

Semi Analytical Analysis of Steady State Condition of Steam Generator

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1. Introduction

Steam generator is an important device in power plant. Steam generator use the heat to produce steam which then used to drive turbine for producing electricity. Various thermal related processes occurs in steam generator during its normal operation and also during abnormal or accident condition. Therefore perfect treatment of steam generator will include various complex mathematical model which need computational fluid dynamics. However in this chapter we will simplify the model which still give reasonable results. There are many types of steam generators. Figure 1 shows an example of counter flow type steam generator in which hot liquid flow outside the cylinders from top to the bottom while the water-steam flows inside the pipes from the bottom to the top of the steam generator.

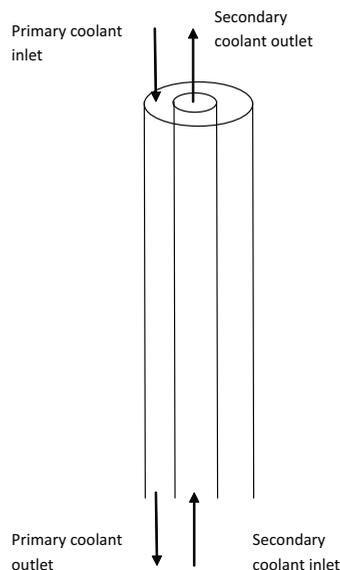


Fig. 1. Simplified schematic of counter flow heat exchanger

2. Mathematical model

The mathematical model of steam generators includes energy conservation equations, momentum conservation equations, and mass conservation equations.

2.1 Energy conservation equations

$$\begin{aligned} c_{p,p}W_p \frac{\partial T_p}{\partial z} - A_p \frac{\partial}{\partial z} \left(k_p \frac{\partial T_p}{\partial z} \right) &= -h_p S_p (T_p - T_W) \\ -\pi(r_{W0}^2 - r_{Wi}^2) \frac{\partial}{\partial z} \left(k_W \frac{\partial T_W}{\partial z} \right) &= h_p S_p (T_p - T_W) - h_s S_s (T_W - T_s) \\ c_{p,s}W_s \frac{\partial T_s}{\partial z} - A_s \frac{\partial}{\partial z} \left(k_s \frac{\partial T_s}{\partial z} \right) &= -h_s S_s (T_W - T_s) \end{aligned} \quad (1)$$

2.2 Momentum conservation equation

$$\begin{aligned} \frac{\partial}{\partial z} \left(\frac{G_p^2}{\rho_p} \right) &= -\frac{\partial p_p}{\partial z} - \frac{f_p}{2\rho_p} D_p |G_p| G_p - \rho_p g \\ \frac{\partial}{\partial z} \left(\frac{G_s^2}{\rho_s} \right) &= -\frac{\partial p_s}{\partial z} - \frac{f_s}{2\rho_s} D_s |G_s| G_s - \rho_s g \end{aligned} \quad (2)$$

2.3 Mass conservation equation

$$\begin{aligned} \frac{\partial G_p}{\partial z} &= 0 \\ \frac{\partial G_s}{\partial z} &= 0 \end{aligned} \quad (3)$$

3. Analytic solution of steady state condition of steam generator

In steam generators, liquid in the primary side is in single phase condition while the liquid in the secondary side change from sub cooled condition, then saturated condition, and then entering super heated steam condition in the last stage.

We will first discuss the analytical solution for single phase counter flow heat exchanger system. The results will be used to analyse some part of steam generator segments.

3.1 Analytical solution of counter flow single phase heat exchanger

Energy conservation equations for single phase counter flow heat exchanger is

$$\begin{aligned} c_{p,p}W_p \frac{\partial T_p}{\partial z} - A_p \frac{\partial}{\partial z} \left(k_p \frac{\partial T_p}{\partial z} \right) &= -h_p S_p (T_p - T_W) \\ -\pi(r_{W0}^2 - r_{Wi}^2) \frac{\partial}{\partial z} \left(k_W \frac{\partial T_W}{\partial z} \right) &= h_p S_p (T_p - T_W) - h_s S_s (T_W - T_s) \\ c_{p,s}W_s \frac{\partial T_s}{\partial z} - A_s \frac{\partial}{\partial z} \left(k_s \frac{\partial T_s}{\partial z} \right) &= -h_s S_s (T_W - T_s) \end{aligned} \quad (4)$$

If the wall is thin and has good heat conduction capability we can simplify the model by eliminating the wall and include its effect in the overall heat transfer coefficient.

$$\begin{aligned} c_{p,p}W_p \frac{\partial T_p}{\partial z} - A_p \frac{\partial}{\partial z} \left(k_p \frac{\partial T_p}{\partial z} \right) &= -h_{eff}S_p(T_p - T_s) \\ c_{p,s}W_s \frac{\partial T_s}{\partial z} - A_s \frac{\partial}{\partial z} \left(k_s \frac{\partial T_s}{\partial z} \right) &= -h_{eff}S_s(T_p - T_s) \end{aligned} \quad (5)$$

Where h_{eff} is overall heat transfer coefficient from primary side to secondary side including the effect of the wall.

In normal condition, usually the effect of heat conduction is small so that we can further simplify the model into:

$$\begin{aligned} c_{p,p}W_p \frac{\partial T_p}{\partial z} &= -h_{eff}S_p(T_p - T_s) \\ c_{p,s}W_s \frac{\partial T_s}{\partial z} &= -h_{eff}S_s(T_p - T_s) \end{aligned} \quad (6)$$

In this stage we set the analytic solution of the above model as

$$\begin{aligned} T_p(z) &= Ae^{kz} + Be^{-kz} \\ T_s(z) &= Ce^{kz} + De^{-kz} \end{aligned} \quad (7)$$

Substituting equation (7) into (6) we get

$$\begin{aligned} A &= \frac{h_p S_p}{kc_{p,p}W_p + h_p S_p} C \\ B &= \frac{h_p S_p}{h_p S_p - kc_{p,p}W_p} D \end{aligned} \quad (8)$$

And,

$$\begin{aligned} h_{eff}^2 S_p S_s &= (kc_{p,p}W_p + h_{eff}S_p)(kc_{p,s}W_s + h_{eff}S_s) \\ k &= \frac{1}{c_{p,p}W} + \frac{1}{c_{p,s}W} \end{aligned} \quad (9)$$

Now we apply boundary condition:

$$\begin{aligned} T_p(0) &= T_{p_{in}} \\ T_s(H) &= T_{s_{in}} \end{aligned} \quad (10)$$

And we get

$$\begin{aligned} A + B &= T_{p_{in}} \\ Ce^{kH} + De^{-kH} &= T_{s_{in}} \end{aligned}$$

Substituting A,B, C and D we get

$$C = \frac{T_{p,in}e^{-kH} - \eta_2 T_{s,in}}{\eta_1 e^{-kH} - \eta_2 e^{kH}}$$

$$D = \frac{\eta_1 T_{s,in} - T_{p,in}e^{kH}}{\eta_1 e^{-kH} - \eta_2 e^{kH}}$$

$$\eta_1 = \frac{h_{eff} S_p}{k c_{p,p} W_p + h_{eff} S_p}$$

$$\eta_2 = \frac{h_{eff} S_p}{h_{eff} S_p - k c_{p,p} W_p} \tag{11}$$

$$A = \eta_1 C$$

$$B = \eta_2 C$$

3.2 Analytical solution of counter flow steam generator

In steam generator we can in general divide it into three regions: sub cooled region, saturated region, and super heated region, see figure 1. In sub cooled region the water-steam side is in the form of water and the steam generator can be treated using the method developed in section 2.1

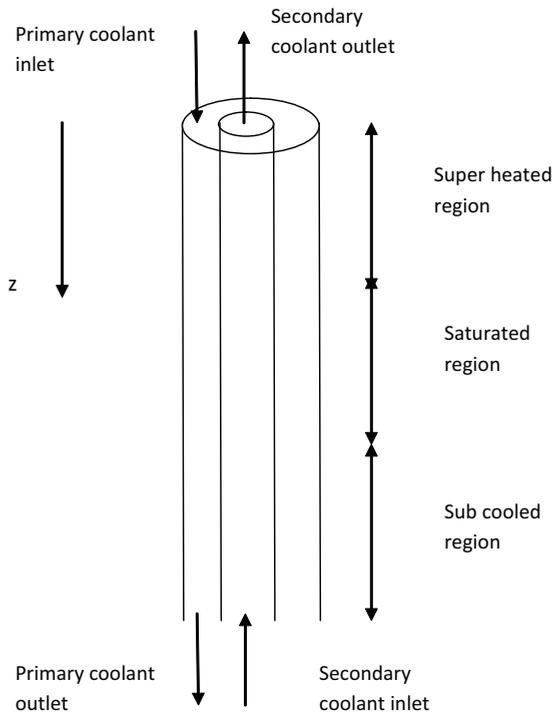


Fig. 2. Simplified model of single channel concentric tubes

In saturated region the water-steam side of SG experiences boiling process, a conversion of water into steam at constant temperature. After all water has been converted into steam then in the super heated section the water-steam side is in the form of steam which experiences temperature increase as it receive heat from the primary side. In this region we can also apply the method developed in section 2.1.

The boundary position between sub cooled region and saturated region and between saturated region and superheated region are influenced by many parameters such as inlet temperature of primary and secondary sides, flowrates in primary and secondary sides, thermal properties of primary and secondary sides, pipes properties, etc. Therefore we use iterative method to determine these boundary positions.

The method to determine these boundary positions is as follows. First we guess these two boundaries and based on these assumption we perform energy balance analysis for this simplified model.

Then we start with upper part in which the primary inlet temperature is $T_{p_{in}}$ and while the secondary inlet temperature is just water saturation temperature. Using the formulated in 2.1 we get primary and secondary temperature distribution. From this stage we get primary outlet temperature.

Next we move to the saturated region. Based on the just previous calculation we use the previous primary outlet temperature as primary inlet temperature in saturated region. The secondary inlet temperature is water-steam saturated temperature in which the water is started to boil. From this stage of calculation we get primary and secondary temperature distributions.

Finally we can set primary site inlet temperature for the sub cooled region from the primary outlet temperature in the saturated region. The secondary outlet temperature in the subcooled region is just the water channel inlet temperature. Therefore we can get temperature distribution for the sub cooled region and therefore we now get for all regions.

Now we must check energy balance consistency in sub cooled and saturated regions. First we check wether or not the heat received by secondary side in the sub cooled region is exactly same with that needed to change the intake sub cooled water to the start of saturation condition.

In case that the heat from the primary side is not enough to increase the sub cooled temperature into saturated temperature then we need to shift the assumption of boundary between sub cooled and saturated regions to be higher than the current position. On the other hand if the saturated condition of water-steam side has been reached before the current sub cooled - saturated regions then we should decrease the boundary.

Similar judgment must be taken for boundary between saturated and super heated regions.

For the saturated region, the energy balance equation can be written as

$$\begin{aligned}
 c_{p,p}W_p \frac{\partial T_p}{\partial z} &= -h_{eff}S_p(T_p - T_s) \\
 c_{p,s}W_s \frac{\partial T_s}{\partial z} &= -h_{eff}S_s(T_p - T_s) \\
 T_s &= \text{saturated temperature}
 \end{aligned}
 \tag{12}$$

We can rearrange the equation (12) as

$$\begin{aligned} c_{p,p}W_p \frac{\partial T_p}{\partial z} + h_{eff}ST_p &= h_{eff}ST_s \\ c_{p,p}W_p \frac{\partial T_p}{\partial z} e^{\alpha z} + h_{eff}ST_p e^{\alpha z} &= h_{eff}ST_s e^{\alpha z} \\ \frac{d}{dz}(\beta T_p e^{\alpha z}) &= h_{eff}ST_s e^{\alpha z} \end{aligned} \quad (13)$$

where

$$\begin{aligned} \beta &= c_{p,p}W_p \\ \alpha &= \frac{h_s S}{c_{p,p}W_p} \end{aligned} \quad (14)$$

Solving (13) we get

$$T_p(z) = T_s + \frac{C}{\beta} e^{-\alpha z}$$

Introducing boundary condition $T_p(0)=T_{P_0}$ then we get

$$T_p(z) = T_s + (T_{P_0} - T_s) e^{-\frac{h_s S}{c_{p,p}W_p} z}$$

where C is a constant.

Note that z is assumed started at the boundary between saturated and super heated region.

For the sub cooled region as in super heated region we can use the method describe in the section of 2.1.

3.3 Algorithm and program for semi analytical method of steam generator analysis

The algorithm to solve counter flow steam generator system is as follows

- Set an assumption of boundary between sub-cooled region and saturated region and also between saturated region and super heated region.
- Calculate temperature distribution in the superheated region using the method described in the section 2.1 and using inlet primary liquid temperature as $T_{p,in}$ and water saturated temperature as secondary side inlet temperature
- Calculate temperature distribution along primary side of saturated region using the method describe in the section 2.2 using primary side outlet temperature of super heated section as primary inlet temperature
- Calculate temperature distribution in the sub-cooled region using the method described in the section 2.1 and using primary side outlet temperature of saturated region as $T_{p,in}$ and water inlet temperature secondary side inlet temperature
- Check consistency of the assumed boundary. Is secondary side in sub-cooled region reach transition between sub-cooled and saturated region at the end of this region? Is secondary side of saturated region reaches transition between saturated region and super heated region at the end of this region?

f. If the consistency check in e. is fail then we have to readjust the assumption considering the results in e, other wise the boundaries are right and the calculation is finished. Here the program in Fortran language to solve this problem.

For initialization process:

```

c
c This subroutine is to calculate thermohydraulic of Steam Generator
c using semi analytical method
c
subroutine semansg
INCLUDE "common1.f"
write(6,*)'enter anasg routine:tp,ts',tpin,tsin
astp=ssgs
psys=psyst
tsat=temsw(psys)-273.15
enthfl=entw(psys)
enthgs=entstv(psys)
enthfg=enthgs-enthfl
tpout=tsin
tsout=tpin
mxz=maxsub+maxsat+maxsph
mx2=maxsub+maxsat
gp=wp
gs=ws
tsin=tsin0
c
c superheated region preparation, setting parameters
c
tsin=tsat
tpav=(tpin+tsat)/2.0
tsav=(tsout+tsat)/2.0
tpsav=(tpav+2.0*tsav)/3.0
hshv=entshv(psys,tsav)
cpp=cpc(tpav)
cps=cpslv(hshv,psys)
cpp1=cpp
cps1=cps
diam=2.0*ro
a1=3.0**0.5/4.0*pitcsg**2-3.14159*diam**2/8.0
pw1=3.14159*diam/2.0
dep=4.0*a1/pw1
de=dep
des=2.0*ri
rep=gp/asgp*dep/visc(tpav)
prp=visc(tpav)*cpc(tpav)/conc(tpav)
pecp=rep*prp

```

```

pod=pitcsg/diam
xnusp=7.55*pod-6.3/pod**(17*pod*(pod-0.81))
xnusp=xnusp+0.0174*(1.0-exp(-6.0*(pod-1.0)))*(pecp-200.0)**0.9
hpp=xnusp*conc(tpav)/dep
res=gs/asgs*des/visshv(hshv,psys)
prs=visshv(hshv,psys)*cpshv(hshv,psys)/conshv(hshv,psys)
xnus=0.024*res**0.8*prs**0.4
hss=0.5*xnus*conshv(hshv,psys)/ri
hmt=2.0*3.14159*conm(tpsav)/alog(ro/ri)
u=1.0/(1.0/hpp+1.0/hss+astp/hmt)
u1=u
tmp1=-6.28*ro*u*ztsg*(1.0/(gs*cps)-1.0/(gp*cpp))
tmp2=-6.28*ro*u*(1.0/(gs*cps)-1.0/(gp*cpp))
tsin=tsat
aa=(tpin-tsin)/(exp1(tmp1)-gp*cpp/(gs*cps))
bb=tpin-(tpin-tsin)/(1.0-gp*cpp/(gs*cps)/exp1(tmp1))
bb1=tsin-gp*cpp/(gs*cps)*aa

```

c

c saturated region preparation, setting parameters

c

```

tpav=(tsgp(mx2)+tsat)/2.0
tsav=tsat
tpsav=(tpav+2.0*tsav)/3.0
cpp=cpc(tpav)
cpp2=cpp
rep=gp/asgp*dep/visc(tpav)
prp=visc(tpav)*cpc(tpav)/conc(tpav)
pecp=rep*prp
pod=pitcsg/diam
xnusp=7.55*pod-6.3/pod**(17*pod*(pod-0.81))
xnusp=xnusp+0.0174*(1.0-exp(-6.0*(pod-1.0)))*(pecp-200.0)**0.9
hpp=xnusp*conc(tpav)/dep
hmt=2.0*3.14159*conm(tpsav)/alog(ro/ri)
u2=1.0/(1.0/hpp+astp/hmt)

```

c

c subcooled region preparation, setting parameters

c

```

tpav=(tsgp(maxsub)+tsin0)/2.0
tsav=(tsgp(maxsub)+tsin0)/2.0
tpsav=(tpav+2.0*tsav)/3.0
tsub=(tsin0+tsat)/2.0
hsbw=entsbw(psys,tsub)
cpp=cpc(tpav)
rep=gp/asgp*dep/visc(tpav)
prp=visc(tpav)*cpc(tpav)/conc(tpav)
pecp=rep*prp

```

```

pod=pitcsg/diam
xnusp=7.55*pod-6.3/pod**(17*pod*(pod-0.81))
xnusp=xnusp+0.0174*(1.0-exp(-6.0*(pod-1.0)))*(pecp-200.0)**0.9
hpp=xnusp*conc(tpav)/dep
cpp3=cpp
cps3=cpw(hsbw,psys)
res=gs/asgs*des/visw(hsbw,psys)
prs=visw(hsbw,psys)*cpw(hsbw,psys)/conw(hsbw,psys)
xnus=0.024*res**0.8*prs**0.4
hss=0.5*xnus*conw(hsbw,psys)/ri
hmt=2.0*3.14159*conm(tpsav)/alog(ro/ri)
u3=1.0/(1.0/hpp+1.0/hss+astp/hmt)

```

The following iteration routine is used to calculate temperature distribution across steam generators iteratively until the consistency check become successful.

```

c
c  searching routine
c
  tsgpa=tsat
  tsgsa=tsat
  tsgpb=tsat
  tsgsb=tsat
  tsgpo=tsin
  tsgso=tpin
  aboun0=aboun
  bboun0=bboun
  numblp=0
c
c  super heated region -> iteration
c
50 tsin=tsat
  tpav=(tpin+tsgpb)/2.0
  tsav=(tsgso+tsat)/2.0
  tpsav=(tpav+2.0*tsav)/3.0
  cpp1=cpc(tpav)
  hshv=entshv(psys,tsav)
  cps1=cpslv(hshv,psys)
  cpp=cpc(tpav)
  cps=cpslv(hshv,psys)
  cpp1=cpp
  cps1=cps
  rep=gp/asgp*dep/visc(tpav)
  prp=visc(tpav)*cpc(tpav)/conc(tpav)
  pecp=rep*prp
  xnusp=7.55*pod-6.3/pod**(17*pod*(pod-0.81))
  xnusp=xnusp+0.0174*(1.0-exp(-6.0*(pod-1.0)))*(pecp-200.0)**0.9

```

```

hpp=xnusp*conc(tpav)/dep
res=gs/asgs*des/visshv(hshv,psys)
prs=visshv(hshv,psys)*cpshv(hshv,psys)/conshv(hshv,psys)
xnus=0.024*res**0.8*prs**0.4
hss=0.5*xnus*conshv(hshv,psys)/ri
hmt=2.0*3.14159*conm(tpsav)/alog(ro/ri)
u1=1.0/(1.0/hpp+1.0/hss+astp/hmt)
write(6,*)'tpav,tsav,xnus,hpp,hss,hmt,u1:'
write(6,*)'tpav,tsav,xnus,hpp,hss,hmt,u1'
c
c saturated region -> iteration
c
tpav=(tsgpa+tsgpb)/2.0
tsav=tsat
tpsav=(tpav+2.0*tsav)/3.0
cpp2=cpc(tpav)
rep=gp/asgp*dep/visc(tpav)
prp=visc(tpav)*cpc(tpav)/conc(tpav)
pecp=rep*prp
pod=pitcsg/diam
xnusp=7.55*pod-6.3/pod**(17*pod*(pod-0.81))
xnusp=xnusp+0.0174*(1.0-exp(-6.0*(pod-1.0)))*(pecp-200.0)**0.9
hpp=xnusp*conc(tpav)/dep
hmt=2.0*3.14159*conm(tpsav)/alog(ro/ri)
u2=1.0/(1.0/hpp+astp/hmt)
write(6,*)'tpav,tsav,xnus,hpp,hmt,u2:'
write(6,*)'tpav,tsav,xnus,hpp,hmt,u2'
c
c subcooled region -> iteration
c
tpav=(tsgpo+tsgpa)/2.0
tsav=(tsat+tsin0)/2.0
tpsav=(tpav+2.0*tsav)/3.0
tavsb=(tsin0+tsat)/2.0
hsbw=entsbw(psys,tavsb)
cpp3=cpc(tpav)
cps3=cpw(hsbw,psys)
res=gs/asgs*des/visw(hsbw,psys)
prs=visw(hsbw,psys)*cpw(hsbw,psys)/conw(hsbw,psys)
xnus=0.024*res**0.8*prs**0.4
hss=0.5*xnus*conw(hsbw,psys)/ri
cpp=cpc(tpav)
rep=gp/asgp*dep/visc(tpav)
prp=visc(tpav)*cpc(tpav)/conc(tpav)
pecp=rep*prp
xnusp=7.55*pod-6.3/pod**(17*pod*(pod-0.81))

```

```

xnusp=xnusp+0.0174*(1.0-exp(-6.0*(pod-1.0)))*(pecp-200.0)**0.9
hpp=xnusp*conc(tpav)/dep
hmt=2.0*3.14159*conm(tavsb)/log(ro/ri)
u3=1.0/(1.0/hpp+1.0/hss+astp/hmt)
write(6,*)'tpav,tsav,xnus,hss,hpp,hmt,u3:'
write(6,*)tpav,tsav,xnus,hss,hpp,hmt,u3
tmp1=-6.28*ro*u1*(ztsg-bboun)*(1.0/(gs*cps1)-1.0/(gp*cpp1))
tmp2=-6.28*ro*u1*(1.0/(gs*cps1)-1.0/(gp*cpp1))
aa1=(tpin-tsav)/(exp1(tmp1)-gp*cpp1/(gs*cps1))
bb1=tpin-(tpin-tsav)/(1.0-gp*cpp1/(gs*cps1)/exp1(tmp1))
tsgpb=(tpin-tsav)/(exp1(tmp1)-gp*cpp1/(gs*cps1))+bb1
tmpsat=6.28*ro*u2/(gp*cpp2)*(bboun-aboun)
tsgpa=tsat+(tsgpb-tsav)*exp1(-tmpsat)
tmp3=-6.28*ro*u3*aboun*(1.0/(gs*cps3)-1.0/(gp*cpp3))
tmp4=-6.28*ro*u3*(1.0/(gs*cps3)-1.0/(gp*cpp3))
aa3=(tsgpa-tsin0)/(exp1(tmp3)-gp*cpp3/(gs*cps3))
bb3=tsgpa-(tsgpa-tsin0)/(1.0-gp*cpp3/(gs*cps3)/exp1(tmp3))
tsgsa=(tsgpa-tsin0)/(exp1(tmp3)-gp*cpp3/(gs*cps3))*
&    gp*cpp3/(gs*cps3)*exp1(tmp4*aboun)+bb3
hqq=(tsgpb-tsav)*gp*cpp2*(1.0-exp1(-tmpsat))/gs
aa=(tsgpa-tsin0)/(exp1(tmp3)-gp*cpp3/(gs*cps3))
bb=tsgpa-(tsgpa-tsin0)/(1.0-gp*cpp3/(gs*cps3)/exp1(tmp3))
zzz=0.0
tsgpo=(tsgpa-tsin0)/(exp1(tmp3)-gp*cpp3/(gs*cps3))*
&    exp1(tmp4*zzz)+bb
aa=(tpin-tsav)/(exp1(tmp1)-gp*cpp1/(gs*cps1))
bb=tpin-(tpin-tsav)/(1.0-gp*cpp1/(gs*cps1)/exp1(tmp1))
zzz=ztsg
tsgso=(tpin-tsav)/(exp1(tmp1)-gp*cpp1/(gs*cps1))*
&    gp*cpp1/(gs*cps1)*exp1(tmp2*zzz)+bb
errp=1.0+errstd
errm=1.0-errstd

```

c

c Checking the consistency

c

c

```

if (hqq.lt.errm*enthfg) then
  if (tsgsa.gt.errp*tsat) then
    aboun=aboun-daboun
  else
    bboun=bboun+dbboun
  endif
  if (tsgsa.lt.errm*tsat) then
    aboun=aboun+daboun
  endif
endif

```

```

if (hqq.gt.errp*enthfg) then
  if (tgsa.gt.errp*tsat) then
    aboun=aboun-daboun
    bboun=bboun-dbboun
  else
    bboun=bboun-dbboun
  endif
endif
c
c If all consistent then finish, otherwise readjust the boundary between
c sub-cooled region and saturated region and between saturated region and
c super heated region
c
  if ((abs(tgsa-tsat).lt.errstd*tsat).and.
& (abs(hqq-enthfg).lt.errstd*enthfg)) goto 90
  if ((abs(hqq-enthfg).lt.errstd*enthfg).and.
& (tgsa.gt.errp*tsat)) aboun=aboun-daboun
  if ((abs(hqq-enthfg).lt.errstd*enthfg).and.
& (tgsa.lt.errm*tsat)) aboun=aboun+daboun
  if (aboun.lt.0.0) aboun=0.0
  if (bboun.lt.0.0) aboun=0.0
  if (aboun.gt.ztsg) aboun=ztsg
  if (bboun.gt.ztsg) bboun=ztsg
  numblp=numblp+1
write(6,*)'loop number :',numblp,maxlop
  if (numblp.gt.maxlop) goto 90
  if (numblp.eq.1) then
    tgsao=tgsa
    hqqo=hqq
    goto 50
  endif
  tcheck=(tgsao-tsat)*(tgsa-tsat)
  qcheck=(hqqo-enthfg)*(hqq-enthfg)
  if (numblp.eq.2) then
    tgsao=tgsa
    hqqo=hqq
    tcheco=tcheck
    qcheco=qcheck
    goto 50
  endif
  tcheco=tcheck
  qcheco=qcheck
  if ((tcheck.lt.0.0).and.(tcheco.lt.0.0)) then
    daboun=daboun/2.0
  endif
  if ((qcheck.lt.0.0).and.(qcheco.lt.0.0)) then

```

```

    dbboun=dbboun/2.0
endif
tsgsao=tsgsa
hqo=hq
goto 50
c
c After convergent calculate final temperature distribution across
c primary and secondary sides and also estimation of wall temperature
c distribution
c
90 max1=int(aboun/ztsg*mxz)
   if (zsg(max1+1).lt.aboun) max1=max1+1
   max2=int(bboun/ztsg*mxz)
   if (zsg(max2+1).lt.boun) max2=max2+1
   aa=(tsgpa-tsin0)/(exp1(tmp3)-gp*cpp3/(gs*cps3))
   bb=tsgpa-(tsgpa-tsin0)/(1.0-gp*cpp3/(gs*cps3)/exp1(tmp3))
   do 60 i=1,max1
     zzz=zsg(i)
     tsgp(i)=(tsgpa-tsin0)/(exp1(tmp3)-gp*cpp3/(gs*cps3))*
&     exp1(tmp4*zzz)+bb
     tsgs(i)=(tsgpa-tsin0)/(exp1(tmp3)-gp*cpp3/(gs*cps3))*
&     gp*cpp3/(gs*cps3)*exp1(tmp4*zzz)+bb
     tsgm(i)=(tsgp(i)+tsgs(i))/2.0
c   write(6,*)i,zzz,tsgp(i),tsgs(i),tsgm(i)
60 continue
   do 70 i=max1+1,max2
     zzz=(zsg(i)-bboun)/(bboun-aboun)
     tsgp(i)=(tsgpb-tsai)*exp1(tmpsat*zzz)+tsai
     tsgs(i)=tsai
     tsgm(i)=(tsgp(i)+tsgs(i))/2.0
70 continue
   aa=(tpin-tsai)/(exp1(tmp1)-gp*cpp1/(gs*cps1))
   bb=tpin-(tpin-tsai)/(1.0-gp*cpp1/(gs*cps1)/exp1(tmp1))
   do 80 i=max2+1,mxz
     zzz=zsg(i)-bboun
     tsgp(i)=(tpin-tsai)/(exp1(tmp1)-gp*cpp1/(gs*cps1))*
&     exp1(tmp2*zzz)+bb
     tsgs(i)=(tpin-tsai)/(exp1(tmp1)-gp*cpp1/(gs*cps1))*
&     gp*cpp1/(gs*cps1)*exp1(tmp2*zzz)+bb
     tsgm(i)=(tsgp(i)+tsgs(i))/2.0
c   write(6,*)i,zsg(i),tsgp(i),tsgs(i),tsgm(i)
80 continue
   i=1
   write(6,*)i,zsg(i),tsgp(i),tsgs(i),tsgm(i)
   i=mxz
   write(6,*)i,zsg(i),tsgp(i),tsgs(i),tsgm(i)

```

```

call pdrsg
100 format(i5,f8.2,2x,f12.4,2x,f12.4)
return
end
c

```

This is the end of the program.

3.4 Examples of calculation results

In this example the primary side is lead-bismuth eutectic liquid metal while the secondary side is water-steam system. The system parameters are shown in the following table

Parameter	Value
Height (m)	4
Inner radius of pipe (cm)	1.1
Outer radius of pipe (cm)	1.25
Pipe pitch(cm)	4
Primary side flow rate (kg/s)	2250
Secondary side flow rate (kg/s)	30
Number of bundles	200
Secondary side inlet temperature (C)	225
Primary side inlet temperature (C)	510
System pressure(MPa)	7

Table 1. Steam generator parameters for calculation example
The calculation results is shown in the following figure

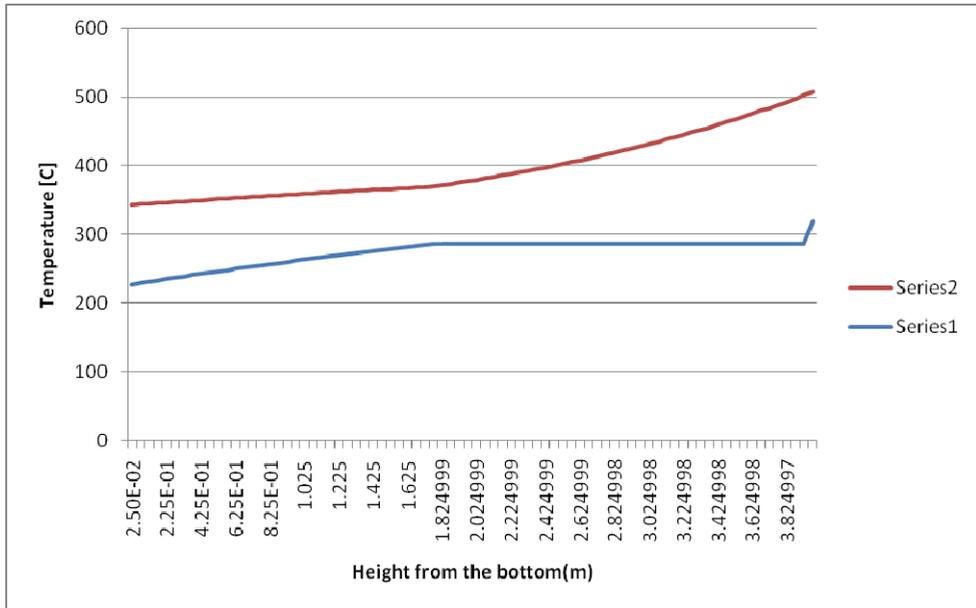


Fig. 3. Example of heat exchanger semi analytical analysis

3.5 Discussion and application

It is important to note that many thermal-hydraulic related constants for liquid metal Pb-Bi and water-steam system must be obtained and used during analysis. Such data can be obtained from references, e.g references number 1-5. In the program given in section 2.3 some thermal hydraulic constants are calculated using specific function such as

temsw(P) : to calculate water-steam system saturated temperature

entshv(psys,tsav): to calculate enthalphy of super heated vapour

cpc(tp):to calculate specific heat of primary coolant

conc(tp):to calculate thermal conductivity of primary coolant

visshv(hshv,psys): to calculate viscosity of super heated vapour

conshv(hshv,psys): to calculate thermal conductivity of super heated vapour

To calculate the pressure drop across the pipe inner and outer we can integrate the momentum balance equation. In general we have gravitational, friction, acceleration, and form related pressure drop components and we need specific correlation for friction and form pressure drop. To calculate this we can use the correlation from the references: 1,3,4,5. The data from the third reference is useful especially when we have the flow regime is in transition between laminar and turbulence.

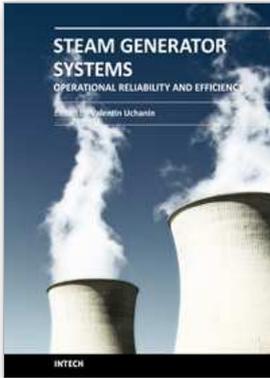
The semi analytical analysis of steam generator in a certain level can be used for transient analysis of power system for example as long as the transient is relatively slow so that quasi-static approach can be adopted.

To get more accurate steam generator analysis we can use direct numerical solution of equations 1-3 and use the result of semi analytical analysis as initial guess of primary and

secondary side temperature distributions. In general the results from semi analytical analysis has good accuracy compared to that from direct numerical calculations.

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