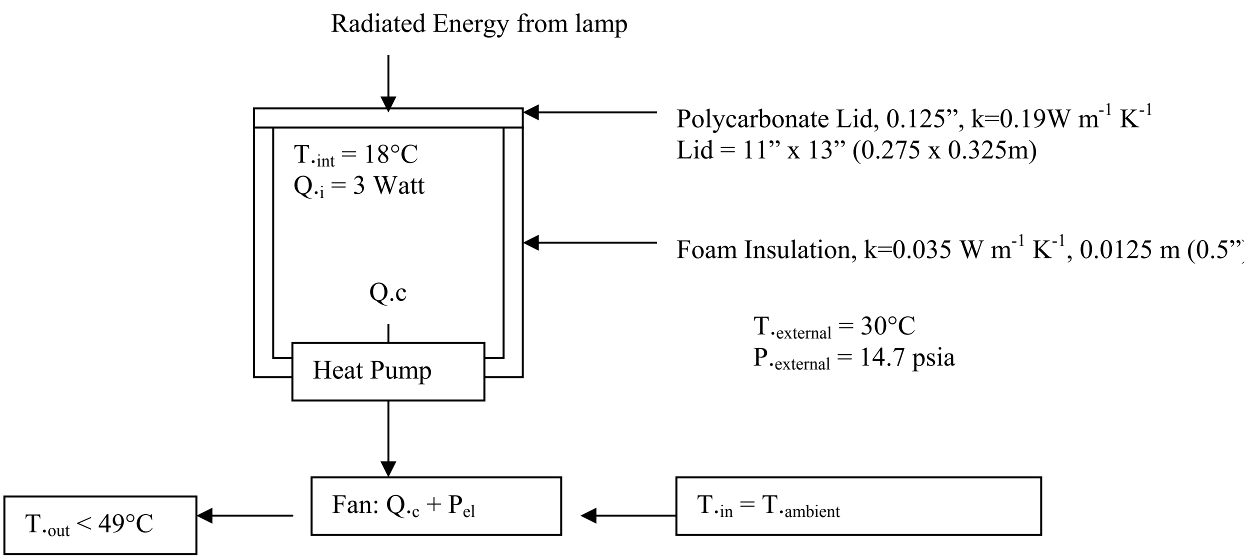
Name: ____________________ Unique Identifier: __________________ Due Date: Tu 10/21/03

Homework 2 - Thermal Design

We will design a sealed plant growth chamber for use aboard the International Space Station. The sealed and insulated green house has the following performance requirements:

Internal Geometry of greenhouse (usable space):	L=0.275m x W=0.325m x H0.30m
Insulation: Baseline:	
Pyrell foam on outside of 5 walls	$k=0.035\ W\ m^{-1}\ K^{-1}$, 0.0125 m thick (0.5”) chamber is 0.30m tall, 0.275 x 0.325 foot print)
Clear Lexan (Polycarbonate) lid on top (0.275x0.325m), 0.125” thick, $k = 0.19\ W\ m^{-1}\ K^{-1}$	
Heat Sources inside plant chamber:	
2 internal circulation fans, 2 watt each,	4 Watt
sensor assembly (CO2, temp., humidity)	3 Watt
radiated energy from lights:	$50\ Watt/m^2$, all absorbed inside chamber
Water to condense	$m_{dot.H2O} = 300$ ml/day; Heat of condensation L=2,256,000 Joule/kg
Required rate of cooling	0.05°C/min
Internal Temperature	18°C
External Temperature	30°C
Air Inlet Temperature	30°C
Max. allowed Air Outlet Temperature	49°C
Cabin Pressure	14.7 psia nominal / 10.2 psia during spacewalk



1. Calculate the Parasitic Heat (heat transferred from outside to inside of chamber due to thermal conductivity)

   basic equation for thermal conductivity through flat plate with thermal conductivity k and area A, thickness t: $Q_p = k/t * A * (T_{outside} - T_{inside})$:
   (http://www.colorado.edu/engineering/ASEN/asen5519/08incubator-heat.htm)

   - calculate Q_p using the foam-covered surface area A_{foam} and foam insulation on five walls, and the clear Lexan wall A_{lid} on the 6th wall ($Q_p = Q_{foam} + Q_{lid}$):

     $Q_{foam} = k_{foam}/t_{foam} * A_{foam} * (T_{outside} - T_{inside})$ Q_{foam} = ____________ Watt

     $Q_{lid} = k_{lid}/t_{lid} * A_{lid} * (T_{outside} - T_{inside})$ Q_{lid} = ____________ Watt

$Q_p = Q_{foam} + Q_{lid}$ _____________ Watt

However, for multi-layer walls, it may be more convenient to use a notation using 'thermal resistance' or R_Θ in units of [°C/watt] (http://www.colorado.edu/ASEN/asen5519/09fans-heat.htm)

- The plant chamber wall (not including the clear lid) is a multi-layered wall, consisting of the foam insulation in contact with the ambient temperature of 30°C and a thickness of t_1=0.50" (Pyrell, k_1=0.035 W $m^{-1}s^{-1}$). The foam is in contact with a t_2=0.065" thick fiberglass face sheet (k_2=0.17 W $m^{-1}s^{-1}$), followed by a honeycomb core (t_3=0.25", k_3=3 W $m^{-1}s^{-1}$), followed by the internal aluminum face sheet (t_4=0.065", k_4=170 W $m^{-1}s^{-1}$).

  The thermal conductivity of this multi-layered wall can be calculated using:

  $Q_{foam.ml} = 1 / (k_1/t_1*A_1 + k_2/t_2*A_2 + k_3/t_3*A_3 + k_4/t_4*A_4) * (T_{outside} – T_{inside})$,

  Simplify with $A_1=A_2=A_3=A_4$ (all 5 walls), and calculate the heat conducted through this multi-layered wall.
  Using thermal resistances R_i, this equation can be re-written as:

  $Q_{foam.ml} = (\Sigma R_i)^{-1} * (T_{outside} – T_{inside})$, with $R_i = t_i / (k_i * A_i)$

$$Q_{foam.ml} = \frac{(T_{outside} - T_{inside})}{\frac{t_1}{k_1 * A_1} + \frac{t_2}{k_2 * A_2} + \frac{t_3}{k_3 * A_3} + \frac{t_4}{k_4 * A_4}} = \frac{(T_{outside} - T_{inside})}{R_1 + R_2 + R_3 + R_4}$$

  $Q_{foam\ ml}$ = _____________ Watt

  Compare that to the calculated single foam insulation Q_{foam} = ____________ Watt
  Why is there hardly any difference ?

  ____

- Calculate the new parasitic heat into the chamber using the multi-layer insulation:
- Q_{lid} = ____________ Watt

  $Q_{p.ml} = Q_{foam.ml} + Q_{lid}$ $Q_{p.ml} = Q_{foam.ml} + Q_{lid}$ = ____________ Watt

- In all cases, we purposely neglected the contribution of heat transfer to the wall by means of convection. Let's consider convective heat transfer for the lid only, since the foam-insulated walls have no convective transfer – they are inside a box with $T_{box} = T_{outside}$):

  Convective heat transfer is described by $Q = h * A * \Delta T$. If we use thermal resistance to describe the heat transfer to a wall (convection) and through a wall (multi-layer, conduction) and back to air (convection), we get:
  Using $R_{convection} = 1 / (h * A)$

$$Q_{lamp\text{-}chamber} = \frac{(T_{lamp} - T_{inside})}{\frac{1}{h_1 * A_{lid}} + \frac{t_2}{k_2 * A_{lid}} + \frac{t_3}{k_3 * A_{kid}} + \frac{t_4}{k_4 * A_{lid}} + \frac{1}{h_5 * A_{lid}}} = \frac{(T_{lamp} - T_{inside})}{R_1 + R_2 + R_3 + R_4 + R_5}$$

h1: The lamp box has internal circulation fans and we assume from experience that the convective heat transfer coefficient between the lamp box air and the Lexan lamp lid is h_1 = 25 watt m^{-2} K^{-1}.

h5: The plant chamber has internal circulation fans at higher speed and we assume from experience that the convective heat transfer coefficient between the chamber lid and the chamber air is h_2 = 50 watt m^{-2} K^{-1}.

Since the lid transferred so much heat in our previous calculations, we build a double wall lid, with an insulating air gap in between. The thickness of each of the Lexan lids is 0.0675", i.e. two thinner lids of 0.0675" make the same thickness as the previous single lid with 0.125" thickness. The two Lexan lids are separated by a 0.125" thin layer of 'stagnant' air. Obviously, in microgravity, this layer of air has very little convection.

k2=k4=lid: The lamp lid is t_2= t_4=0.0675" thick, Lexan (k_2= k_4=0.19W m^{-1} K^{-1}).

k3 air gap: The air layer is t_3=0.125" thick, air (k_3=0.0257 W m^{-1} K^{-1}).

Tl_{amp} is unknown. But since it is cooled by convection to ambient air, lets assume that the air inside the lamp is about 5°C warmer than ambient air. We can verify that later.
$Tl_{amp} = T_{ambient}$ + 5°C = 30°C + 5°C = 35°C

The heat from the lamp air to chamber air is: $Q_{lamp\text{-}chamber}$ = __________ watt

Now, that the chamber is so much better insulated, we use the previously calculated parasitic heat through the multi-layered foam insulated chamber ($Q_{foam.ml}$) and the heat conducted through the double-pane lid ($Q_{lamp\text{-}chamber}$) to calculate the amount of parasitic heat to pump out of the chamber:

$Q_{p.ml} = Q_{foam.ml} + Q_{lamp\text{-}chamber}$ = ______________________ watt

<u>Calculate the additional heat that has to be removed from the greenhouse to maintain steady state temperature, i.e., heat in = heat out.</u>

Internally dissipated heat: $Q_i = \Sigma P_{el}$, where P_{el} = fans + sensor ______ watt
Heat by light source: $Q_{rad} = h\nu * A$, where $h\nu$ = 50 watt/m^2, and A = lid area (0.25 x 0.3 m^2) ______ watt

- $Q_{int} = Q_i + Q_{rad}$

Q_{int} = _____________ Watt

<u>Calculate the total amount of heat that has to be removed under steady state condition, i.e. dT/dt = 0 (no tempertaure change with time), and therefore $\Sigma Q = 0$ ($Q_{in} = Q_{out}$).</u>

Heat to be pumped out, Q_{out}, = $Q_{in} = Q_{p.ml} + Q_{rad} + Q_i$

Q_{out} = ____________ Watt

Calculate the total amount of heat that has to be removed to condense the plant transpiration water (only consider heat of condensation, not cooling moist air), i.e. Q = m.dot.H2O * L.

Heat pump capacity to condense water, $Q_{condense}$, = $M_{.dot.H2O}$ * L

$Q_{condense}$ = ____________ Watt

Heat pump capacity to cool from 25°C to 18°C.

- The green house contains 3 liter of water and 500 gram of polycarbonate hardware (root tray, walls, etc.) The green house should be cooled from 25°C to 18°C at a rate of dT/dt=0.05°C/min. Calculate the necessary heat pump capacity, Q_{dt}:
  $Q_{dt} = dE/dt = (\Sigma\, m_i\, Cp_i) * dT/dt$.

Q_{dt} = ____________ Watt

[Cp_{H20} = 4183 joule kg^{-1} K^{-1}, ρ_{H20} = 998.2 kg m^{-3}, Cp_{lexan} = 1440 joule kg^{-1} K^{-1}]

Calculate the entire heat pump capacity for steady state and instationary cooling capacity.

$Q_{HP} = Q_{out} + Q_{dt}$

Q_{HP} = ____________ Watt

Find a thermoelectric heat pump that can pump that amount of heat Q_{HP}.

To simplify this homework, use the following data:

TEC-model	ΔT_{max}	Q_{max}	I_{max}	V_{max}	$P_{max} = I_{max} * V_{max}$
CP1.0-127-06L	67°C	25.7 Watt	3.0 Amps	15.4 Volt	46.2 watt
CP1.4-127-10L	70°C	33.4 Watt	3.9 Amps	15.4 Volt	60.1 watt
CP1.4-127-06L	67°C	51.4 Watt	6.0 Amps	15.4 Volt	92.4 watt

- The TEC can pump a maximum Q_{max} if $\Delta T = 0$°C
- The TEC can maintain a maximum ΔT, if Q_{pump}=0.
- One could write this as $Q_{pump-max} = Q_{max} - Q_{max}/\Delta T_{max} * \Delta T$
- To make the system more efficient, we will only use 50% of Q_{max}, and instead increase the number of TECs. One could write this as $Q_{pump} = 0.5 * [\, Q_{max} - Q_{max}/\Delta T_{max} * \Delta T \,]$
- The ΔT referred to in the dimensioning of the TEC is defined as $\Delta T = T_{hot} - T_{cold}$.
- T_{hot} is the base temperature of the air heat exchanger, rejecting the heat into the cabin air. The cabin air is T_{amb}=30°C. With most heat exchanger (actually: a very good heat exchanger), one can assume that T_{hot} is approximately 5 – 10°C hotter than the cooling air. Assume a very good heat exchanger (expensive, good air flow, high fin density) and make $T_{hot} = T_{ambient}$ + 5°C = 30°C + 5°C = 35°C.
- Similarly, to make the green house air to reach 18°C, the internal heat exchanger has to be colder than the chamber (assume rule of thumb: approximately 5°C colder).
  T_{cold} = Tint - 5° = 18°C - 5°C = 13°C.

- Calculate the ΔT for our application: T_{int} = 18°C, T_{amb}=30°C, $T_{cold} = T_{int}$-5°C=13°C, T_{hot} = T_{amb}+5°C = 35°C.

ΔT = ____________ °C

- Using above simplifications, calculate how much each of the TECs listed above could pump under this condition (ΔT).

TEC-model	$\Delta T = T_{hot} - T_{cold}$	Q_{max}	$Q_{pump} = 0.5 * [Q_{max} - Q_{max}/\Delta T_{max} * \Delta T]$
CP1.0-127-06L			
CP1.4-127-10L			
CP1.4-127-06L			

- How many TECs does it take to pump the amount of heat from our plant chamber. That should be $\#TEC = Q_{HP} / Q_{pump}$. Round UP to closed whole number of TECs get the number of TECs needed (conservative).

TEC-model	Q_{HP}	Q_{pump}	$\#TEC = int(Q_{HP} / Q_{pump} + 0.5)$
CP1.0-127-06L			
CP1.4-127-10L			
CP1.4-127-06L			

- Since we dimensioned the TECs such that we use them only at 50% of capacity to maintain good efficiency, we can assume (very simple, but good enough for rule of thumb) that we only use 50% of V_{max} (voltage) and 50% of I_{max} (current), and therefore $P = V * I = 0.5*V_{max} * 0.5 * I_{max} = 0.25*P_{max}$, with P_{max} the maximum electric power given by the manufacturer at Q_{max}.
  Calculate the electric power necessary to pump the heat Q_{HP}, using the #TECs necessary for each model.

TEC-model	#TECs	$P_{el} = \#TECs * 25\% * P_{max}$
CP1.0-127-06L		
CP1.4-127-10L		
CP1.4-127-06L		

- How much heat Q_{HX} does the air heat exchanger have to reject ?? Obviously, the hot side receives the amount of heat pumped, Q_{HP}, and the electric power P_{el} used to pump, so $Q_{HX} = Q_{HP} + P_{el}$. Pick the system with the least power, P_{el}, to pump the heat Q_{HP}.

  Q_{HX} = _____________ watt

- What is the minimum air flow rate through a heat exchanger, that will transport that amount of heat, Q_{HX}, and not exceed our earlier assumption, that $T_{hot} = T_{amb} + 5°C$? To simplify, assume that T_{out} (air exit temperature) = T_{hot} = 35°C+5°C = 40°C.
  [$\rho_{air} = 1.2045$ kg m^{-3}, $Cp_{air} = 1005$ joule kg^{-1} K^{-1}, $Q_{air} = CFM * \rho_{air} * Cp_{air} * \Delta T$]
  $\Delta T = T_{hot} - T_{amb}$, and with $Q_{air} = Q_{HX}$,

  Min. required air flow = _____________ CFM

- You have the following 4 fans available to you. The back pressure in your air circulation system has been measured to be 0.075" H2O. Which fan are you using ? Simplify the fan performance as follows: Fan delivers a dead head pressure of ΔP_{max} at CFM=0. It also delivers CFM_{max} at ΔP=0. Assume linear correlation, this means:
  $CFM(\Delta P) = CFM_{max} * (1-\Delta P/\Delta P_{max})$

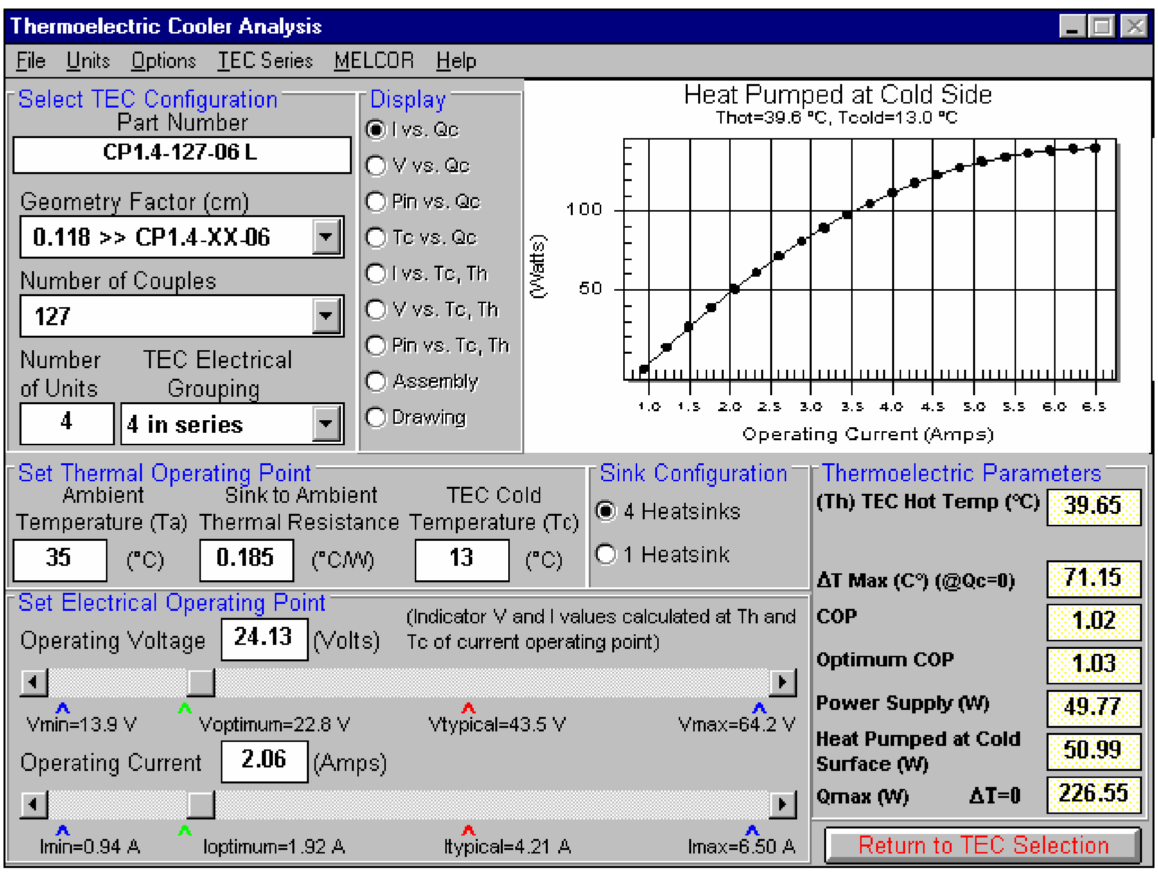
Fan Model	CFM_{max} [CFM]	DP_{max} [in H2O]	P_{el} [watt]	DP act [in H2O]	CFM(ΔP)
3412L	36	0.1	1.3	0.075	
3412M	42	0.15	1.8	0.075	
3412G	49	0.2	2.4	0.075	
3412H	55	0.25	3.4	0.075	

Calculate the actual flow rate under the system backpressure and pick the fan that provides you the required air flow.

Good luck, all information necessary should be provided. All simplifications and rules of thumb are listed. Should you need additional information, send me an email.
The following graphs are depicting one solution, your numbers will be slightly different and DO NOT have to match the results below. These graphs are from the Melcor TEC selection program Aztec, which can be downloaded from their web page, BUT IT WILL NOT HELP YOU for this homework. The program is, however, an easy way of designing and evaluating thermoelectric coolers.

If you want to download AZTEC, it's on the ASEN5519 web page: AZTEC, or download from Melcor at http://www.melcor.com/download.htm

Using 4 heat sinks (of the shelf, with R=0.185°C/watt) for lowest Hot Side Temperature (39.65):



Using 1 heat sink, but a good one (R=0.1°C/watt) for lowest Hot Side Temperature: