## P1.2-6: Freezer Wall

You have designed a wall for a freezer. A cross-section of your freezer wall is shown in Figure P1.2-6. The wall separates the freezer air at $T_f$ = -10°C from air within the room at $T_r$ = 20°C. The heat transfer coefficient between the freezer air and the inner wall of the freezer is $\overline{h}_f$ = 10 W/m$^2$-K and the heat transfer coefficient between the room air and the outer wall of the freezer is $\overline{h}_r$ = 10 W/m$^2$-K. The wall is composed of a $th_b$ = 1.0 cm thick layer of fiberglass blanket sandwiched between two $th_w$ = 5.0 mm sheets of stainless steel. The thermal conductivity of fiberglass and stainless steel are $k_b$ = 0.06 W/m-K and $k_w$ = 15 W/m-K, respectively. Assume that the cross-sectional area of the wall is $A_c$ = 1 m$^2$. Neglect radiation from either the inner or outer walls.

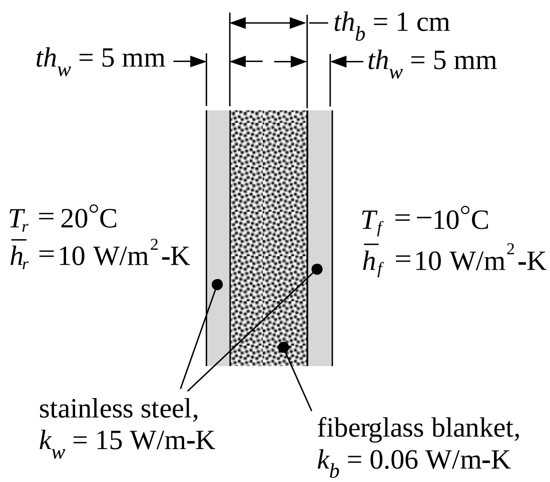


**Figure P1.2-6: Freezer wall.**

a.) Draw a resistance network to illustrate this problem. Be sure to label the resistances in your network so that it is clear what each resistance is meant to represent.

There are five resistances associated with the problem; convection to the room and the freezer, $R_{conv,r}$ and $R_{conv,f}$, and conduction through each of the stainless steel walls and the fiberglass blanket, $R_{cond,w}$ and $R_{cond,f}$. These are placed in series since the heat transfer must pass through all of them, as shown in Figure P1.2-6-2.

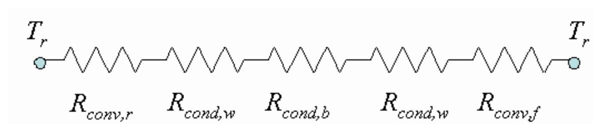


**Figure P1.2-6-2: Thermal resistance network.**

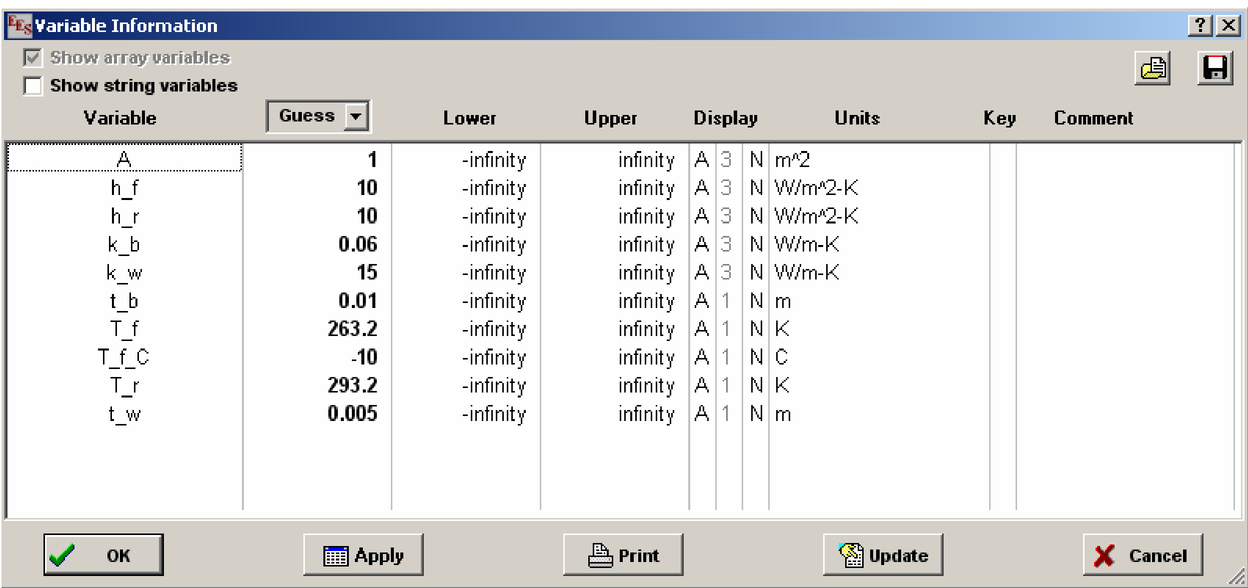
b.) Enter all of the inputs in the problem into an EES program. Convert each input into the corresponding base SI unit (i.e., m, kg, K, W, N, etc.) and set the unit for each variable using the Variable Information window. Using comments, indicate what each variable means. Make sure that you set and check units of each variable that you use in the remainder of the solution process.

The inputs are entered in EES and converted to base SI:

```
$UnitSystem SI MASS RAD PA  K J
$TABSTOPS   0.2 0.4 0.6 0.8 3.5 in

"Inputs"
t_w = 5.0 [mm]*convert(mm,m)                      "SS wall thickness"
t_b = 1.0 [cm]*convert(cm,m)                      "fiberglass thickness"
T_r = converttemp(C,K,20)                         "room air temperature"
h_r = 10 [W/m^2-K]
    "room air to outer wall heat transfer coefficient"
k_w = 15 [W/m-K]                                  "SS conductivity"
k_b = 0.06 [W/m-K]                                "fiberglass conductivity"
h_f = 10 [W/m^2-K]
    "freezer air to inner wall heat transfer coefficient"
T_f_C=-10 [C]                                     "freezer temperature in C"
T_f = converttemp(C,K,T_f_C)                      "freezer air temperature in K"
A = 1 [m^2]                                       "freezer area"
```

The units for each variable are set in the Variable Information window (see Figure P1.2-6-3).




| Variable | Guess | Lower | Upper | Display | | | Units | Key | Comment |
|---|---|---|---|---|---|---|---|---|---|
| A | 1 | -infinity | infinity | A | 3 | N | m^2 | | |
| h_f | 10 | -infinity | infinity | A | 3 | N | W/m^2-K | | |
| h_r | 10 | -infinity | infinity | A | 3 | N | W/m^2-K | | |
| k_b | 0.06 | -infinity | infinity | A | 3 | N | W/m-K | | |
| k_w | 15 | -infinity | infinity | A | 3 | N | W/m-K | | |
| t_b | 0.01 | -infinity | infinity | A | 1 | N | m | | |
| T_f | 263.2 | -infinity | infinity | A | 1 | N | K | | |
| T_f_C | -10 | -infinity | infinity | A | 1 | N | C | | |
| T_r | 293.2 | -infinity | infinity | A | 1 | N | K | | |
| t_w | 0.005 | -infinity | infinity | A | 1 | N | m | | |

**Figure P1.2-6-3: Variable Information window**

c.) Calculate the net heat transfer to the freezer (W).

The values of each of the resistances in Figure P1.2-6-2 are calculated. The convection resistances between the room air and the outer wall of the freezer and the freezer air and the inner wall are:

$$R_{conv,r} = \frac{1}{h_r A} \tag{1}$$

$$R_{conv,f} = \frac{1}{h_f\ A} \tag{2}$$

```
R_conv_r = 1/(h_r*A)          "convection resistance with room air"
R_conv_f=1/(h_f*A)            "convection resistance with freezer air"
```

The units of the two resistances are set in the Variable Information window (to K/W) and the units are checked to ensure that the equations entered are dimensionally consistent.

The two conduction resistances are:

$$R_{cond,w} = \frac{t_w}{k_w\ A} \tag{3}$$

$$R_{cond,b} = \frac{t_b}{k_b\ A} \tag{4}$$

```
R_cond_w=t_w/(k_w*A)          "conduction resistance through SS wall"
R_cond_b=t_b/(k_b*A)          "conduction resistance through fiberglass wall"
```

The total heat transfer through the wall ($\dot{q}$) is:

$$\dot{q} = \frac{\left(T_r - T_f\right)}{R_{conv,r} + 2\,R_{cond,w} + R_{cond,b} + R_{conv,f}} \tag{5}$$

```
q_dot=(T_r-T_f)/(R_conv_r+R_cond_w+R_cond_b+R_cond_w+R_conv_f)
          "net heat transfer to freezer"
```

The Solution Window is shown in Figure P1.2-6-4, the heat load on the freezer is 81.7 W per $m^2$ of wall area.

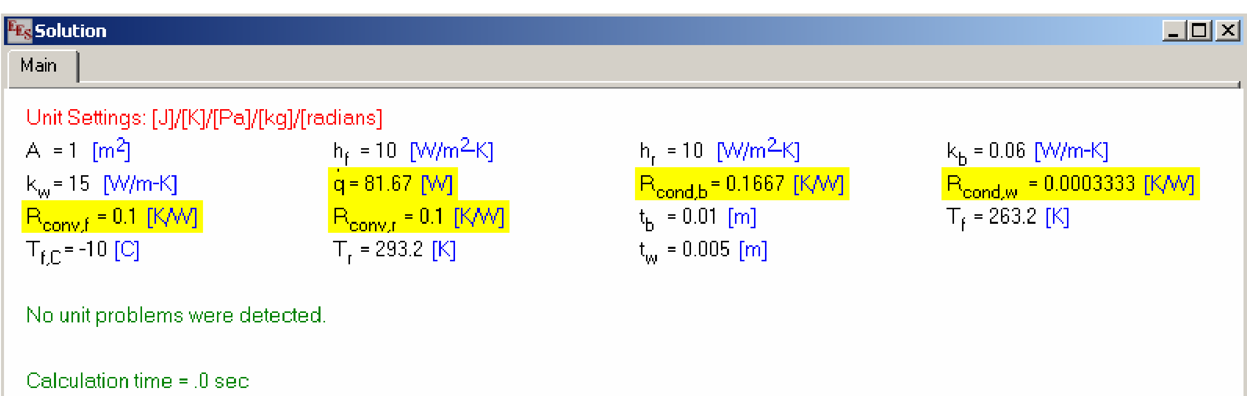



**Figure P1.2-6-4: Solution window.**

d.) Your boss wants to make a more energy efficient freezer by reducing the rate of heat transfer to the freezer. He suggests that you increase the thickness of the stainless steel wall panels in order to accomplish this. Is this a good idea? Justify your answer briefly.

The value of the resistances are highlighted in Figure P1.2-6.4. Notice that $R_{cond,w}$ is approximately 1000x less than the others. Your boss' idea is not so good because in a series combination of resistances, it is the large resistances that dominate the problem. The wall is not important from a heat transfer standpoint.

e.) Prepare a plot showing the heat transfer to the freezer as a function of the thickness of the stainless steel walls. Prepare a second plot showing the heat transfer to the freezer as a function of the thickness of the fiberglass. Make sure that your plots are clear (axes are labeled, etc.)

A parametric table must be created to vary the thickness of the steel walls. Select New Parametric Table from the Tables menu (Figure P1.2-6-5) and place the variables q_dot and t_w in the table (highlight these variables from the list in the left hand box and select Add, then hit OK).

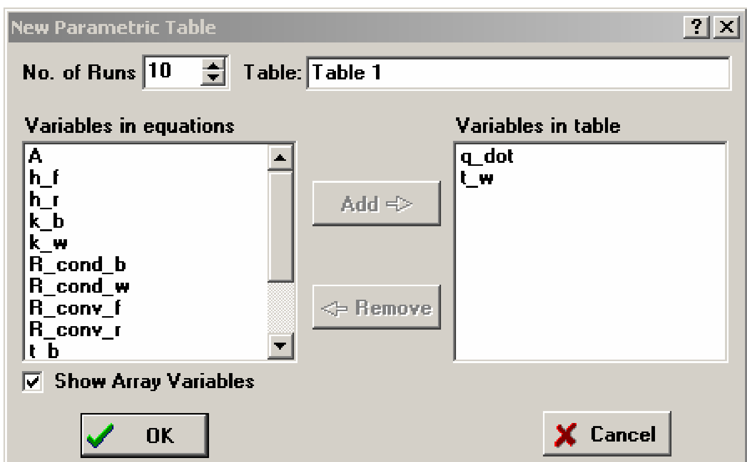



**Figure P1.2-6-5: New Parametric Table dialog**

Vary the thickness of the stainless steel walls from 0 to 2.0 cm (which corresponds to an extremely heavy freezer); right-click on the column of the parametric table that contains the variable t_w and select Alter Values (Figure P1.2-6-6).

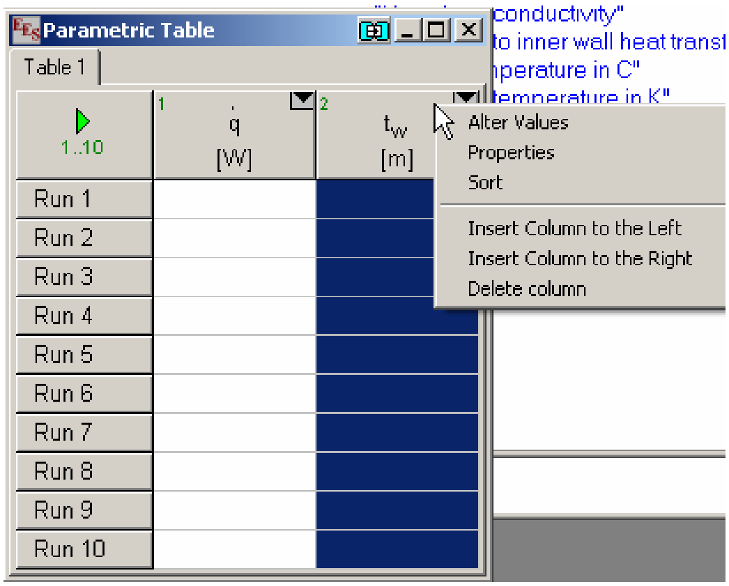



**Figure P1.2-6-6: Alter values of t_w to carry out the parametric investigation.**

A dialog window will open asking what range you would like to vary t_w over; select 0 to 0.02 m (Figure P1.2-6-7) and hit OK.

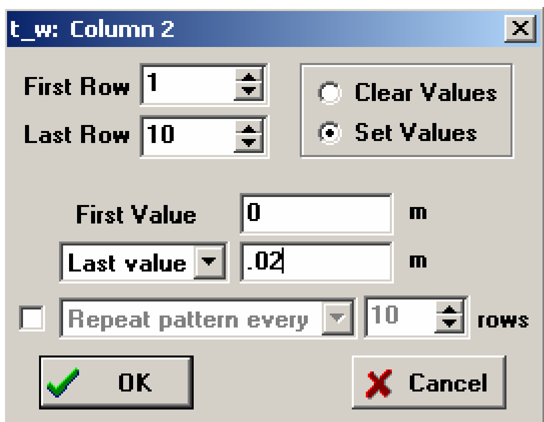



**Figure P1.2-6-7: Vary t_w from 0 to 0.02 m.**

The entries in the t_w column will be automatically filled in. Each time one row of the Table is solved, the corresponding value of t_w will be used in the Equations Window; therefore, it is necessary to remove the value of t_w from the Equations Window. In order to do this temporarily (you will want to go back to the value in the problem statement), you should highlight the section of the code that specifies the value and right click. Select Comment to temporarily remove the code (Figure P1.6-2-8); subsequently performing the same operation and selecting Undo Comment will remove the comment indicators and "reactivate" the assignment.

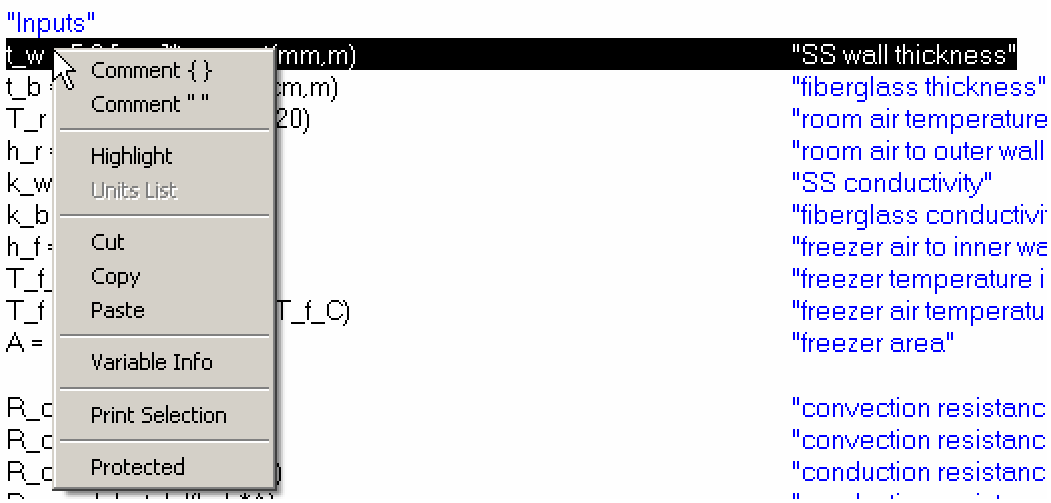
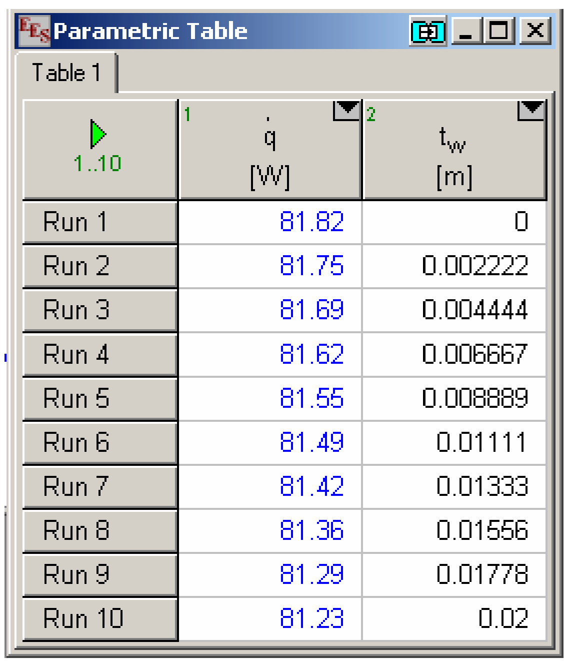



**Figure P1.2-6-8: Comment out the assignment of t_w in the Equation window**

Solve the table by selecting Solve Table from the Calculate menu; the corresponding value of q_dot will be entered in each row of the parametric table (Figure P1.2-6-9).



Parametric Table

Table 1

| 1..10 | $\dot{q}$ [W] | $t_w$ [m] |
|---|---|---|
| Run 1 | 81.82 | 0 |
| Run 2 | 81.75 | 0.002222 |
| Run 3 | 81.69 | 0.004444 |
| Run 4 | 81.62 | 0.006667 |
| Run 5 | 81.55 | 0.008889 |
| Run 6 | 81.49 | 0.01111 |
| Run 7 | 81.42 | 0.01333 |
| Run 8 | 81.36 | 0.01556 |
| Run 9 | 81.29 | 0.01778 |
| Run 10 | 81.23 | 0.02 |

**Figure P1.2-6-9: Parametric table with solution**

The solution can be plotted by selecting New Plot Window from the Plots menu and then X-Y plot to bring up the dialog shown in Figure P1.2-6-10. Select the source of the data (there is only one source in your EES file which is the single parametric table that exists) and specify that t_w will be on the x-axis and q_dot on the y-axis.

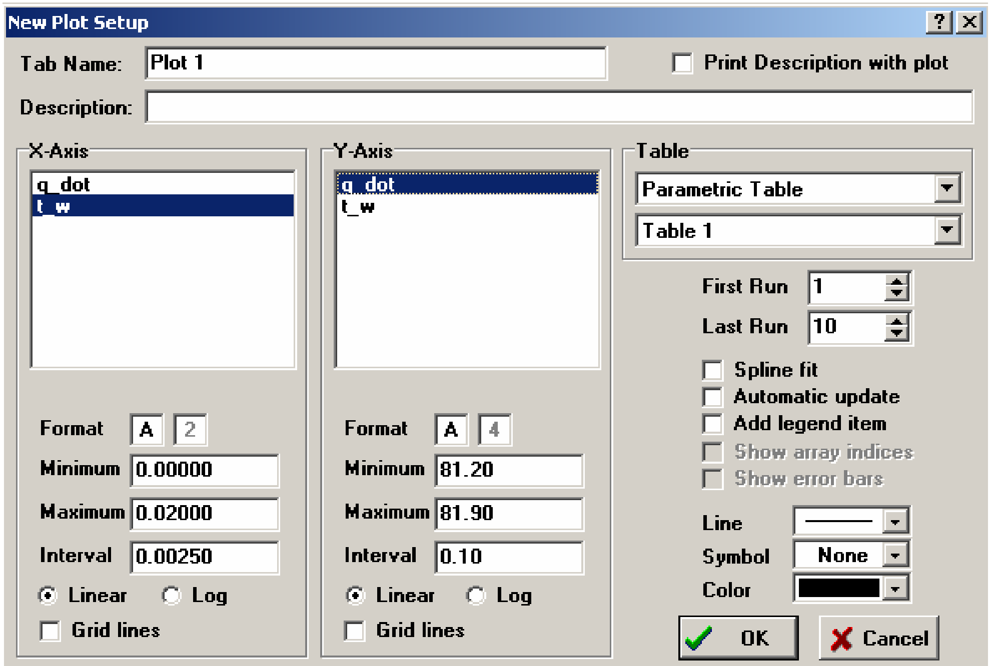


**Figure P1.2-6-10: New Plot Setup window.**

Select OK to create the plot and then edit it so that it looks good (include axes with descriptive names and units, grid line, etc.); the result should be similar to Figure P1.2-6-11.

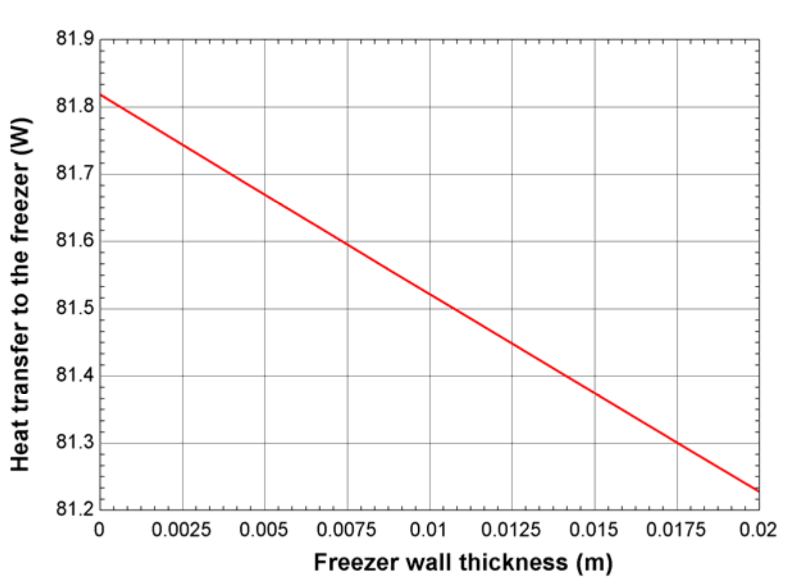


**Figure P1.2-6-11: Heat transfer to the freezer as a function of the freezer wall thickness.**

Follow the same steps to generate Figure P1.2-6-12, which shows the freezer load as a function of the fiberglass thickness. Note that you will need to un-comment the line in the code where you specify the wall thickness.

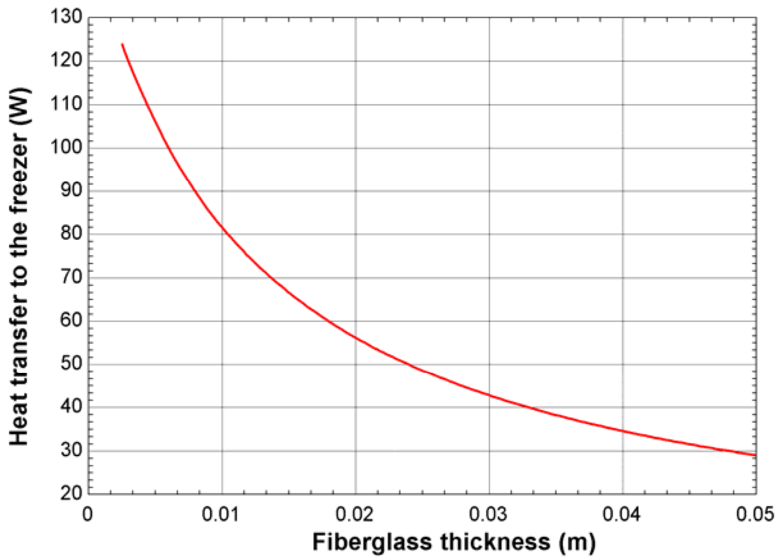



**Figure P1.2-6-12: Heat transfer to the freezer as a function of the fiberglass thickness.**

f.) What design change to your wall would you suggest in order to improve the energy efficiency of the freezer.

The largest resistance in Figure P1.2-6-4 is the conduction resistance through the fiberglass; I suggest that the thickness be increased.

g.) One of your design requirements is that no condensation must form on the external surface of your freezer wall, even if the relative humidity in the room reaches 75%. This implies that the temperature of the external surface of the freezer wall must be greater than 15°C. Does your freezer wall satisfy this requirement? Calculate the external surface temperature (°C).

The temperature at the surface of the freezer wall ($T_s$) corresponds to the node between $R_{conv,r}$ and $R_{cond,w}$ in Figure P1.2-6-2; the value of this temperature can be calculated according to:

$$T_s = T_r - \dot{q}\, R_{conv,r} \tag{6}$$

```
T_s = T_r-q_dot*(R_conv_r+R_cond_w)          "surface temperature"
T_s_C=converttemp(K,C,T_s)                    "surface temperature in C"
```

The solution indicates that $T_s$ =11.8°C which is less than 15°C and therefore condensation on the outside of the freezer is likely.

h.) In order to prevent condensation, you suggest placing a heater between the outer stainless steel wall and the fiberglass. How much heat would be required to keep condensation from forming? Assume that the heater is very thin and conductive.

The addition of the heater provides an additional heat input ($\dot{q}_w$) to the resistance network that enters between $R_{cond,w}$ and $R_{cond,b}$ on the air-side of the circuit, as shown in Figure P1.2-6-13.

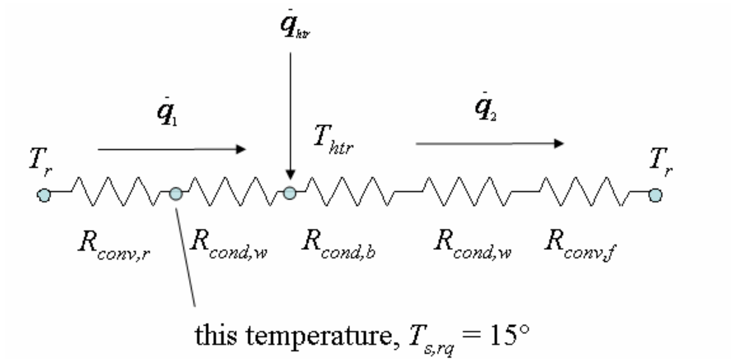



**Figure P1.2-6-13: Heater power added to the resistance network.**

The required surface temperature is $T_{s,rq}$ = 15°C. Therefore, the heat transfer through $R_{conv,r}$ ($\dot{q}_1$) is:

$$\dot{q}_1 = \frac{\left(T_r - T_{s,rq}\right)}{R_{conv,r}} \tag{7}$$

```
"With the heater added"
T_s_rq = converttemp(C,K,15)              "required surface temperature"
q_dot_1=(T_r-T_s_rq)/R_conv_r             "heat transfer from the room"
```

The heater temperature ($T_{htr}$) is therefore:

$$T_{htr} = T_{s,rq} - \dot{q}_1\, R_{cond,w} \tag{8}$$

and the heat transfer to the freezer space ($\dot{q}_2$) is:

$$\dot{q}_2 = \frac{\left(T_{htr} - T_f\right)}{R_{cond,b} + R_{cond,w} + R_{conv,f}} \tag{9}$$

The heat transfer required by the heater ($\dot{q}_{htr}$) is obtained by an energy balance on the heater node:

$$\dot{q}_{htr} = \dot{q}_2 - \dot{q}_1 \tag{10}$$

```
T_htr=T_s_rq-q_dot_1*R_cond_w                        "heater temperature"
q_dot_2=(T_htr-T_f)/(R_cond_b+R_cond_w+R_conv_f)     "heat transfer to freezer space"
q_dot_htr=q_dot_2-q_dot_1                            "heater power"
```

The solution indicates that $\dot{q}_{htr}$ = 43.6 W.

i.) Prepare a plot showing the amount of heat required by the heater as a function of the freezer air temperature.

The plot is generated following essentially the same steps discussed in part (e) and shown in Figure P1.2-6-14.

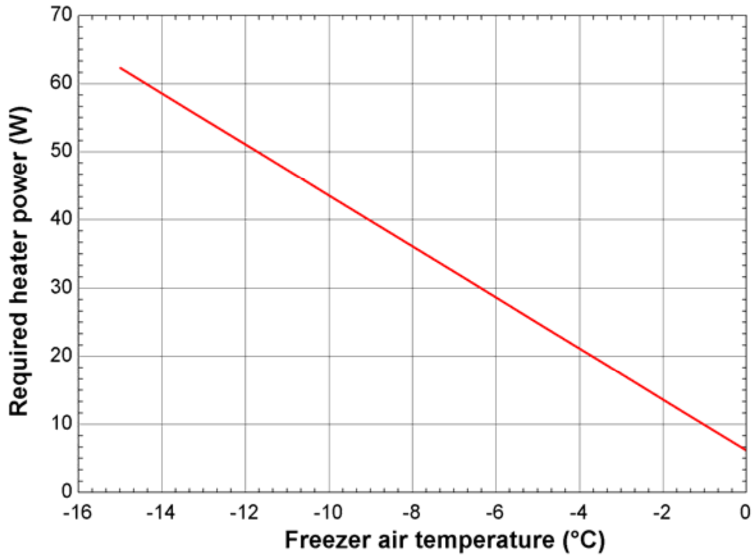



**Figure P1.2-6-14: Heater power as a function of the freezer air temperature.**