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

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

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

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

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

Fig.3 Detailed Results for Desired Variables

Fig. 6 Radius vs Cost

Appendix C: Equations

Appendix D: EES Code

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                    "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
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                    "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"
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-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)
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