Steam Generator U-Tube

Natural Circulation type

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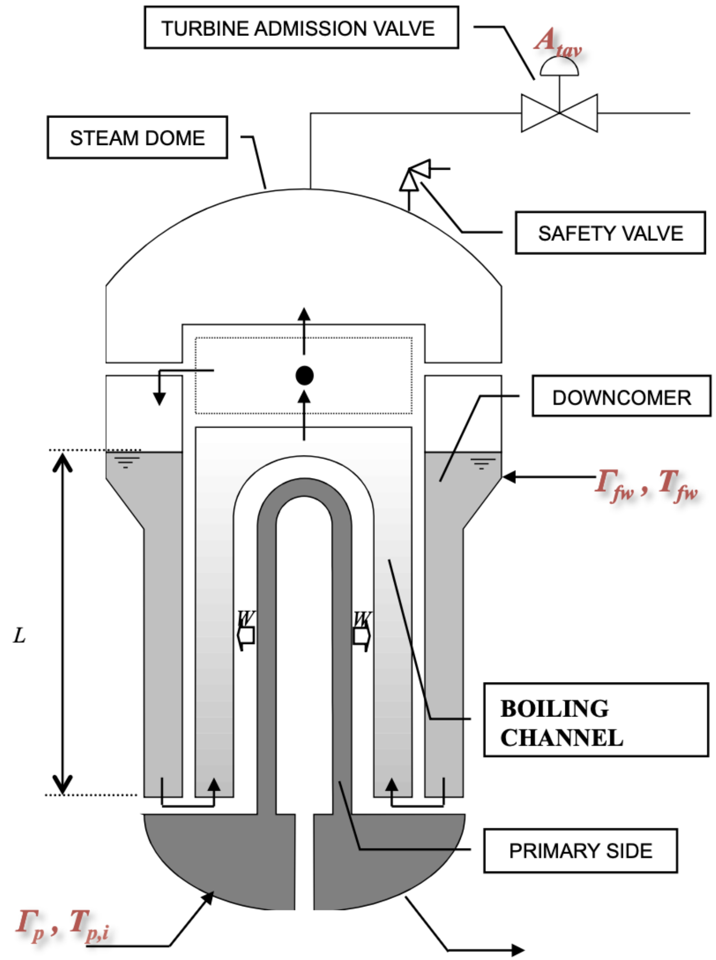
Introduction and aims

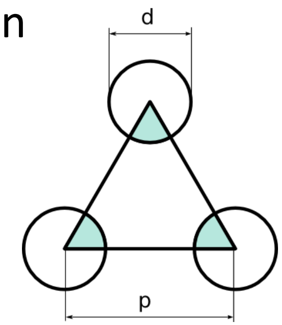
Dimensioning with steady-state model:

1. **the number of tubes;**
2. **the tube-bundle average length;**
3. **the liquid level in the downcomer region, to sustain the Natural Circulation mode.**



Solution strategy and main equations

Part 1: the number of tubes can be easily found just using the given geometrical data.



Equations:

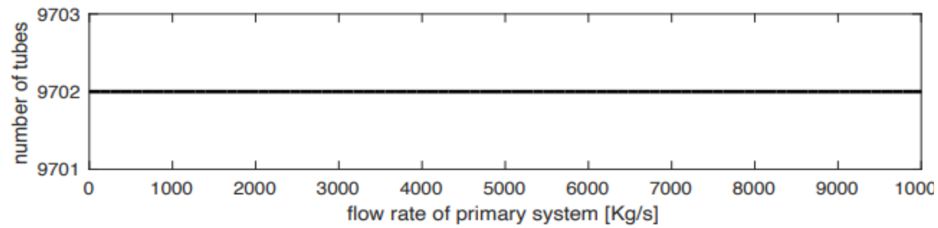
- pitch = pitch_ratio × $Tube_{od}$
- Lattice Area = $^1/_4\, pitch^2 \times \sqrt{3}$
- Area Utile = $^1/_4\, \pi \times barrel\_D^2$
- $N_{Tubes} = {^1/_2} \times occ_f \times \frac{Area\ Utile}{Lattice\ Area}$

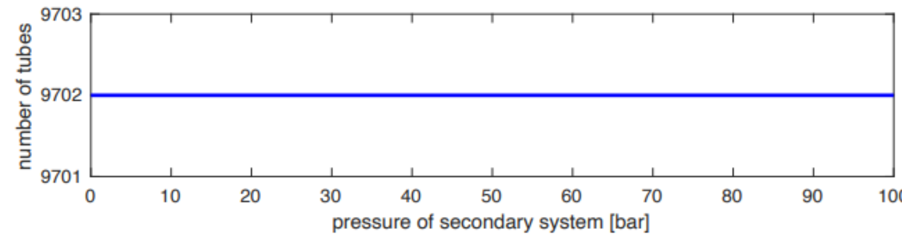
	Steam Generator U-Tube	
	A_{tav} = Turbine Admission Valve opening	100%
	Γ_{fw} = feedwater flow rate	480 kg/s
	T_{fw} = feedwater temperature	223.5 degC
	Steam quality at Steam Line inlet	1
	$\Gamma_{p,i}$ = primary flow rate, inlet	4419 kg/s
	$T_{p,i}$ = primary fluid temperature, inlet	327 degC
	$T_{p,i}$ = primary fluid temperature, outlet	292 degC
	Primary pressure	155 bar
	Secondary pressure	69 bar
	Steam separators and steam dryers efficiency	100%
	Steam quality at Steam separators inlet	15%
Tube_od	Tube outer diam.	19 mm
pitch_ratio	Tube pitch (triangular)/SG Tube OD	1.4
occ_f	Tube bundle occupancy factor	90%
	Tube roughness	4×10^{-6} m
	Lower shell inner diam.	3.4 m
barrel_D	Barrel diam.	2.90 m

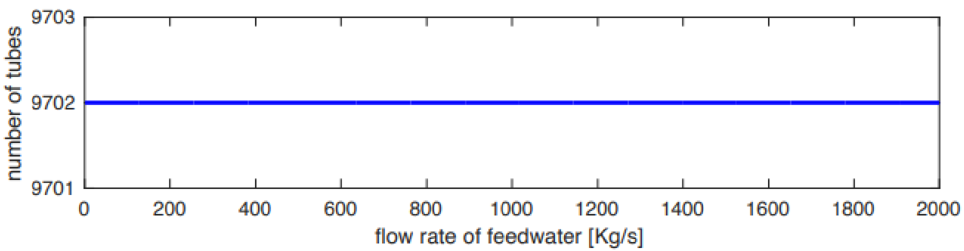
Part 1: Number of Tubes

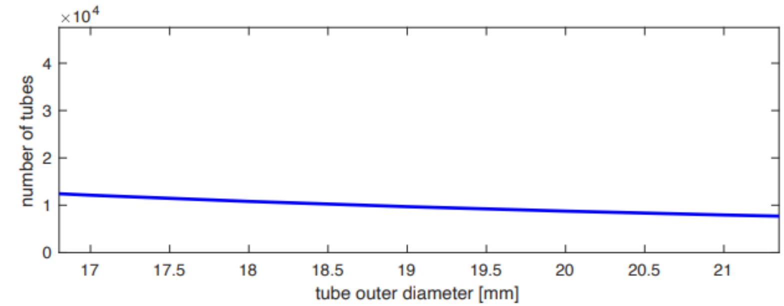
```
function[N_tube]=N_tubes(Tube_od,pitch_ratio,barrel_D,occ_f)
%[N_tube]=N_tubes(0.019,1.4,2.9,0.90)
% occ_f defines the occupancy factor
% Tube_od defines tube outer diameter
% pitch_ratio defines the ratio btw the tube pitch and the tube outer d
% barrel_D stays for barrel diameter
    pitch=pitch_ratio*Tube_od;
    lattice_area=pitch^2*sqrt(3)/4;
    area_utile=pi*barrel_D^2/4;
    N_t=occ_f*(area_utile/lattice_area)/2;
    N_tube=ceil(N_t);
end
```

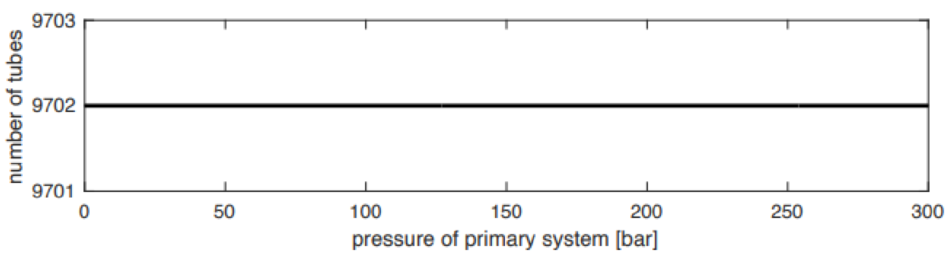
Sensitivity Analysis (Number of Tubes)

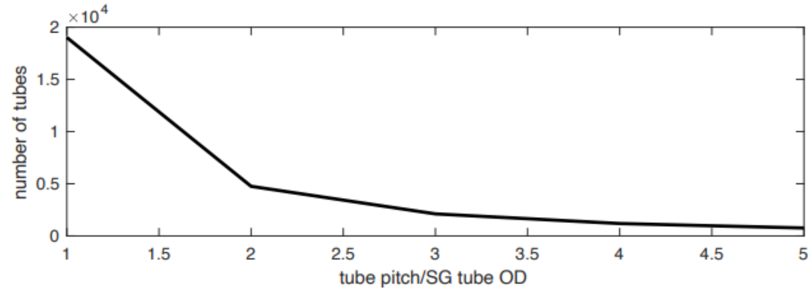








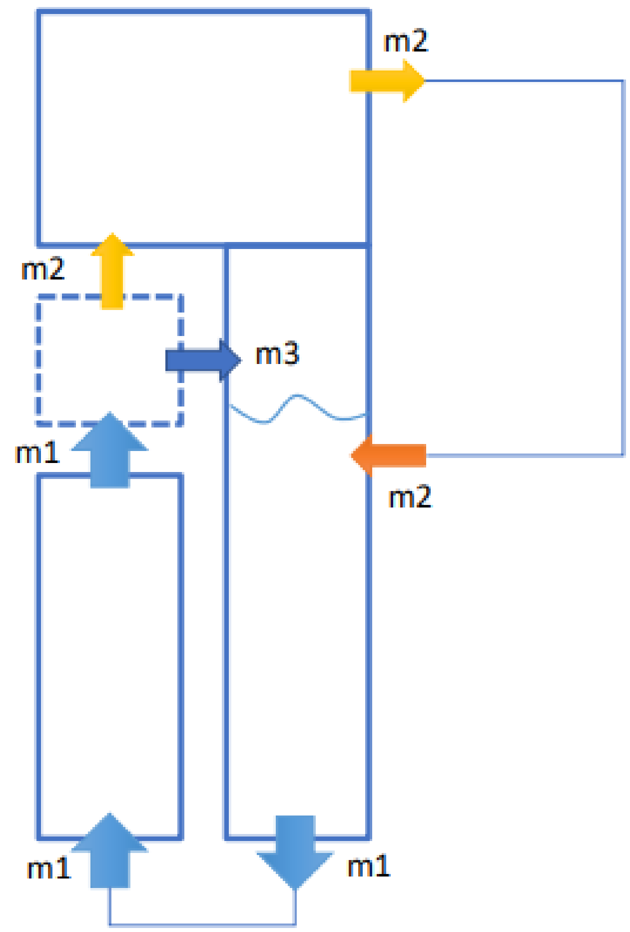




Solution strategy and hypothesis

Part 2:

- we consider the steam generator divided into three parts
- we consider the pressure in both the primary and the secondary fluid as constant
- we consider that all the thermal power given by the primary side is all received by the secondary fluid (no thermal losses)
- the heat transfer coefficients in both the primary and the secondary liquids are considered as constant



Main datas

	Steam Generator U-Tube	
	A_{tav} = Turbine Admission Valve opening	100%
Mfw	Γ_{fw} = feedwater flow rate	480 kg/s
Tfw	T_{fw} = feedwater temperature	223.5 degC
	Steam quality at Steam Line inlet	1
Mp	$\Gamma_{p,i}$ = primary flow rate, inlet	4419 kg/s
Tp_in	$T_{p,i}$ = primary fluid temperature, inlet	327 degC
Tp_out	$T_{p,i}$ = primary fluid temperature, outlet	292 degC
Pp	Primary pressure	155 bar
Ps	Secondary pressure	69 bar
	Steam separators and steam dryers efficiency	100%
x	Steam quality at Steam separators inlet	15%
Tube_od	Tube outer diam.	19 mm
pitch_ratio	Tube pitch (triangular)/SG Tube OD	1.4
	Tube bundle occupancy factor	90%
	Tube roughness	$4x10^{-6}$ m
	Lower shell inner diam.	3.4 m
barrel_D	Barrel diam.	2.90 m

Main equations (zone 1)

- Mass balances for secondary fluid: $M_s = M_{gamma} + M_{fw}$
- Newton's law for the first zone: $W_1 = \mathcal{U}_{tot1} \times \mathcal{A}_1 \times \Delta T\ell n$
- Delta T logarithmic in parallel flow: $$\Delta T\ell n = \frac{(Tp_{in} - Ts_{in}) - (Tp_{gamma1} - Tgamma)}{\log\frac{(Tp_{in} - Ts_{in})}{(Tp_{gamma1} - Tgamma)}}$$
- Energy balances for the first zone: $$\mathcal{W}1_s = {}^1\!/_2 \times \mathrm{Ms} \times (hgamma - hs_{in})$$ $$\mathcal{W}1_p = M_p \times (hp_{in} - hpgamma1)$$
- Global heat transfer coefficent : $\mathcal{U}_{tot1} = \alpha_{conv} + \alpha_{cond}$
- Dittus-Boelter correlation for single phase flow: $$\mathcal{N}u = 0{,}023 \times \mathcal{R}e^{0{,}8} \times \mathcal{P}r^{0{,}4}$$
- Average tube lenght: $$\mathcal{L}_1 = \frac{\mathcal{A}_1}{\pi \times Tube_{od} \times Ntubes}$$

Part 2. Average length of the tubes

```
Ms=Mgamma+Mfw;
Tgamma = XSteam('Tsat_p',Ps);
Ts_in = (Tgamma*Mgamma + Tfw*Mfw)/Ms;
hgamma = XSteam('hL_p',Ps);
hs_in = XSteam('h_pT',Ps,Ts_in);
hp_in = XSteam('h_pT',Pp,Tp_in);

%thermal power needed by the secondary
W1_s=(Ms/2)*(hgamma-hs_in);
hp_gamma1=hp_in-(W1_s/Mp);
W1_p=Mp*(hp_in-hp_gamma1);
Tp_gamma1=XSteam('T_ph',Pp,hp_gamma1);
%calculation of the delta T logarithmic
delta_Tp_sx_L=((Tp_in-Ts_in)-(Tp_gamma1-Tgamma))/log((Tp_in-Ts_in)/(Tp_gamma1-Tgamma));
```

Part 2. Average length of the tubes

```
%calculation of the heat transfer coefficient
%(all the values are expressed in IS (due to this we have the multiplication
%of 1000 for the cp))
%convection in the secondary side
pitch = pitch_ratio*Tube_od;
%A_passunit = ((pitch^2)*sqrt(3)/4) - (pi*(Tube_od^2)/8)
%wetted_per = pi*Tube_od;
Deq_s=0.58*pitch;
Ts_mean = (Ts_in+Tgamma)/2;
rho_s_mean = XSteam('rho_pT',Ps,Ts_mean);
A_pass_s = (pi*(barrel_D^2)/8) - ((pi/4)*(Tube_od^2)*N_tubes);
v_s_mean = Ms/(A_pass_s*rho_s_mean);
my_s_mean = XSteam('my_pT',Ps,Ts_mean);
Re_s = rho_s_mean*v_s_mean*Deq_s/my_s_mean;
cp_s_mean = XSteam('Cp_pT',Ps,Ts_mean);
k_cond_s_mean = XSteam('tc_pT',Ps,Ts_mean);
Pr_s = cp_s_mean*my_s_mean/(k_cond_s_mean);
%Diltuss-Boeltter correlation
Nu_s = 0.023*(Re_s^0.8)*(Pr_s^0.4);
alpha_conv_s= Nu_s*k_cond_s_mean/Deq_s;
%conductivity from the primary to the secondary
alpha_cond_sp= (((Tube_od/2)*log(Tube_od/Tube_id))/k_acc)^-1;
U_tot_l=alpha_conv_s+alpha_cond_sp;
%now we have the final correlation for the tube length 1/Rtot*A*delta_T=Wl_p
Al=Wl_p*1000/(U_tot_l*delta_Tp_sx_L);
Ll=Al/(pi*Tube_od*N_tubes);
```

Main equations (zone 2)

- Newton's law for the second zone: $W_2 = \mathcal{U}_{tot2} \times \mathcal{A}_2 \times \Delta T \ell n$

- Delta T logarithmic in counter flow: $$\Delta T \ell n = \frac{(Tp_{gamma2} - Tgamma) - (Tp_{out} - Ts_{in})}{\log \frac{(Tp_{gamma2} - Tgamma)}{(Tp_{out} - Ts_{in})}}$$

- Energy balances for the second zone: $W_2 = W_1$
  $W_{2p} = M_p \times (hp_{gamma2} - hp_{out})$

- Global heat transfer coefficent : $\mathcal{U}_{tot2} = \mathcal{U}_{tot1}$

- Dittus-Boelter correlation
  for single phase flow: $\mathcal{N}u = 0{,}023 \times \mathcal{R}e^{0{,}8} \times \mathcal{P}r^{0{,}4}$

- Average tube lenght: $$\mathcal{L}_2 = \frac{\mathcal{A}_2}{\pi \times Tube_{od} \times Ntubes}$$

Part 2. Average length of the tubes

```
%for the length of tubes until liquid saturation on the right side (L2) we use
%the same method. What changes is the fact that here we have a counter flow
%thermal exchange, and not a parallel one as above
hp_out=XSteam('h_pT',Pp,Tp_out);
W2_s=W1_s;
hp_gamma2=hp_out+(W2_s/Mp);
W2_p=Mp*(hp_gamma2-hp_out);
Tp_gamma2=XSteam('T_ph',Pp,hp_gamma2);
delta_Tp_dx_L=((Tp_gamma2-Tgamma)-(Tp_out-Ts_in))/log((Tp_gamma2-Tgamma)/(Tp_out-Ts_in));
%as we assume the heat transfer coefficients constant in the liquid phase,
%we can use the ones above.
A2=W2_p*1000/(U_tot_l*delta_Tp_dx_L);
L2=A2/(pi*Tube_od*N_tubes);
```

Solution strategy and main equations (zone 3)

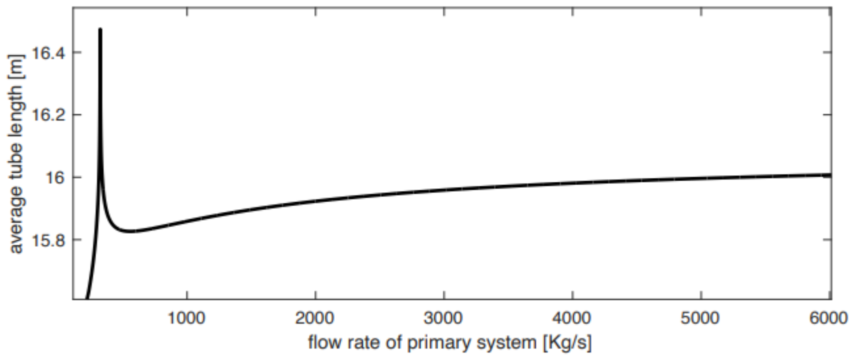
Now that we have calculated the length of the tubes for the liquid phase to be saturated, we have to model a code to find the length for which we reach a vapour title of x=0.15.

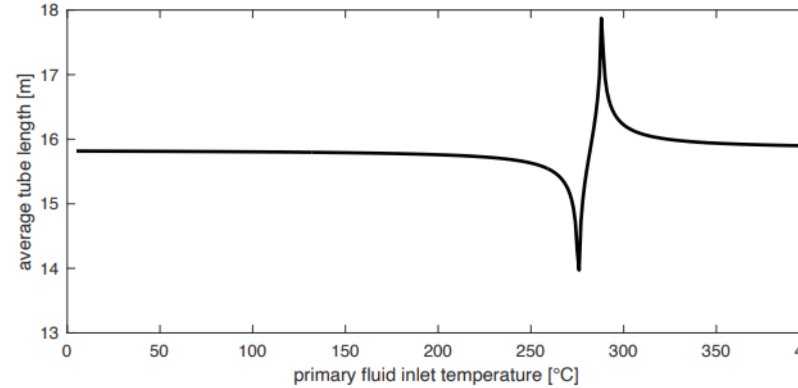
- Energy balance: $\mathcal{Q}_{vap} = \mathcal{M}_s \times \left(h_{x15} - h_{gamma}\right)$
- Jens-Lottes correlation for two-phase flow: $q_{areic} = \dfrac{e^{\left(\frac{4 \times P_S}{6,2}\right)} \times (Twall - Tbulk)^4}{25^4}$
- $T_{bulk} = T_{gamma}$
- Using tabulated data we found out that we can consider the temperature of the wall given by this value: $T_{wall} = 289,25°C$
- $A = \dfrac{Q_{vap}}{q_{areic}}$
- $L_{vap} = \dfrac{A}{\pi \times Tube_{od} \times N_{tubes}}$
- $L_{tot} = L_1 + L_2 + L_{vap}$

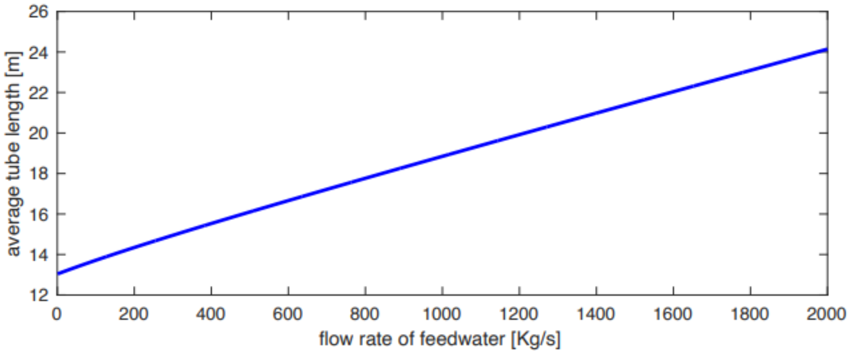
Part 2. Average length of the tubes

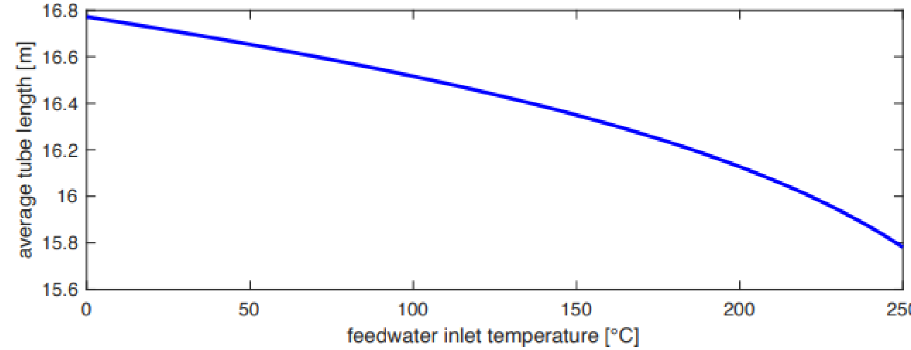
```
hx15=XSteam('h_px',69,0.15);
Qvap=Ms*(hx15-hgamma);
%In the correlation we use the temperature of the secondary side (Ps), the
%temperature of the bulk (Tgamma), and then the temperature of the wall
%which we put doing these consideration: the T_wall will be given by the
%medium temperature of the primary side made between the temperatures in
%the primary at the level "gamma" (the saturation level of secondary),
%and then we will have to account that we have a
%thermal resistance due to conduction, and thermal losses.
T_bulk=Tgamma;
%Using tabulated data we found out that we can consider the temperature of
%the wall given by this value
T_wall=289.25;
%calculation of q_areic with the correlation (in MW)
q_areic= (1/(25^4))*exp(4*Ps*0.1/6.2)*(T_wall-T_bulk)^4;
A=Qvap/(q_areic*1000);
Lvap= A/(pi*Tube_od*N_tubes);

%Now that we have all the length that compose the entire tube we can
%calculate the total needed length of the tubes
Ltot=L1+L2+Lvap;

end
```

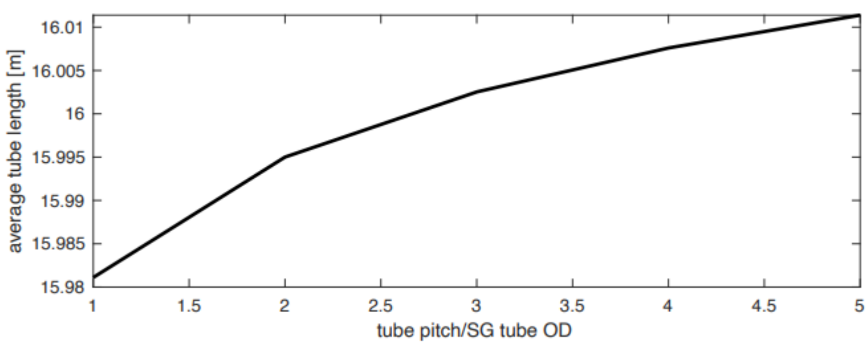
Sensitivity Analisis (Averege lenght of the tubes)

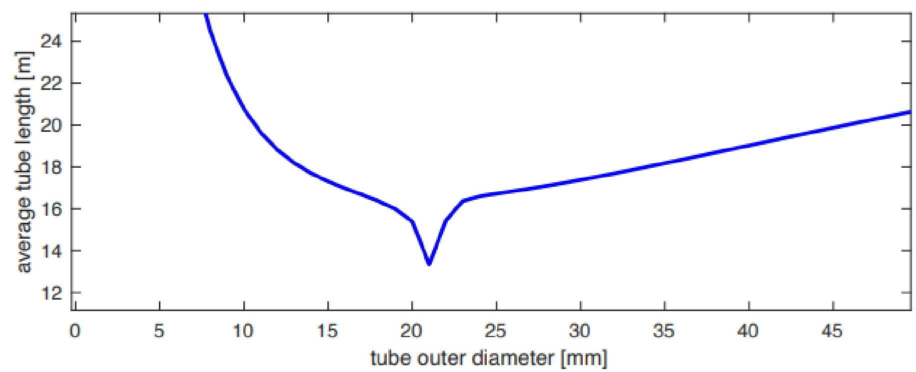








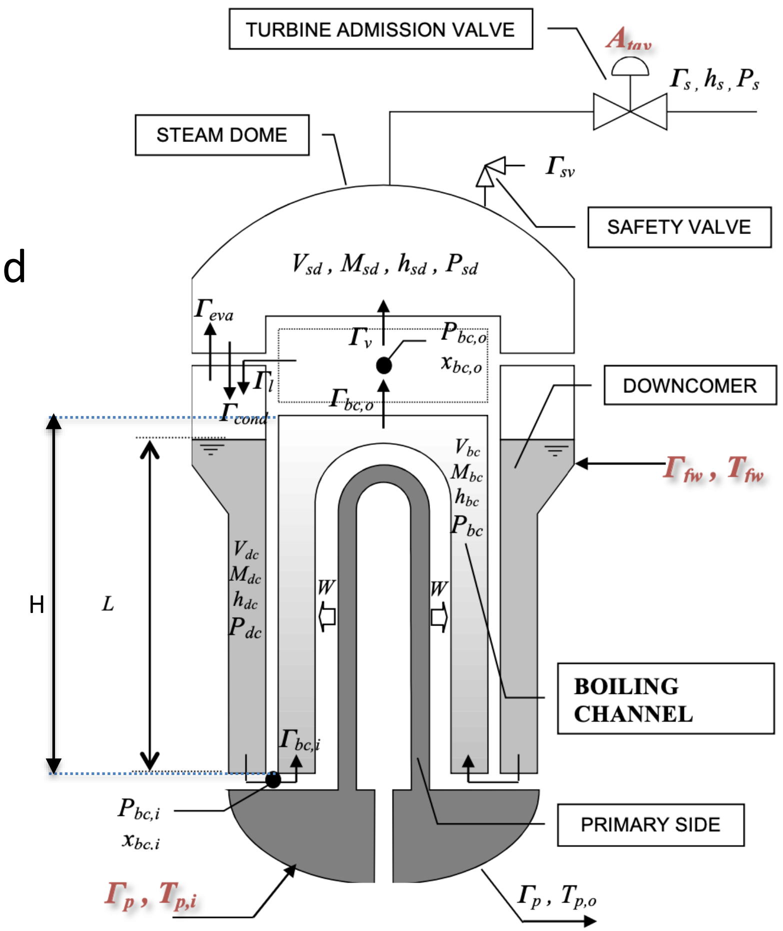




Solution strategy

Part 3:

- the liquid level in the downcomer can be found (with a certain approssimation) using balance equations for mass (both on the downcomer and on the boiling channel) and pressure. In this way we can find L by equalizing the pressure gained moving downward.



Main equations

- Balance of mass in the downcomer: $$M_{bc} = \frac{M_{fw}}{x}$$
- Calculation of the pressure drops:
  - Gravitational pressure drops: $$\Delta P_g = \rho \times g \times H$$
  - Concentrated pressure drops: $$\Delta P_c = K \times \rho \times \frac{v^2}{2}$$
  - Distributed pressure drops: $$\Delta P_d = L \times 2 \times f \times \rho \times \frac{v^2}{D_{eq}}$$
- Friction Factor: $$f = [3{,}8 \times \log_{10}(\frac{10}{Re} + 0{,}2 \times \frac{\varepsilon}{D_{eq}})]^{-2}$$
- Balance of pressure:

$$\rho_{dc} \times g \times L - \Delta P_{dc}, c - \Delta P_{dc}, d - \rho_{bc} \times g \times H - \Delta P_{bc}, d - \Delta P_{mix}, d - \Delta P_l, c = 0 \Rightarrow L$$

3. Liquid level in the downcomer

```
function [L_D] = L_Downcomer(Mfw,Psd,Tfw,x,Do,Di,N_tube,Tube_od,pitch,P1,P2,P3,P4,P5,H)
%[L_D]=LIQLEV2(480,69,223.5,0.15,3.4,2.9,9702,0.019,0.0266,3.5,3.5,3.5,3.5,3.5,10)
%mass flowrate from balance of mass on the downcomer
%Mbc = Mfw + Ml = Mfw + (1-x)*Mbc
Mbc = Mfw/x;
%feedwater density
rhofw = XSteam('rho_pT',Psd,Tfw);
%density of saturated liquid at 69 bar
rhol = XSteam('rhoL_p',Psd);
%density of saturated steam at 69 bar
rhov = XSteam('rhoV_p',Psd);
%average density in the downcomer (assumed as constant)
rhodc = (((1-x)*Mbc*rhol)+(Mfw*rhofw))/Mbc;
%average density of the LIQUID part in the boiling channel
rhobcL = (rhodc+rhol)/2;
%density of mixture with a quality of 15%
rho15 = (x*rhov)+((1-x)*rhol);
%average density of the MIXTURE part in the boiling channel
rhomix = (rho15+rhol)/2;
```

3. Liquid level in the downcomer

```
%TOTAL average density inside the boiling channel
rhoM = (rhomix+rhobcL)/2;
%area of the downcomer
Adc = pi/4*(Do^2-Di^2);
%velocity of the liquid in the downcomer
Vdc = Mbc/(rhodc*Adc);
%number of U-Tubes given by N_tubes function
%total barrel area
AA = pi*(Di^2)/4;
%boiling channel free area
Abc = AA - ((N_tube*(pi/4)*Tube_od^2)*2);
%velocity of the LIQUID part in the boiling channel
VbcL = Mbc/(rhobcL*Abc);
%velocity of the MIXTURE part in the boiling channel
Vmix = Mbc/(rhomix*Abc);
%splitting of L formula (balance of pressure) in two parts for
%semplification of the code
L1 = ((P1*((Vdc^2)/2)*rhodc)+(P2*rhodc)+(P3*((VbcL^2)/2)*rhobcL))/(rhodc*9.81);
L2 = ((P4*((Vmix^2)/2)*rhomix)+(rhoM*9.81*H)+(P5*rhol))/(rhodc*9.81);
L_D = L1+L2;

end
```

Sensitivity Analisis (Liquid level in the downcomer)