

   f) The afterburner exit temperature, T_5, is the nozzle inlet temperature. What is the nozzle exit temperature, T_6?

   g) What is the thermal efficiency of the afterburning engine cycle?
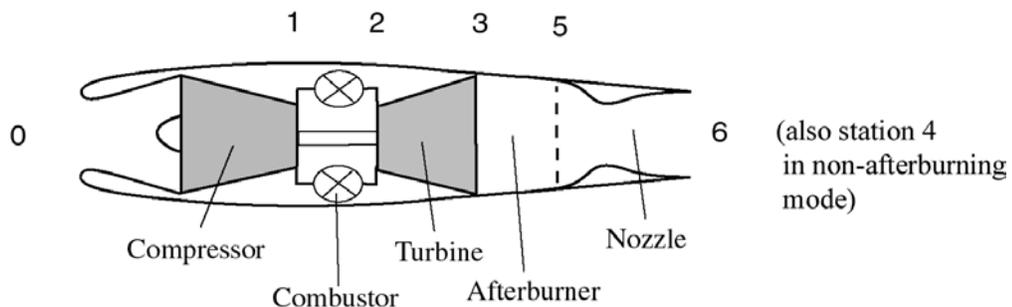
$T_1/T_0 = \tau_s = 2$

$T_{max}/T_0 = 10$

7. In a manufacturing process, a transparent film is being bonded to a substrate as shown in the sketch below. To cure the bond at a temperature T_0, a radiant source is used to provide a heat flux $\dot{q}_0$ (W/m²), all of which is absorbed at the bonded surface ($\dot{q}_0$ is completely transmitted in the transparent film). The back of the substrate is maintained at T_1 while the free surface of the film is exposed to air at T_∞ and a convection heat transfer coefficient of h. The thickness of the bond can be neglected.
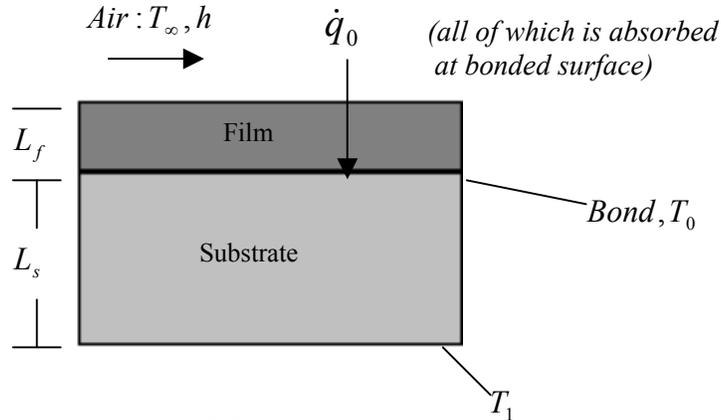
$$L_f = 0.25mm$$
$$k_f = 2.5 \times 10^{-2} W / mK$$
$$L_s = 1.0mm$$
$$k_s = 5.0 \times 10^{-2} W / mK$$

a) Sketch the thermal circuit representing the steady-state heat transfer situation. Be sure to label *all* elements, nodes, and heat rates.

b) Calculate all thermal resistances in your thermal circuit.

c) For conditions of T_∞=20°C, h=50 W/m²K and T_1=30°C, calculate the heat flux $\dot{q}_0$ required to maintain the bonded surface at T_0=60°C.

8. Two parallel plates are at temperatures 1000°C and 500°C. The space between the plates is evacuated. Calculate the net radiation heat transfer per m² if

a) the plates are black,

b) the plates are gray with an emissivity=0.6.

A third plate is inserted between the two plates that are again at temperatures 1000°C and 500°C. The third plate can be assumed thin.

c) Explain in a sentence or two what "thin" implies in the context of this heat transfer problem.

d) Calculate the net radiation heat transfer per m² if all three plates are black.

Properties of Saturated Nitrogen

Refer to:
Van Wylen, Sonntag & Borgnakke, *Fundamentals of Classical Thermodynamics*, 6th Ed.
Wiley. pp. 714, Table B.6.1.

Properties of Saturated Steam (Liquid-Vapor)

| Press., MPa | Temp., C | Specific Volume m³/kg | | Internal Energy kJ/kg | | Enthalpy kJ/kg | | Entropy kJ/kgK | |
		Sat. Liquid v_f	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g
0.05	81.33	1030	3.2400	340.44	2483.9	340.49	2645.9	1.0910	7.5939
0.1	99.63	1043	1.6940	417.36	2506.1	417.46	2675.5	1.3026	7.3594
1.0	179.91	1127	0.1944	761.68	2583.6	762.81	2778.1	2.1387	6.5865
2.0	212.42	1177	0.0996	906.44	2600.3	908.79	2799.5	2.4474	6.3409
3.0	233.90	1217	0.0667	1004.78	2604.1	1008.42	2804.2	2.6457	6.1869
4.0	250.40	1252	0.0498	1082.31	2602.3	1087.31	2801.4	2.7964	6.0701
5.0	263.99	1286	0.0394	1147.81	2597.1	1154.23	2794.3	2.9202	5.9734
6.0	275.64	1319	0.0324	1205.44	2589.7	1213.35	2784.3	3.0267	5.8892
7.0	285.88	1351	0.0274	1257.55	2580.5	1267.00	2772.1	3.1211	5.8133
8.0	295.06	1384	0.0235	1305.57	2569.8	1316.64	2758.0	3.2068	5.7432
9.0	303.40	1418	0.0205	1350.51	2557.8	1363.26	2742.1	3.2858	5.6722
10.0	311.06	1452	0.0180	1393.04	2544.4	1407.56	2724.7	3.3596	5.6141
11.0	318.15	1489	0.0160	1433.70	2529.8	1450.1	2705.6	3.4295	5.5527
12.0	324.75	1527	0.0143	1473.0	2513.7	1491.3	2684.9	3.4962	5.4924