# Homework #5

MEMS 0051 - Introduction to Thermodynamics

Assigned February $16^{\text{th}}$, 2018
Due: February $23^{\text{rd}}$, 2018

## Problem #1

Use you tables to determine the change in enthalpy ($h_2$-$h_1$) for each of the following cases:

a) Concrete cooled from 40°C to 20°C
For a solid material, we obtain the specific heat from Table A.3:

$$h_2 - h_1 = C(T_2 - T_1) = (0.88\,[\text{kJ/kg-K}])(20^\circ\text{C} - 40^\circ\text{C}) = -17.6\,[\text{kJ/kg}]$$

b) Butane heated up from 25°C to 55°C
For a liquid, we obtain the specific heat from Table A.4:

$$h_2 - h_1 = C(T_2 - T_1) = (2.47\,[\text{kJ/kg-K}])(55^\circ\text{C} - 25^\circ\text{C}) = 74.1\,[\text{kJ/kg}]$$

c) Argon gas heated from 20°C to 50°C
For a gas with small temperature changes near STP, we can use the specific heat formula with $C_{PO}$ from Table A.5:

$$h_2 - h_1 = C_{PO}(T_2 - T_1) = (0.520\,[\text{kJ/kg-K}])(50^\circ\text{C} - 20^\circ\text{C}) = 15.6\,[\text{kJ/kg}]$$

d) Superheated water vapor at 200 [kPa] cooled from 300°C to 200°C
For superheated water vapor, we use Table B.1.3 to look up enthalpy values:

$$h_2 - h_1 = 2870.46\,[\text{kJ/kg}] - 3071.79\,[\text{kJ/kg}] = -201.33\,[\text{kJ/kg}]$$

e) Saturated water at 100°C that goes from a quality of 0.4 to a quality of 0
For saturated water, we obtain enthalpy values from Table B.1.1. First, we have to compute the initial enthalpy based on the given quality:

$$h_1 = h_f + xh_{fg} = 419.02\,[\text{kJ/kg}] + 0.4(2257.03\,[\text{kJ/kg}]) = 1321.8\,[\text{kJ/kg}]$$

Then we can determine the change in enthalpy, since h2=hf (because quality is 0):

$$h_2 - h_1 = h_f - h_1 = 419.02\,[\text{kJ/kg}] - 1321.8\,[\text{kJ/kg}] = -902.8\,[\text{kJ/kg}]$$

## Problem #2

Consider air that is heated from 300 K to 600 K.

a) Use the specific heats in Table A.5 to estimate the change in internal energy ($u_2$-$u_1$) and the change in enthalpy ($h_2$-$h_1$).

$$u_2 - u_1 = C_{\forall O}(T_2 - T_1) = (0.717\,[\text{kJ/kg-K}])(600\,[\text{K}] - 300\,[\text{K}]) = 215.1\,[\text{kJ/kg}]$$

$$h_2 - h_1 = C_{PO}(T_2 - T_1) = (1.004\,[\text{kJ/kg-K}])(600\,[\text{K}] - 300\,[\text{K}]) = 301.2[\text{kJ/kg}]$$

b) Use the tabulated values for air in Table A7.1 to determine the change in internal energy ($u_2$-$u_1$) and the change in enthalpy ($h_2$-$h_1$).

$$u_2 - u_1 = 435.10\,[\mathrm{kJ/kg}] - 214.36\,[\mathrm{kJ/kg}] = 220.74\,[\mathrm{kJ/kg}]$$

$$h_2 - h_1 = 607.32\,[\mathrm{kJ/kg}] - 300.47\,[\mathrm{kJ/kg}] = 306.85\,[\mathrm{kJ/kg}]$$

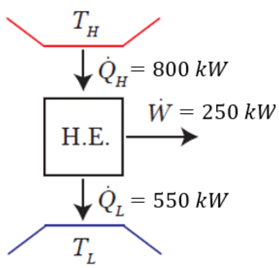
c) Compare your estimated values from part a) to the exact values in b). Do you think that it's okay to apply the specific heat formulas to estimate ($u_2$-$u_1$) and ($h_2$-$h_1$) for this process? Explain.
Comparing the estimated values in a) to the actual values in b) gives the following errors:
% error in $u_2 - u_1$: 100%*((215.1 [kJ/kg]-220.74 [kJ/kg])/220.74 [kJ/kg])=-2.56%
% error in $h_2 - h_1$: 100%*((301.2 [kJ/kg]-306.85 [kJ/kg])/306.85 [kJ/kg])=-1.84%

Using the specific heat formulas resulted in under-estimating the actual changes by more than 1. Therefore, it is not okay to apply the specific heat formulas to estimate ($u_2 - u_1$) and ($h_2 - h_1$) for this process. Note: as a rule of thumb, err on the side of caution and use Tables A.7-A.8 to calculate ($u_2 - u_1$) and ($h_2 - h_1$) of ideal gases if the temperature change is > 100 [K] and/or temperatures exceed 400 [K].

## Problem #3

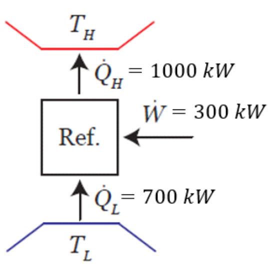
For each of the following devices, draw a schematic that labels and quantifies all of the energy flows ($\dot{W}$,$\dot{Q}_H$, $\dot{Q}_L$) between two thermal reservoirs ($T_H$,$T_L$). Then calculate the correct metric of performance ($\eta$, $\beta$, or $\beta'$) for each device.

a) A heat engine that converts 800 [kW] of heat into 250 [kW] of power.



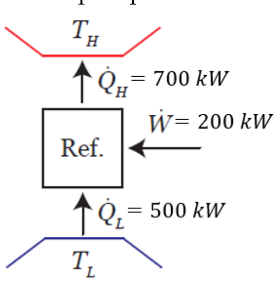

$$\eta = \frac{\dot{W}}{\dot{Q}_H} = \frac{250\,[\mathrm{kW}]}{800\,[\mathrm{kW}]} = 0.3125$$

b) A refrigerator with a power input of 300 [kW] that rejects 1000 [kW] of heat to the environment.




$$\beta = \frac{\dot{Q}_L}{\dot{W}} = \frac{700\,[\mathrm{kW}]}{300\,[\mathrm{kW}]} = 2.33$$

c) A heat pump that takes in 500 [kW] of heat and outputs 700 [kW] of heat.




$$\beta' = \frac{\dot{Q}_H}{\dot{W}} = \frac{700\,[\mathrm{kW}]}{200\,[\mathrm{kW}]} = 3.5$$

## Problem #4

Do the following systems violate the $2^{nd}$ Law of Thermodynamics? Why or why not? Hint: use the Kelvin-Planck Statement, the Clausius Statement, and/or Perpetual Motion Machines to explain your answers.

a) A system that transfers heat from a cold reservoir to a warm reservoir spontaneously.
Yes, this violates the $2^{nd}$ law according to the Clausius Statement, which says that it's impossible to transfer heat from cold to hot with no power input.

b) A system that transfers heat from a cold reservoir to a warm reservoir with a power input.
No, this isn't a violation of the $2^{nd}$ law because the Clausius Statement only prohibits heat transfer from cold to hot in the absence of a power input. This is simply describing a refrigeration system, which doesn't violate the $2^{nd}$ law.

c) A system that produces power by taking in heat and rejecting heat to a colder reservoir.
No, this doesn't violate the $2^{nd}$ law because it doesn't violate the Kelvin-Planck Statement because there is a heat rejection to a colder reservoir. This is simply describing a heat engine, which isn't in violation of the $2^{nd}$ law.

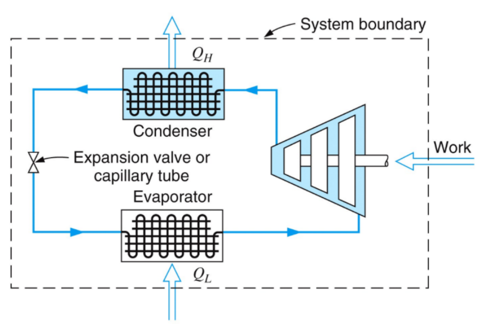
d) A system that produces power by taking in heat and not rejecting any heat.
Yes, this is a violation of the $2^{nd}$ law because it violates the Kelvin-Planck Statement, which states that no cyclic device can perfectly convert heat into work. This system describes a PPM (of the $2^{nd}$ kind), which is thermodynamically impossible.

e) A system that does work without any heat transfers.
Yes, this is in violation of the $2^{nd}$ law because it is a PPM of the 1st kind, generating energy from nothing. This is also a violation of the $1^{st}$ law, which states that energy cannot be created.

f) A system that converts heat to work with 30% efficiency.
No, this isn't a violation of the $2^{nd}$ law because it has an efficiency less than 100%. This system could describe a heat engine that converts 30% of the incoming heat to power and rejects the other 70% to a colder reservoir.

## Problem #5

Consider the refrigeration cycle shown below, where a refrigerant cycles through a compressor, an evaporator, an expansion valve, and a condenser. The compressor requires an electrical input, the evaporator removes heat from the inside of the refrigerator, and the condenser rejects heat to the air in the room.




a) What are some sources of irreversibility in this cycle? List at least two.
   i) Heat transfer - there must be a finite temperature difference at the evaporator and the compressor in order for heat to be transferred into and out of the system. This results in irreversibility at both locations of heat transfer.
   ii) Compression & expansion - the compression and expansion of the refrigerant (across the compressor and the expansion valve, respectively) results in irreversible losses.
   iii) Friction - anytime you have a liquid flowing through pipes, there are frictional losses at the inner pipe walls, resulting in irreversibility.

b) What are some modifications you could make to this system to make it more reversible? Describe at least two modifications.
   i) Reduce temperature drops for heat transfer - make the temperature differences smaller between the condenser and the environment and between the inside of the refrigerator and the evaporator. This will result in slower heat transfers, but will reduce irreversibility.

ii) Reduce the refrigerant flow-rate - flowing the refrigerant more slowly through the system will result in reduced friction and compression/expansion losses. However, it will also reduce the rate at which heat can be removed from the refrigerator.