ME 332 Project Assignment 2

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Heat Transfer Project 2

Objective

For a small chemical plant, a heat exchanger needs to be designed to cool a constant supply of a boiling solution from 100ºC down to 30ºC. Due to a limited budget, the goal is that the heat exchanger should be at its lowest cost both in material and operation. To achieve the optimized design, the diameter of the pipe changes as an independent variable; and the length of the heat exchanger, the coolant flow rate and the outlet temperature of coolant need to be analyzed. As the diameter of the pipe changes, different behaviors of the solution flow will be considered. Besides, a comparison between parallel flow and count flow exchangers will be conducted to accomplish the goal. With the identified details about the heat exchanger and coolant, the total cost can be identified.

Assumptions:

- The flow is fully developed.
- The flow of coolant and solution is turbulent.
- Assume that all properties of the coolant are similar to air at 15 ºC.
- Assume that all properties of the solution are similar to water at 60 ºC.
- Assume a steady state condition has been established.
- The solution will be flow through the inner portion of the annulus.
- Only the heat transfer within the heat exchanger will be considered
- The tube wall thickness should be 20% of the outer radius. Additionally, assume that the inner radius of the outer tube is twice the inner radius of the inner tube.
- Inconel 625 has a density of 8.44 g/cm^3 and a thermal conductivity of 9.8 W/m-K.
- Assume no fouling will exist. The surface roughness is 0.03 mm
- Manufacturing costs are based solely on weight.

Design Constraints:

In this project the primary constraints are pressure contained within air pipes, cost of material, the cost of the air pump, and physics. Using the air to cool, the more we can use the more our cooling power can be. We must, for safety reasons limit our pressure in the air pipes, which restricts our flow rate and heat transfer. Since our heat transfer is limited we need to find a design which will work with our maximum heat transfer constraint, some designs may not work due to violation of physics. If the tubes are too small, it may be possible that cooling the liquid that far is impossible. Once a range of physically possible designs are found, it must be chosen by making a compromise between costs of material and electricity resulting in the lowest possible cost.

Approach:

The correct approach starts with identifying the mass flow rates and velocities of solution and air. All solution values can be found from

$$q_{sol} = m_{solution}\, cp\, (T_{mo} - T_{mi}) \qquad m_{sol} = \rho U_m A_c$$

For the air is not so simple as the air outlet temperature is unknown, it must be solved for by relationships of friction factor, reynolds number and turbulent flow in a pipe.

$$f = \frac{dp/dx * D}{(\rho U m^2)/2} \qquad \frac{1}{\sqrt{f}} = -2 * \log\left(\frac{e/d}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \qquad Re = \frac{\rho V D}{\mu}$$

The only unknown is U_m air. So outlet temperature and mass flow rate can be solved for

With all reynolds number known we can calculate hi, and ho

$$Nu = \frac{hD}{k} \quad \text{where } Nu = \frac{(f/8)(Re - 1000)pr}{1+12.7(f/8)^{1/2}pr^{2/3}-1}$$

Now overall heat transfer coefficient is solved for

$$q = UA * \Delta T_{lm} \text{ ,where } \Delta T_{lm} = \frac{\Delta T2 - \Delta T1}{ln\,(\Delta T2/\Delta T1)}$$

Now length of exchanger is solved for

$$\frac{1}{UA} = \frac{1}{h_{air} \cdot \pi \cdot Inner_{tube,ID} \cdot L} + \frac{1}{h_{solution} \cdot \pi \cdot Inner_{tube,OD} \cdot L} + R_w$$

$$R_w = \frac{\ln\left[\frac{inner_{tube,IR} + t_{inner,tube}}{inner_{tube,IR}}\right]}{2 \cdot \pi \cdot L \cdot k_{pipe}}$$

Find the cost of the metal to make the exchanger

$$Cost\ tubes = (Volume_{inner} + Volume_{outer})L * \rho * cost/kg$$

Find the cost to pump the air

$$Cost\ Electricity = price/kg * m_{dot}\ air * time$$

Results:

Analysis for this heat exchanger showed that there is a range of physically possible designs. If the diameter is too small then it is physically impossible to remove the required amount of heat required for this application. For this situations we analyzed a parallel and counter flow heat exchanger.
The results for the best heat exchangers for the specified diameters are listed, also the optimized counterflow heat exchanger

Type of Heat Exchanger	Counterflow	Parallel flow	Ideal Counterflow
Inner Tube inner radius [m]	0.01	0.150	0.009925
Heat Exchanger Length L [m[	7.938	7.876	7.95
Coolant Flow Rate [kg/hr]	2425	7071	2399
Outlet Temperature of Coolant [c]	35.46	12.2	35.86
Cost of Heat Exchanger (Metal) [$]	5623	12554	5547
Operating Cost per Hour[$]	1212	3525	1199
Overall Heat Transfer Coefficient UA [w/k]	532	503.7	533.9
Total cost [$]	6835	16079	6746

Fig1 : Optimal result summary

If I could change one aspect of the heat exchanger to reduce the cost, it would be to reduce the diameter even further. The pipe radius found from quadratic approximations is illustrated in green above. This increases the length and the outlet temperature of the air.
The differences may seem minor, but the cost is ~$15 less per hour. Running constantly that adds to a savings of $113,880 per year. Over the life of a machine this can save a company millions.
Full results and graphs are available in appendix.

Conclusions:

The assumption that manufacturing costs are based solely on weight, and that all diameters are available gave lots of freedom. In reality considerations of available pipe diameters must be considered since specialty pipe diameters can be much more expensive. This analysis was also only over 50 hours. If the company has little use for the machine they will want to find the exchanger that reduces the cost of metal.

Appendix A: Schematic

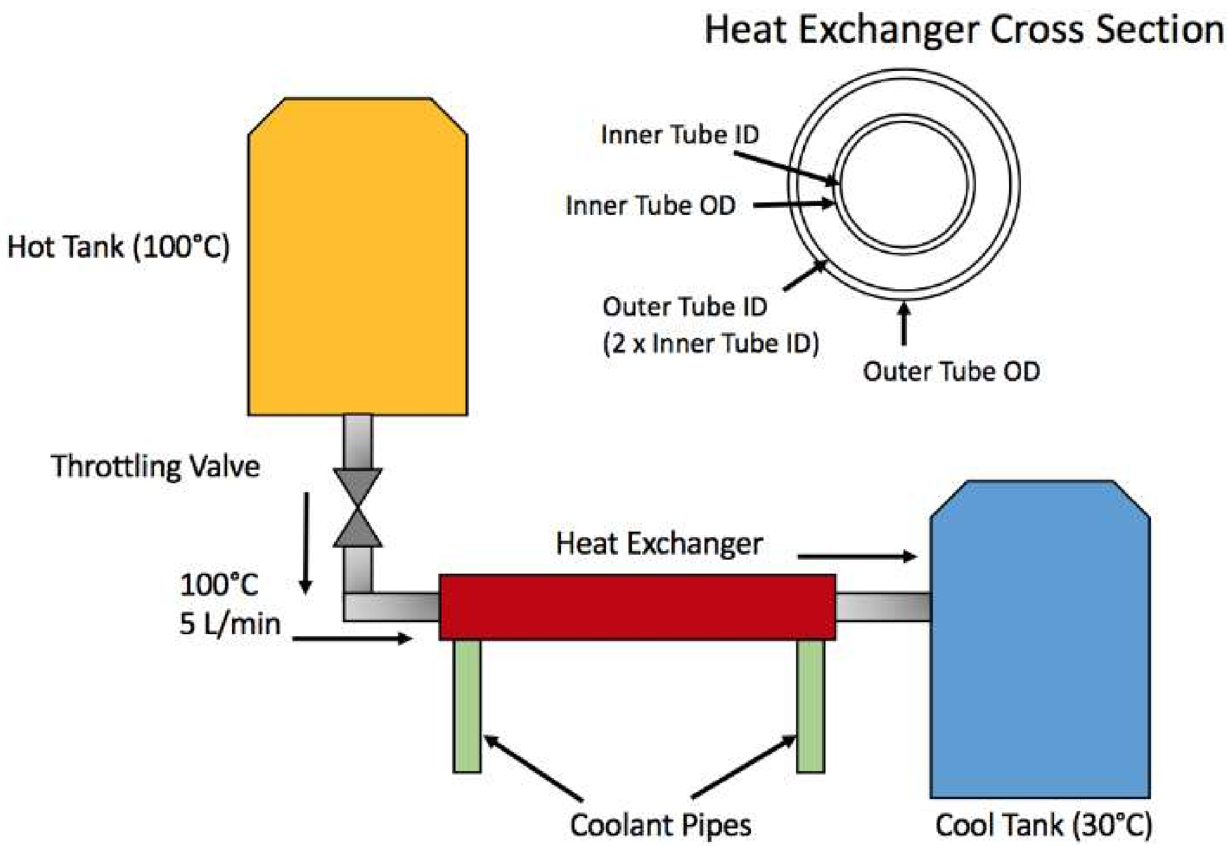

Fig.1 Schematic of Model

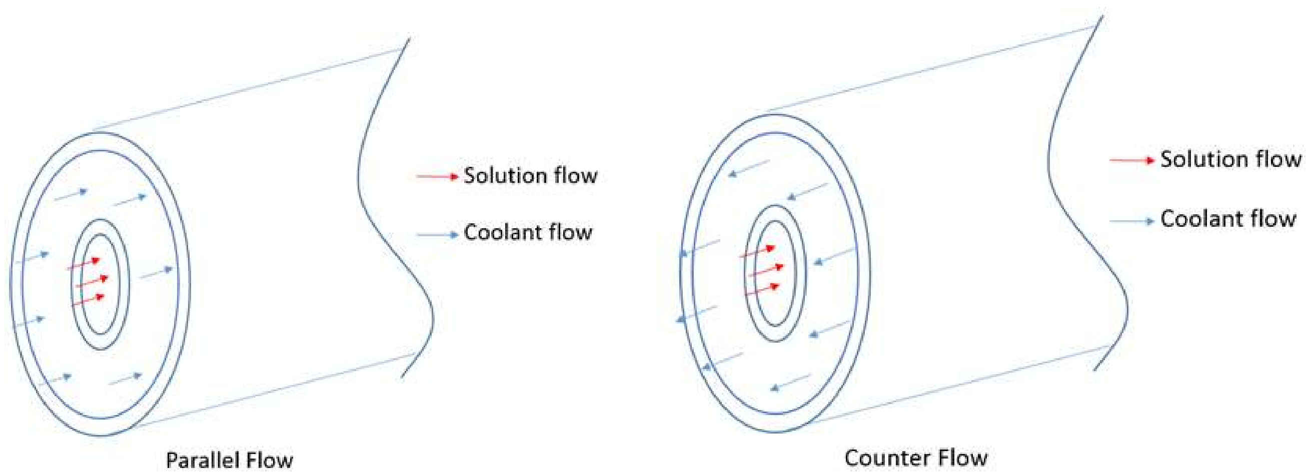

Fig.2 Schematic of flow rate direction

Appendix B: Detailed Results

Note: If a particular inner radius of the heat exchanger does not work, please note your observation.

Parallel Flow											
Item	Units	Value	Value								
Inner Tube inner radius	meters	0.005	0.010	0.015	0.020	0.025	0.030	0.035	0.040	0.045	0.050
Heat Exchanger Length L	meters	32.96	70.31	7.876	7.924	8.765	9.929	11.33	12.95	14.82	16.99
Coolant Flow Rate	kg/hr	388.00	2425.00	7051	15009	26944	43434	65014	92178	125395	165109
Outlet Temperature of Coolant	°C	221.60	35.46	12.2	5.73	3.192	1.98	1.323	0.9329	0.6858	0.5208
Cost of Heat Exchanger (Metal)	$	5838.00	49813.00	12554	22456	38811	63309	98295	146775	212627	300952
Operating Cost per Hour	$	194.00	1212.00	3525	7504	13472	21717	32507	46089	62698	82555
Overall Heat Transfer Coefficient UA	W/K	1651.00	4713.00	503.7	448.5	431.5	424	420.1	417.9	416.4	415.5

Counter Flow											
Item	Units	Value	Value								
Inner Tube inner radius	meters	0.005	0.010	0.015	0.020	0.025	0.030	0.035	0.040	0.045	0.050
Heat Exchanger Length L	meters	-63.39	7.938	6.969	7.55	8.546	9.778	11.21	12.86	14.74	16.93
Coolant Flow Rate	kg/hr	388	2425	7051	15009	26944	43434	65014	92178	125395	165109
Outlet Temperature of Coolant	°C	221.60	35.46	12.2	5.73	3.192	1.98	1.323	0.9329	0.6858	0.5208
Cost of Heat Exchanger (Metal)	$	-11228.00	5623.00	11108	21396	37839	62346	97308	145743	211532	299778
Operating Cost per Hour	$	194.00	1212.00	3525	7504	13472	21717	32507	46089	62698	82555
Overall Heat Transfer Coefficient UA	W/K	-3174.00	532.10	445.7	427.4	420.7	417.6	415.9	414.9	414.3	413.9

Optimized Heat Exchanger		
Type of Heat Exchanger	Counter Flow	
Item	Units	Value
Inner Tube inner radius	meters	0.010
Heat Exchanger Length L	meters	7.94
Coolant Flow Rate	kg/hr	2425.00
Outlet Temperature of Coolant	°C	3506.00
Cost of Heat Exchanger (Metal)	$	5623.00
Operating Cost per Hour	$	1212.00
Overall Heat Transfer Coefficient UA	W/K	532.00

Fig.3 Detailed Results for Desired Variables

1..10	$inner_{tube,IR}$	$u_{m,solution}$ [m/s]	$u_{m,air}$ [m/s]	$\dot{m}_{air,hr}$	$\dot{m}_{air}$ [kg/s]	$T_{air,out}$ [C]	$Re_{d,solution}$	$Re_{d,air}$	Nud_{air}	L [m]	UA	$Cost_{tube}$	$Cost_{operation}$	$Cost_{total}$
Run 1	0.005	1.061	457.1	391.5	0.1087	219.7	22359	239659	736.1	33.01	1661	5847	195.7	6043
Run 2	0.01	0.2653	714.1	2446	0.6796	35.16	11179	748809	1861	70.32	4727	49822	1223	51045
Run 3	0.015	0.1179	922.9	7113	1.976	12.09	7453	1.451E+06	3217	7.847	502.6	12508	3557	16065
Run 4	0.02	0.06631	1105	15142	4.206	5.68	5590	2.317E+06	4753	7.911	448.2	22418	7571	29989
Run 5	0.025	0.04244	1270	27182	7.551	3.164	4472	3.328E+06	6442	8.757	431.3	38773	13591	52364
Run 6	0.03	0.02947	1421	43819	12.17	1.963	3726	4.471E+06	8264	9.923	423.9	63268	21909	85178
Run 7	0.035	0.02165	1563	65589	18.22	1.311	3194	5.736E+06	10206	11.32	420	98252	32794	131046
Run 8	0.04	0.01658	1697	92993	25.83	0.9249	2795	7.116E+06	12257	12.94	417.8	146729	46496	193226
Run 9	0.045	0.0131	1824	126503	35.14	0.6799	2484	8.605E+06	14409	14.82	416.4	212578	63252	275830
Run 10	0.05	0.01061	1945	166568	46.27	0.5164	2236	1.020E+07	16657	16.99	415.5	300899	83284	384183

Fig.4 other properties of parallel flow

1..10	$inner_{tube,IR}$	$u_{m,solution}$ [m/s]	$u_{m,air}$ [m/s]	$\dot{m}_{air,hr}$	$\dot{m}_{air}$ [kg/s]	$T_{air,out}$ [C]	$Re_{d,solution}$	$Re_{d,air}$	Nud_{air}	L [m]	UA	$Cost_{tube}$	$Cost_{operation}$	$Cost_{total}$
Run 1	0.005	1.061	457.1	391.5	0.1087	219.7	22359	239659	736.1	-63.88	-3215	-11315	195.7	-11119
Run 2	0.01	0.2653	714.1	2446	0.6796	35.16	11179	748809	1861	7.895	530.7	5593	1223	6816
Run 3	0.015	0.1179	922.9	7113	1.976	12.09	7453	1.451E+06	3217	6.953	445.4	11084	3557	14640
Run 4	0.02	0.06631	1105	15142	4.206	5.68	5590	2.317E+06	4753	7.541	427.2	21370	7571	28941
Run 5	0.025	0.04244	1270	27182	7.551	3.164	4472	3.328E+06	6442	8.539	420.6	37810	13591	51402
Run 6	0.03	0.02947	1421	43819	12.17	1.963	3726	4.471E+06	8264	9.773	417.5	62315	21909	84224
Run 7	0.035	0.02165	1563	65589	18.22	1.311	3194	5.736E+06	10206	11.21	415.9	97274	32794	130068
Run 8	0.04	0.01658	1697	92993	25.83	0.9249	2795	7.116E+06	12257	12.85	414.9	145706	46496	192202
Run 9	0.045	0.0131	1824	126503	35.14	0.6799	2484	8.605E+06	14409	14.74	414.3	211493	63252	274744
Run 10	0.05	0.01061	1945	166568	46.27	0.5164	2236	1.020E+07	16657	16.92	413.9	299736	83284	383020

Fig.5 other properties of counter flow

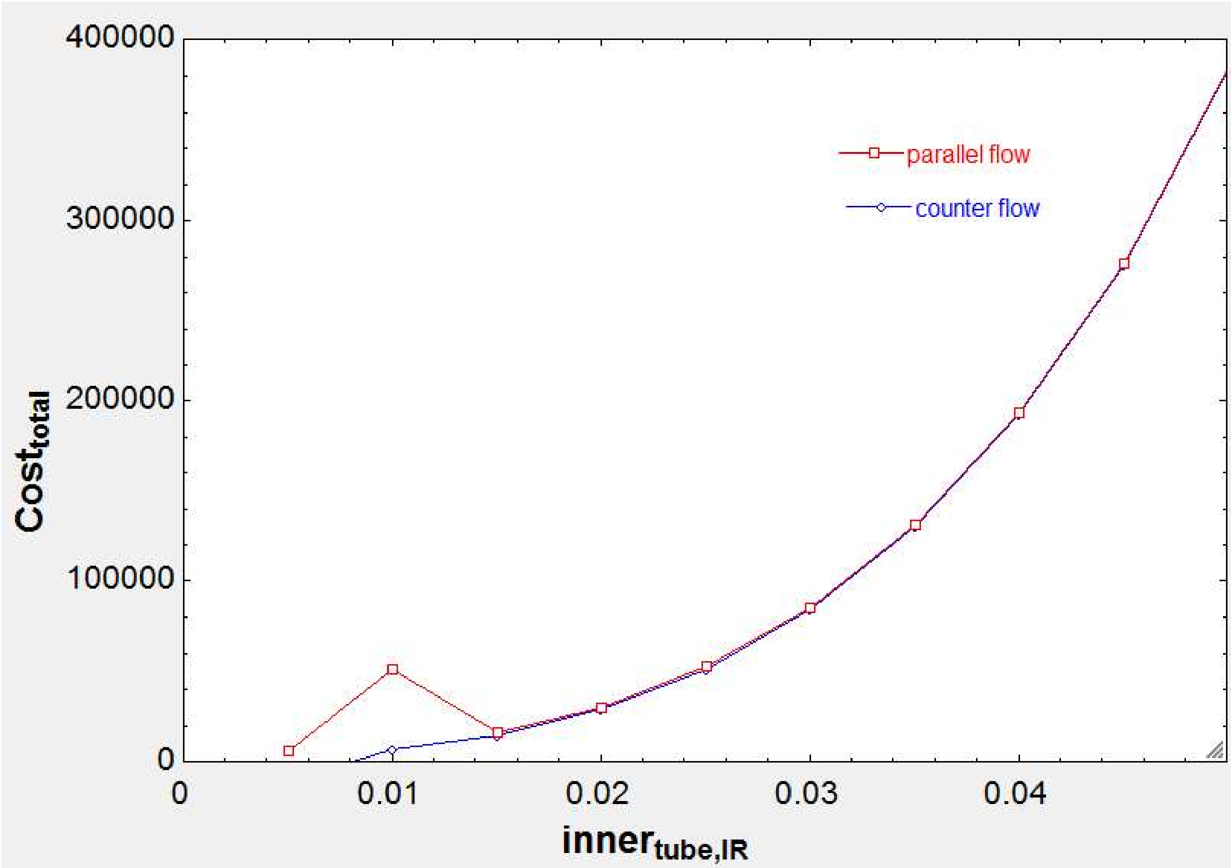

Fig. 6 Radius vs Cost

Appendix C: Equations

Flow rate/Reynolds

Solution flow

$$\dot{V}_{solution} = 5 \cdot \left| 0.0000166667 \cdot \frac{m^3/s}{L/min} \right|$$

$$\dot{m}_{solution} = \dot{V}_{solution} \cdot \rho_{solution}$$

$$\dot{m}_{solution} = \rho_{solution} \cdot u_{m,solution} \cdot Ac_{inner}$$

$$Re_{d,solution} = \frac{\rho_{solution} \cdot u_{m,solution} \cdot Inner_{tube,ID}}{\mu_{solution}}$$

if the $Re_{d,solution}$ > 2300, the solution flow is considered as turbulent. The following eqns will be valid

$$\frac{1}{\sqrt{f_{solution}}} = -2 \cdot \log\left[\frac{roughness_{in}}{3.7} + \frac{2.51}{Re_{d,solution} \cdot \sqrt{f_{solution}}}\right]$$

$$NuD_{solution} = \frac{\frac{f_{solution}}{8} \cdot \left[Re_{d,solution} - 1000\right] \cdot pr_{solution}}{1 + 12.7 \cdot \left[\frac{f_{solution}}{8}\right]^{\left[1/2\right]} \cdot \left[pr_{solution}^{\ (2/3)} - 1\right]}$$

$$NuD_{solution} = h_{solution} \cdot \frac{Inner_{tube,ID}}{k_{water}}$$

Air Flow

$$dpdx = 500 \cdot \left| 1000 \cdot \frac{Pa/m}{KPa/m} \right|$$

$$f_{air} = \frac{dpdx \cdot Dh_{outer}}{\frac{\rho_{air} \cdot u_{m,air}^{2}}{2}}$$

if the $Re_{d,air}$ > 2300, the air flow is considered as turbulent. The following eqns will be valid

$$\frac{1}{\sqrt{f_{air}}} = -2 \cdot \log\left[\frac{roughnessair}{3.7} + \frac{2.51}{Re_{d,air} \cdot \sqrt{f_{air}}}\right]$$

$$Re_{d,air} = \rho_{air} \cdot u_{m,air} \cdot \frac{Dh_{outer}}{\mu_{air}}$$

$$Nud_{air} = \frac{\frac{f_{air}}{8} \cdot [Re_{d,air} - 1000] \cdot pr_{air}}{1 + 12.7 \cdot \left[\frac{f_{air}}{8}\right]^{[1/2]} \cdot [pr_{air}^{(2/3)} - 1]}$$

$$Nud_{air} = h_{air} \cdot \frac{Dh_{outer}}{k_{air}}$$

if the $Re_{d,air}$ <= 2300, the solution flow is considered as laminar. The following eqns will be valid

$f_{air} = 64/Re_{d,air}$

Energy balance

$$q_{solution} = \dot{m}_{solution} \cdot cp_{solution} \cdot [T_{sol,out} - T_{sol,in}]$$

$$q_{air} = -q_{solution}$$

$$q_{air} = \dot{m}_{air} \cdot cp_{air} \cdot [T_{air,out} - T_{air,in}]$$

$$\dot{m}_{air} = \rho_{air} \cdot u_{m,air} \cdot Ac_{outer}$$

$$-q_{solution} = UA \cdot \delta_{t,lm,cnt}$$

$$arg1 = \frac{dT_2}{dT_1}$$

$$\delta_{t,lm,cnt} = \frac{dT_2 - dT_1}{\ln[arg1]}$$

$$dT_1 = T_{sol,in} - T_{air,out}$$

$$dT_2 = T_{sol,out} - T_{air,in}$$

UA

$$\frac{1}{UA} = \frac{1}{h_{air} \cdot \pi \cdot Inner_{tube,ID} \cdot L} + \frac{1}{h_{solution} \cdot \pi \cdot Inner_{tube,OD} \cdot L} + R_w$$

$$R_w = \frac{\ln\left[\frac{inner_{tube,IR} + t_{inner,tube}}{inner_{tube,IR}}\right]}{2 \cdot \pi \cdot L \cdot k_{pipe}}$$

total costs

$$Cost_{tube} = \left[\frac{\pi}{4} \cdot \left(Outer_{tube,OD}{}^2 - Outer_{tube,ID}{}^2\right) + \frac{\pi}{4} \cdot \left(Inner_{tube,OD}{}^2 - Inner_{tube,ID}{}^2\right)\right] \cdot L \cdot \rho_{pipe} \cdot 95$$

$$Cost_{operation} = \dot{m}_{air} \cdot \left|3600 \cdot \frac{kg/hr}{kg/s}\right| \cdot 50 \cdot 0.01$$

$$Cost_{total} = Cost_{tube} + Cost_{operation}$$

$$\dot{m}_{air,hr} = \dot{m}_{air} \cdot \left|3600 \cdot \frac{kg/hr}{kg/s}\right|$$

Appendix D: EES Code

```
                    "known temperatures"
T_sol_in = 100 [C]
T_sol_out = 30 [C]
T_air_in = 0 [C]

T_air_calc = 10
T_solution_calc = 60

                    "properties"

"given"
k_pipe = 9.8 [W/m*k]
rho_pipe = 8.44*convert(g/cm^3,kg/m^3)

"Solution"
rho_solution = density(Water,T= T_solution_calc ,P =101[kpa])
cp_solution = specheat(Water,T= T_solution_calc,P =101[kpa])
mu_solution = viscosity(Water,T= T_solution_calc,P =101[kpa])
 k_water = conductivity(Water,T= T_solution_calc,P =101[kpa])
pr_solution = (cp_solution*mu_solution)/k_water


"air"
rho_air = density(Air, T= T_air_calc,P =101[kpa] )
cp_air = specheat(Air,T= T_air_calc)
mu_air = viscosity(Air,T= T_air_calc)
 k_air = conductivity(Air,T= T_air_calc)
pr_air = (cp_air*mu_air)/k_air

                    "Geometry"
"inner_tube_IR = .005"
Inner_tube_ID = 2*inner_tube_IR
Inner_tube_OD = inner_tube_ID + 2* t_inner_tube
t_inner_tube = .2*(Inner_tube_IR + t_inner_tube)

Outer_tube_IR = 2*Inner_tube_IR
Outer_tube_ID =2*Outer_tube_IR
Outer_tube_OD =Outer_tube_ID + 2* t_Outer_tube
t_Outer_tube = .2*(Outer_tube_IR + t_Outer_tube)

Dh_outer = Outer_tube_ID - inner_tube_OD

Ac_inner = (pi/4)*Inner_tube_ID^2
Ac_outer=(pi/4)*(Outer_tube_ID ^2 - inner_tube_OD^2)
roughnessin = .00003/inner_tube_ID
roughnessair = .00003/Dh_outer
```

```
                    "Flow rate/Reynolds"

"Solution flow"
V_dot_solution = 5*convert(L/min,m^3/s)
m_dot_solution = V_dot_solution*rho_solution
m_dot_solution = rho_solution *u_m_solution *Ac_inner
Re_d_solution = (rho_solution*u_m_solution*Inner_tube_ID)/mu_solution

" if the Re_d_solution > 2300, the solution flow is considered as turbulent. The following eqns will be valid"

 {colebrook equations}
1/sqrt(f_solution) = (-2)*log10((roughnessin)/3.7+(2.51)/(Re_d_solution*sqrt(f_solution)))
NuD_solution =
(((f_solution)/8)*(Re_d_solution-1000)*Pr_solution)/(1+12.7*(((f_solution)/8)^(1/2))*(Pr_solution^(2/3)-1))
NuD_solution = h_solution*Inner_tube_ID/k_water

"Air Flow"

dpdx =500*convert(KPa/m,Pa/m)
f_air=(dpdx*Dh_outer)/((rho_air*u_m_air^2)/2)

"if the Re_d_air > 2300, the air flow is considered as turbulent. The following eqns will be valid"
  {colebrook equations}
1/sqrt(f_air) = (-2)*log10((roughnessair)/3.7+(2.51)/( Re_d_air*sqrt(f_air)))
Re_d_air = rho_air*u_m_air*Dh_outer/mu_air

Nud_air = (((f_air)/8)*(Re_d_air-1000)*Pr_air)/(1+12.7*(((f_air)/8)^(1/2))*(Pr_air^(2/3)-1))
Nud_air = h_air*Dh_outer/k_air

" if the Re_d_air <= 2300, the solution flow is considered as laminar. The following eqns will be valid"
"f_air = 64/Re_d_air"

                    "Energy balance"

q_solution = m_dot_solution*cp_solution*(T_sol_out-T_sol_in)
q_air =-q_solution
q_air = m_dot_air*cp_air* (T_air_out - T_air_in )
m_dot_air =  rho_air *u_m_air *Ac_outer

                    "Parallel flow "
"-q_solution= UA* delta_t_lm_prl
arg1 =dT_2/dT_1
delta_t_lm_prl = (dT_2-dT_1)/ln(arg1)
dT_1 = T_sol_in-T_air_in
dT_2 = T_sol_out-T_air_out"

                    "Counter flow"
```

-q_solution= UA* delta_t_lm_cnt
arg1 =dT_2/dT_1
delta_t_lm_cnt = (dT_2-dT_1)/ln(arg1)
dT_1 = T_sol_in-T_air_out
dT_2 = T_sol_out-T_air_in

"UA"

1/(UA)=1/(h_air*pi*inner_tube_ID*L)+1/(h_solution*pi*inner_tube_OD*L)+R_w
R_w = ln((Inner_tube_IR+t_inner_tube)/Inner_tube_IR)/(2*pi*L*k_pipe)

"total costs"

Cost_tube = ((pi/4)*(Outer_tube_OD^2-Outer_tube_ID^2)+
(pi/4)*(inner_tube_OD^2-inner_tube_ID^2))*L*rho_pipe*95
Cost_operation = m_dot_air*convert(kg/s,kg/hr)*50*.01
Cost_total = Cost_tube + Cost_operation
m_dot_air_hr = m_dot_air*convert(kg/s,kg/hr)