1)

Parameters

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| State # | State |  |  |  |  |  |  |
| 1 | Saturated Liquid | 6 |  |  |  |  |  |
| 2s | Subcooled Liquid |  |  |  |  |  |  |
| 2 | Subcooled Liquid |  |  |  |  |  |  |
| 3 | Superheated Vapour | 10,000 | 480 |  |  |  |  |
| 4s | Superheated Vapour | 700 |  |  |  |  |  |
| 4 | Superheated Vapour | 700 |  |  |  |  |  |
| 5 | Superheated Vapour | 700 |  |  |  |  |  |
| 6s | Saturated Liquid-Vapour Mixture |  |  |  |  |  |  |
| 6 | Saturated Liquid-Vapour Mixture |  |  |  |  |  |  |

Assuming isentropic expansion in turbine and compression in pump, and neglecting energy losses in all other thermodynamic processes for simplicity ;

Where is the mass flow rate of steam.

Now

and assuming the steam generator efficiency, to be 90% and the calorific value of coal, , to be 25 MJ/kg[*Power Plant Engineering,3rd ed., p.426, by P.K. Nag*].

Where is the rate at which fuel is burned. Thus the evaporation factor, , is given by

## Boiler/Evaporator Section

For effective natural circulation, the down comer tubes are assumed to be insulated (and thus unheated) and the riser tubes near the furnace walls [to induce maximum density difference and hence pressure head available for natural circulation].

The range of acceptable circulation ratios, , is 6-26 [*Power Plant Engineering,3rd ed., p.332, by P.K. Nag*]. The Top Dryness Fraction, or is related to as



Now assuming that the height of the furnace, , is 45 m, and saturated liquid flows down the down comer tubes, at 150 bar, so that the densities in the down comer, at the riser top and mixture in the riser tube, , and , respectively are evaluated as:

and the range of possible pressure head available for natural circulation is obtained from



The typical diameter of down comer tubes, , is large; in the range of 150-200 mm or even larger[*Power Plant Engineering,3rd ed., p.333, by P.K. Nag*]

The mass flow rate of saturated liquid water in a single down comer tube, , neglecting the thickness of the pipe due to large diameters, is given by



From this, the number of required down comer tubes, , can be estimated from



From the above plots it can be inferred (as well as from intuition) that mores tubes will be required for smaller tube diameters. Thus we finalise the down comer size to 164 mm, corresponding to 8 tubes.

The typical outer diameter of riser tubes, , is smaller, in the range of 62.5-76.5 mm [*Power Plant Engineering,3rd ed., p.333, by P.K. Nag*], and a typical value for wall thickness, , is 3 mm. Further, the circulation velocity, , is typically between 0.4 and 1.4 m/s; directly related to [*Power Plant Engineering,3rd ed., p.333, by P.K. Nag*]

Thus is assumed to be 1.8 m/s to account for the high mass flow rate obtained earlier.

Then the rate of steam formation in the riser, , can be evaluated from



Increasing

and the number of riser tubes,



Increasing

The heat absorption rate per unit projected area, , of the riser is given by



Increasing

From the plots above it can be seen that a compromise must be reached for adequate heat rate, that is not too high to cause thermal failure/rupture, nor too low to hinder heat transfer, and for the compactness of the boiler.

The slip ratio, , is assumed to be 1.2 due to the high operating pressure of the boiler; at high pressures, and increases up to values of 10 for lower pressures.



I then choose a of 8 and to be 74 mm.

The resulting (approximate) values of the parameters of interest, corresponding to the values of the design decisions (in italics) are summarised in the table below.

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameter** | **Symbol** | **Value** | **Unit** |
| *Circulation Ratio* |  | *8* | *-* |
| *Riser Tube Diameter* |  | *74* | *mm* |
| *Slip Ratio* |  | *1.2* | *-* |
| *Circulation Velocity* |  | *1.8* | *m/s* |
|  |  |  |  |
| Available Pressure Head |  | 52.7 | kPa |
| Top Dryness Fraction |  | 0.1250 | - |
| Void Fraction at Riser Exit |  | 0.4262 | - |
| Number of Riser Tubes |  | 1103 | - |
| Steam Exit Rate per Riser Tube |  | 0.165 | kg/s |
| Heating Rate Flux |  | 49.71 | kW/m2 |
|  |  |  |  |
| *Down Comer Tube Diameter* |  | 164 | *mm* |
|  |  |  |  |
| Number of Down Comer Tubes |  | 8 | - |
| Mass Flow Rate per Tube |  | 22.81 | kg/s |

## Economiser Section

The Flue Gas velocity, , is in the range of 10-12 m/s (in order to restrict erosion by fly ash). Further, the flue gas temperature exiting, the economiser section is assumed to be 450; further assumed to be an ideal gas where its specific heat at constant pressure, , is taken to be 1.12 kJ/kJ.K.

Additionally, the flue gas mass flow rate, , is assumed to be 1000 kg/s. [N.B. This is finally (iteratively) set to 1800 kg/s for to be within the range of 370-540 [*Power Plant Engineering,3rd ed., p.356, by P.K. Nag*] and is assumed to be 12 m/s to maximise maximise heat transfer rate.

The range of outer coil diameters used to build the heat exchanger (economiser), , is 45-70 mm (assuming it to be 70 mm with a 5 mm thickness). The pitch of these coils, , is around 45-50 mm (depending on the type fuel and ash characteristics) for 180o bends/turns arranged in a 3-D array, which I choose to be 45 mm for minimum height; compactness [Power Plant Engineering,3rd ed., by P.K. Nag].

Further, is assumed to be 80 kW/m2.K.

Where

Further,

Where and are the width and clearance of the economiser duct, assumed to be 5 m and 5 mm respectively, and

The resulting (approximate) values of the parameters of interest, corresponding to the values of the design decisions (in italics) are summarised in the table below.

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameter** | **Symbol** | **Value** | **Unit** |
| *Coil Outer Diameter* |  | *70* | *mm* |
| *Coil Wall Thickness* |  | *5* | *mm* |
| *Coil Pitch* |  | *45* | *mm* |
| *Water Velocity* |  | *1.8* | *m/s* |
| *Flue Gas Velocity* |  | *12* | *m/s* |
| *Overall Heat Transfer Coefficient of Coils* |  | *80* | *kW/m2.K* |
| *Duct Width* |  | *5* | *m* |
| *Coil Lateral Clearance with Duct on each side* |  | *5* | *mm* |
|  |  |  |  |
| Total Heat Rate |  | 160 | MW |
| Mass Flow rate per tube |  | 3.07 | kg/s |
| Total Heat Transfer Surface Area |  | 9.7 | km2 |
| Number of Coils |  | 60 | - |
| Length of a Coil |  | 735.5 | m |
| Number of Turns per Coil |  | 148 | - |
| Total Height |  | 6.63 | m |

## Air Preheater Section

Since the Air Preheater follows on from the Economiser section, therefore the inlet temperature is the same as that at the economiser exit;

The flue gases are assumed to be cooled to and the air to be preheated is assumed to enter at . Further assumptions include the overall heat transfer coefficient of the tubes, , the outer and inner diameters of the tubes, & , are 65 and 60 mm respectively, mass flow rate of air, , is 1250 kg/s[Adjusted to 1500 kg/s for realistic logarithmic mean temperature difference][*Power Plant Engineering,3rd ed., p.418 & 427 by P.K. Nag*].

Where

The resulting (approximate) values of the parameters of interest, corresponding to the values of the design decisions (in italics) are summarised in the table below.

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameter** | **Symbol** | **Value** | **Unit** |
| *Tube Outer Diameter* |  | *65* | *mm* |
| *Tube Inner Diameter* |  | *60* | *mm* |
| *Flue Gas Velocity* |  | *12* | *m/s* |
| *Overall Heat Transfer Coefficient of Tubes* |  | *30* | *kW/m2.K* |
|  |  |  |  |
| Total Heat Rate |  | 600 | MW |
| Mass Flow rate per tube |  | 0.0166 | kg/s |
| Total Heat Transfer Surface Area |  | 439.9 | km2 |
| Number of Tubes |  | 1334 | - |
| Length of a Tube |  | 1.6 | km |

## Super Heater Section

Assuming the maximum heat flux, , to be limited to 140 kW/m2, inner tube diameter and thickness, and , to be 50 mm and 5 mm, respectively and steam velocity, , to be 10 m/s

The resulting (approximate) values of the parameters of interest, corresponding to the values of the design decisions (in italics) are summarised in the table below.

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameter** | **Symbol** | **Value** | **Unit** |
| *Tube Inner Diameter* |  | *50* | *mm* |
| *Tube Wall Thickness* |  | *5* | *Mm* |
| *Steam Flow Velocity* |  | *10* | *m/s* |
| *Allowable Heat Flux* |  | *140* | *kW/m2* |
|  |  |  |  |
| Total Heat Rate |  | 150 | MW |
| Mass Flow rate per tube |  | 1.99 | kg/s |
| Total Heat Transfer Surface Area |  | 1.09 | km2 |
| Number of Tubes |  | 97 | - |
| Length of a Tube |  | 59.8 | m |

Finally, the overall plant efficiency can be estimated (by assuming that the turbine and electric generator efficiencies, and , are 92% and 94%, respectively and that 5% of the power produced is consumed by the Plant auxiliaries) from

Where

## Appendix – MATLAB Code

clc

clear all

close all

format long

% Specific Enthalpies at respective states [kJ/kg]

h1 = 3450.47;

h2 = 2065.31;

h3 = 191.812;

h4 = 206.9;

h5 = 727.143;

vf = 0.00165696; %Specific Volume of Sat. Liquid @ 150 bar

vg = 0.0103401; %Specific Volume of Sat. Vapour @ 150 bar

hf = 1610.15; %Specific Enthalpy of Sat. Liquid @ 150 bar

hg = 2610.86;%Specific Enthalpy of Sat. Vapour @ 150 bar

hfg = hg - hf;%Saturation Length on P-h curve for 150 bar

wT = h1 - h2;%Turbine Work Out [kJ/kg]

wP = h4 - h3;%Pump Work In [kJ/kg]

W = 250e3;%Net Power Output [Given Parameter] [kW]

m = W/(wT-wP)%Mass Flow Rate of steam [kg/s]

C = 25e3;%Calorific Value of Coal [kJ/kg]

eta\_stg = 0.9;%Steam Generator Efficiency

mf = m\*(h1-h5)/(eta\_stg\*C)%Rate at which Coal is Burnt [kg/s]

ef = m/mf;%Evaporation factor

H = 45;%Height of boiler [m]

g = 9.81;%Acceleration due to gravity [m/s^2]

rhoD = 1/vf;%Downcomer (Sat. Liquid) Fluid Density

CR = [6:26]';%Range of Acceptable Circulation Ratios

xtop = 1./CR;%Corresponding possible Top Dryness Fractions

figure(5)

plot(CR,xtop)

title('TDF vs CR')

xlabel('Circulation Ratio')

ylabel('Top Dryness Fraction')

grid on

grid minor

vfg = vg - vf;%Saturation Length on P-v curve for 150 bar

vtop = vf+xtop.\*vfg;%Specific Volume at the top of the Riser tubes

rho\_top = 1./vtop;%Correspondig range of possible density at the top of riser tubes

rhom = 0.5.\*(rhoD + rho\_top);%Correspondig range of possible mixture density in riser tubes

p = g\*H.\*(rhoD - rhom);%Pressure Head availabe for Natural Circulation

S = 1.2; %Slip ratio

psi = S\*vf/vg%Psi constant

a = 1./(1+((1-xtop)./xtop).\*psi);%Void Fraction at the top of riser tubes

figure(6)

plot(CR,a)

title('\alpha vs CR')

xlabel('Circulation Ratio')

ylabel('Void Fraction')

grid on

grid minor

Dr = [62.5:0.1:76.5]'./1000;%Range of Riser (Outer) pipe dimaeters

CR = [6:26]';%Range of Circulation Ratios

figure(4)

plot(CR,p)

title('Pressure Head vs CR')

xlabel('Circulation Ratio')

ylabel('Pressure Head [Pa]')

grid on

grid minor

i = 1;

while i <= length(Dr)

CRn(i,:) = CR;

i = i+1;

end

CR = CRn;

%Dr = Drn;

xtop = 1./CR;%Possible top dryness fractions

vfg = vg - vf;%Redefining Saturation Length on P-v curve for 150 bar for Dr

vtop = vf+xtop.\*vfg;%Redefining Specific Volume at the top of the Riser tubes

rho\_top = 1./vtop;%Redefining Correspondig range of possible density at the top of riser tubes

tr = 3e-3;%Tube wall thickness [m]

Uc = 1.8;%Circulation Velocity [m/s]

k = (rho\_top.\*xtop);%Term to be used for Parametric Sweep

i = 1;

while i<= 21

msfr(:,i) = 0.25\*pi.\*(Dr-2\*tr).^2.\*k(:,i);%Steam formation rate at riser exit

i = i+1;

end

nr = m./msfr; %Number of required riser tubes

i = 1;

figure(1)

while i<= 21

plot(Dr,nr(:,i))

hold on

i = i+1;

end

title('Number of tubes vs Riser Diameter for CR = 6-26')

xlabel('Riser Tube Diameter [m]')

ylabel('Number of Tubes')

grid on

grid minor

i = 1;

while i<= 21

Qar(:,i) = msfr(:,i).\*hfg./(H.\*Dr);%Steam formation rate at riser exit

i = i+1;

end

i = 1;

figure(2)

while i<= 21

plot(Dr,Qar(:,i))

hold on

i = i+1;

end

title('Heat Rate vs Riser Diameter for CR = 6-26')

xlabel('Riser Tube Diameter [m]')

ylabel('Heat Rate [kW/m^2]')

grid on

grid minor

i = 1;

figure(3)

while i<= 21

plot(Dr,msfr(:,i))

hold on

i = i+1;

end

title('Rate of Steam Exiting One Riser vs Riser Diameter for CR = 6-26')

xlabel('Riser Tube Diameter [m]')

ylabel('Steam Flow Rate [kg/s]')

grid on

grid minor

Ddc = [150:250]./1000;%Range of Downcomer pipe dimaeters

mD = 0.25\*pi.\*(Ddc).^2.\*rhoD.\*Uc;%Saturated water mass flow rate in a downcomer tube

figure(7)

plot(Ddc,mD)

title('Mass Flow Rate in One Downcomer Tube vs Downcomer Tube Diameter')

xlabel('Downcomer Tube Diameter [m]')

ylabel('Mass Flow Rate [kg/s]')

grid on

grid minor

nD = m./mD; %Number of downcomer tubes

figure(8)

plot(Ddc,nD)

title('Number of tubes vs Downcomer Tube Diameter')

xlabel('Downcomer Tube Diameter [m]')

ylabel('Number of Tubes')

grid on

grid minor

hffw = 719.206;%Specific Enthalpy of Entering Feed Water (approx. Sat. Liquid @170oC)

Tfwi = 170;

Tfwe = 342.158;

Qeco = m\*(hf - hffw);%Heat Transfer in the Economiser section

mfl = 1800;

cp = 1.12;%Specific Heat at Const. Pressure of flue gas [kJ/kg.K]

Tfe = 450;% Flue Gas Exit Temperature in Economiser Section [oC]

Tfi = Qeco/(mfl\*cp)+Tfe% Inlet Flue Gas Temperature [oC]

dTi = Tfi - Tfwi;

dTe = Tfe - Tfwe;

Tlm = (dTi - dTe)/log(dTi/dTe)

Do = 70e-3;%Economiser Tube Outer Diameter

te = 5e-3;%Economiser Tube thickness

Di = Do - 2\*te;%Economiser Tube Inner Diameter

Uo = 80e-3;%Overall Heat Transfer Coefficient [kW/m^2.K]

Ao = Qeco/(Uo\*Tlm);%conomiser Total Heat Exchange Surface

meco = 0.25\*pi\*Di.^2\*Uc/vf;

neco = m./meco;

neco = 60;

leco = Ao/(neco\*pi.\*Do);

B = 5;

C = 5e-3;

nt = leco./(B-2\*C);

nt = 148;

pitch = 45e-3;

Heco = pitch.\*nt;

ma = 1500;

Tai = 35;

cp = 1.12;%Specific Heat at Const. Pressure of flue gas [kJ/kg.K]

cpa = 1.001;%Specific Heat at Const. Pressure of air [kJ/kg.K]

Tfe = 150;% Flue Gas Exit Temperature in Economiser Section [oC]

Tfi = 450;% Inlet Flue Gas Temperature [oC]

Qph = mfl\*cp\*(Tfi-Tfe);%Heat Transfer in the Air Pre Heater section

Tae = Qph/(ma\*cpa)+Tai;

dTi = Tfi - Tae;

dTe = Tfe - Tai;

Tlm = (dTi - dTe)/log(dTi/dTe)

Do = 65e-3;%PH Tube Outer Diameter

Di = 60e-3;%PH Tube Inner Diameter

Uo = 30e-3;%Overall Heat Transfer Coefficient [kW/m^2.K]

Ao = Qph/(Uo\*Tlm);%Air PH Total Heat Exchange Surface

R = 0.287;

vfl = R\*(Tfi+273)/101.325;

Uf = 12;

mph = 0.25\*pi\*Di.^2\*Uf/vfl;

nph = mf/mph

nph = 1334;

lph = Ao/(nph\*pi.\*Do);

hi = 2610.86;

Qsh = m\*(h1-hi)

qm = 140;

Do = 60e-3;

t = 5e-3;

Di = Do - 2\*t;

Ush = 10;

msh = 0.25\*pi\*Di.^2\*Ush/vg;

nsh = m/msh;

nsh = 97;

Ao = Qsh/qm;

lsh = Ao/(nsh\*pi.\*Do)