Project 2 Part C: Boiler Design

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Thermal Fluid Design

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Assumptions:

- Steel tubing (assume hot rolled steel, emissivity = 0.75)
- Constant heat flux boundary conditions
- Inner diameter: 35 mm = .035 m
- Outer diameter: 40 mm = .04 m
- Consider three sections:
    - (i) Subcooled Heating
    - (ii) Phase Change (Mixture)
    - (iii) Superheating
- T_surrounding = 1500 K for single-phase sections (i) and (iii)
- T_surrounding = 2500 K for two-phase section (ii)

Subcooled Phase (i):

a. Find q_in.

q_in = 3.3218e+05 kW

b. Find the Re and Pr numbers inside the tubes.

Re = 2.4222e+05

Pr = 3.5692

c. Find the heat transfer coefficient inside the tubes.

h = 8.6151e+03

d. Find the total resistance network.

r = 0.0027 K / W

e. Calculate the length required using the log-mean-T method

length = 29.2168 m with 500 tubes

Superheated Phase (iii):

a. Find q_in.

q_in = 3.4098e+05 kW

b. Find the Re and Pr numbers inside the tubes.

Re = 4.4085e+05

Pr = 4.1803

c. Find the heat transfer coefficient inside the tubes.

h = 6.5354e+03

d. Find the total resistance network.

r = 0.0023 K / W

e. Calculate the length required using the log-mean-T method
f. Change the number of tubes and iterate until they reach a reasonable length.

length = 64.5963 m with 500 tubes.

Two-Phase (ii):

- T_surrounding = 2500 K for two-phase section (ii)

g. Assume the number of tubes and the tube length.

Number of tubes: 50 tubes

Length of tubes: 200 meters

h. Find the heat flux if the input heat is evenly distributed among the tubes.

q" = 3.3218e+04 (W/m^2)

i. Find quality, X(x), along each tube. (Note that equations we know do not work for X>0.85).

X(x) = 0.0138

j. Find the local heat transfer coefficient along the tube, h(x), where 0<x<tube length (You need first to find H_sp (single phase h) using RE and Pr).

h(x) = 7.5858e+03 (W/m^2*K)

k. Find the total thermal resistance using convection inside the tube, conduction of the tube wall thickness, and radiation on the outer tube surface.

R_tot = 2.7963e-04 (K/W)

l. Find the tube surface temperature, Ts(x), as a function of the tube length.

Ts(x) = 643.29 K.

m. Iterate through your assumptions if needed to ensure the tube surface temperature is below the melting point.

Part D: Extra Credit

Research on heat recovery of a Rankine Cycle, i.e., the heat rejected from the steam in the condensor, and discuss possible methods to use that heat instead of simply rejecting it into the environment.

Combined Heat and Power (CHP) Systems

Overview:

Combined Heat and Power (CHP) systems allow for the dual production of electricity and useful thermal energy, such as heating and cooling, from a single Rankine cycle. In a Rankine cycle heat is rejected from the steam while passing through the condenser, this heat can be turned into useful thermal power for a multitude of applications. In a standard Rankine cycle the heat rejected would be lost and wasted, but with a CHP it can be converted into useful thermal power to heat factories, schools and more.

Applications:

- **Industrial Facilities:** Many factories and manufacturing plants have a need for both electrical power and thermal energy for their processes. CHP systems are ideal for these settings, as they can provide the electrical power generated by the Rankine cycle but can also provide thermal power/energy for other processes, machines, or even just to heat the plants.
- **Commercial Buildings:** Hospitals, Universities, and Hotels can significantly benefit from CHP systems. These buildings often have high heating and cooling demands, along with the need for lots of electrical power. By using CHP systems commercial buildings can cut down on costs and most importantly waste when generating electric power and thermal power.

- **Space Heating:** The thermal energy produced can be used for space heating, particulary important in colder climates.
- **Hot Water Production:** CHP generates a reliable supply of hot water whether for cooking, cleaning, or relaxing.

Benefits:

CHPs provide a significant advantage over a standard Rankine cycle by reusing wasted heat, enabling a variety of applications at the same operational cost as the Rankine cycle. This approach addresses two issues simultaneously, maximizing the use of available resources.

Appendix A

MATLAB Code for Phase I, II, and III

```
% Designing the boiler, split into three phases
% declare constants
emissivity = .75; % assume hot rolled steel tubing
sigma = 5.67E-8; % Stefan-Boltzmann constant, W/m^2*K^4

% declare values
p_max = 20000; % kPa
t_initial = 599.4337; % K
t_saturation = 638.8993; % K
t_final = 813.15; % K
t_surroundingsi = 1500; % K
diameter_i = .035; % m
diameter_o = .04; % m
tubes = 500; % subject to change
m_dot = 178.71 / tubes; % kg / sec

% Phase i

% Find q_in
[h_i_i] = refpropm('H','T',t_initial,'P',p_max,'water');
[h_i_o] = refpropm('H','T',t_saturation,'P',p_max,'water');

q_in_i = m_dot * (h_i_o - h_i_i); % kW

% Find Re and Pr numbers inside the tube
[density_initial, viscosity_initial, cp_initial, k_initial] =
refpropm('DVCL','T',t_initial,'P',p_max,'water');
[density_sat, viscosity_sat, cp_sat, k_sat] =
refpropm('DVCL','T',t_saturation,'P',p_max,'water');

density_i = (density_initial + density_sat) / 2; % average density during phase i
viscosity_i = (viscosity_initial + viscosity_sat) / 2; % average viscosity during
phase i
cp_i = (cp_initial + cp_sat) / 2; % average specific heat capacity during phase i
k_i = (k_initial + k_sat) / 2; % average thermal conductivity during phase i

Re_i = m_dot / (pi*.25*diameter_i*viscosity_i); % dimensionless Reynolds number
during phase 1
Pr_i = (viscosity_i * cp_i) / k_i; % Prandtl number during phase 1

% Find the heat transfer coefficient inside the tubes
Nu_i = .023 * Re_i^.8 * Pr_i^.4; % Nusselt number calculation using the Dittus-
Boelter correlation
heat_transfer_coefficient_i = (Nu_i * k_i) / diameter_i;
```

```
% Find the total resistance newtwork and length
t_avgi = (((t_initial+t_saturation)/2) +t_surroundingsi)/2; % K
LMTDi = ((-t_initial+t_surroundingsi)-(-t_saturation+t_surroundingsi))/log((-
t_initial+t_surroundingsi)/(-t_saturation+t_surroundingsi)); % K
h_rad_i =
emissivity*sigma*((t_avgi)^2+t_surroundingsi^2)*((t_avgi)+t_surroundingsi); % K/W
r_conv_iprime =
1/(heat_transfer_coefficient_i*pi*diameter_i)+log(diameter_o/diameter_i)/(2*pi*k_i)+1
/(h_rad_i*pi*diameter_o); % m*K/W
length_i = (r_conv_iprime*q_in_i) / LMTDi; % m, with 500 tubes
r_conv_i = r_conv_iprime / length_i; % K/W

% Phase iii

% Find q_in
[h_iii_i] = refpropm('H','T',t_saturation,'P',p_max,'water');
[h_iii_o] = refpropm('H','T',t_final,'P',p_max,'water');

q_in_iii = m_dot * (h_iii_o - h_iii_i); % kW

% Find Re and Pr numbers inside the tube
[density_final, viscosity_final, cp_final, k_final] =
refpropm('DVCL','T',t_final,'P',p_max,'water');

density_iii = (density_final + density_sat) / 2; % average density during phase iii
viscosity_iii = (viscosity_final + viscosity_sat) / 2; % average viscosity during
phase iii
cp_iii = (cp_final + cp_sat) / 2; % average specific heat capacity during phase iii
k_iii = (k_final + k_sat) / 2; % average thermal conductivity during phase iii

Re_iii = m_dot / (pi*.25*diameter_i*viscosity_iii); % dimensionless Reynolds number
during phase iii
Pr_iii = (viscosity_iii * cp_iii) / k_iii; % Prandtl number during phase iii

% Find the heat transfer coefficient inside the tubes
Nu_iii = .023 * Re_iii^.8 * Pr_iii^.4; % Nusselt number calculation using the Dittus-
Boelter correlation
heat_transfer_coefficient_iii = (Nu_iii * k_iii) / diameter_i;

% Find the total resistance newtwork and length
t_avgiii = (((t_final+t_saturation)/2) +t_surroundingsi)/2; % K
LMTDiii = ((-t_saturation+t_surroundingsi)-(-t_final+t_surroundingsi))/log((-
t_saturation+t_surroundingsi)/(-t_final+t_surroundingsi)); % K
h_rad_iii =
emissivity*sigma*((t_avgiii)^2+t_surroundingsi^2)*((t_avgiii)+t_surroundingsi); % K/W
```

```
r_conv_iiiprime =
1/(heat_transfer_coefficient_iii*pi*diameter_i)+log(diameter_o/diameter_i)/(2*pi*k_ii
i)+1/(h_rad_iii*pi*diameter_o); % m*K/W
length_iii = (r_conv_iiiprime*q_in_iii) / LMTDiii; % m, with 500 tubes
r_conv_iii = r_conv_iiiprime / length_iii; % K/W

% Phase ii

% Two-Phase Assumptions
N = 50; % Number of tubes
L = 200; % Length of each tube in meters
q_in_two_phase = q_in_i; % Assuming the same input for simplicity

% 1. Find the Heat Flux
q_double_prime = q_in_two_phase * 1000 / (N * L); % W/m^2 (Convert kW to W)

% 2. Find Latent Heat of Vaporization
h_fg = refpropm('H', 'T', t_saturation, 'P', p_max, 'water', 'latent'); % Latent heat
of vaporization
X = zeros(1, N); % Preallocate quality array

for i = 1:N
X(i) = min(q_double_prime / h_fg, 0.85); % Ensure X(x) <= 0.85
End

% 3. Find the Local Heat Transfer Coefficient h(x)
Re_sp = m_dot / (pi * 0.25 * diameter_i * viscosity_i); % Use appropriate viscosity
Pr_sp = (viscosity_i * cp_i) / k_i; % Use appropriate cp and k
Nu_sp = 0.023 * Re_sp^0.8 * Pr_sp^0.3; % Nusselt number
h_sp = (Nu_sp * k_i) / diameter_i; % Local heat transfer coefficient

h_local = h_sp * ones(1, N); % Assuming constant for simplicity

% 4. Find the Total Thermal Resistance
% Assuming T_s will be calculated after its definition
T_fluid = t_saturation; % Assuming the fluid temperature is at saturation
T_s = T_fluid + (q_double_prime ./ h_local); % Surface temperature along the tube

R_conv = 1 ./ (h_local * pi * diameter_i * L); % Convection resistance
R_cond = log(diameter_o / diameter_i) ./ (2 * pi * k_i * L); % Conduction resistance
R_rad = 1 ./ (emissivity * sigma * ((t_surroundingsi^4) + (T_s.^4)) .* (T_s +
t_surroundingsi) * pi * diameter_o * L);

R_total = R_conv + R_cond + R_rad; % Total thermal resistance

% 5. Iterate Through Assumptions
melting_point_steel = 1510; % Example melting point in K
```

```
for i = 1:N
if T_s(i) > melting_point_steel
% Adjust the number of tubes or operational conditions
% Update calculations as needed
end
End

% Display single representative values for each result
disp('Heat Flux (W/m^2):'), disp(q_double_prime);
disp('Quality X(x):'), disp(X(1));
disp('Local Heat Transfer Coefficient (W/m^2*K):'), disp(h_local(1));
disp('Total Thermal Resistance (K/W):'), disp(R_total(1));
disp('Tube Surface Temperature (K):'), disp(T_s(1));
```