Chapter 3 Heat Transport System Thermalhydraulics

3.1 Introduction

The previous chapters laid out the purpose of the HTS along with some schematics of typical designs indicating the main components and their functions. Also described were the desirable properties of these components. This section lays out the fundamental principles governing the mass and heat transfer, setting the scene for subsequent detailed investigations.

3.2 Reactor Heat Balance

The HTS for CANDU reactors, and all other reactor systems, for that matter, is fundamentally simple. Heat is generated by nuclear fission, transferred to a moving heat transport medium, and carried by this medium to the steam generators for steam production. This is indicated in figure 3.1.

Performing an energy balance around the reactor, the energy out of the reactor equals the energy going in plus the reactor energy generation. Thus:

$$Wh_o = Wh_i + Q \quad (1)$$

or

$$Q = W(h_o - h_i) \quad (2)$$

where W = coolant mass flowrate (kg/s);
h_o = core exit enthalpy (kJ/kg);
h_i = core inlet enthalpy (kJ/kg);
Q = reactor power transferred to the coolant (kJ/s or kW).

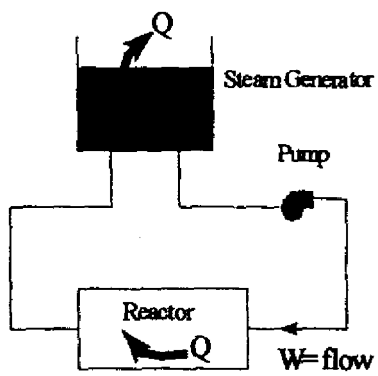

Figure 3.1 HTS simplified schematic

3.3 Steam Generator Heat Transfer

Neglecting minor factors such as pump heat, piping heat losses, pump gland seal leakage and miscellaneous heat losses via auxiliary systems, the power transferred to the steam generator is Q kW. The heat transfer at any point in the steam generator is given by Fourier's law:

$$dQ = U\,(T_p - T_s)\,dA \tag{3}$$

where U = overall heat transfer coefficient (kJ/m^2 -°C),
A = heat transfer area (m^2),
T_p = primary (D_2O) side temperature (°C)
T_s = secondary side (H_2O) temperature (°C).

U is a function of flow, temperature, the amount of boiling (quality), the physical layout, heat exchanger tube material and the degree of crudding or fouling in the steam generator.

Thus the total heat transfer is

$$Q = \int_Q dQ = \int_A U\,(T_p - T_s)\,dA_s \tag{4}$$

However, the D_2O and H_2O temperatures are not constant throughout the steam generator. A schematic representation of the variation is shown in figure 3.2.

Using the 600 MW CANDU as an example, demineralized feedwater (H_2O) enters the preheating section of the steam generator at roughly 175°C and gains heat from the exiting D_2O. The H_2O begins to boil (~265°C at ~5 MPa). The temperature then remains essentially constant as the H_2O travels through the boiler (left to right in figure 2).

The D_2O (primary fluid) enters the boiler section of the steam generator at roughly 310°C at 10 MPa with 4% quality (i.e., 4% by weight of steam).

The heat transfer to the secondary side condenses the steam and the temperature drops as the D_2O travels through the steam

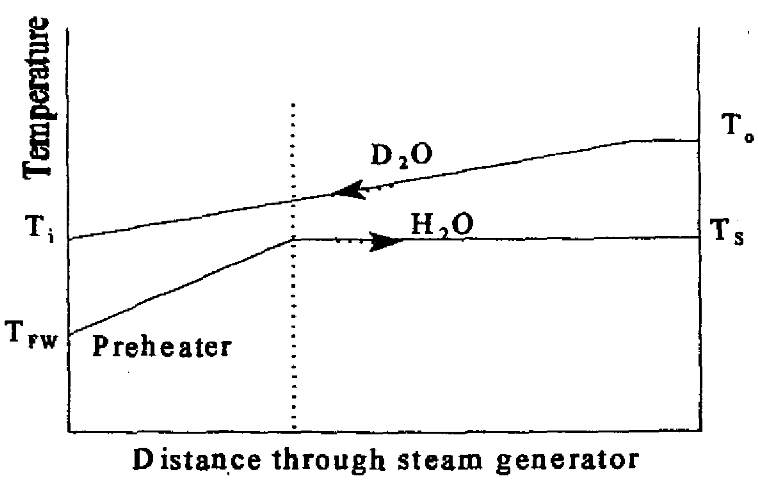

Figure 3.2 Steam Generator Temperature Distribution

generator tubes (right to left in figure 3.2).

For the purposes of discussion, we will simplify equation 4 by assuming a temperature distribution as shown in figure 3.3. Thus we have ignored the preheating section (where the H_2O temperature is less than saturation) and have assumed that no boiling occurs on the primary side. Further we assume that U is constant. These are crude approximations but adequate for discussion purposes.

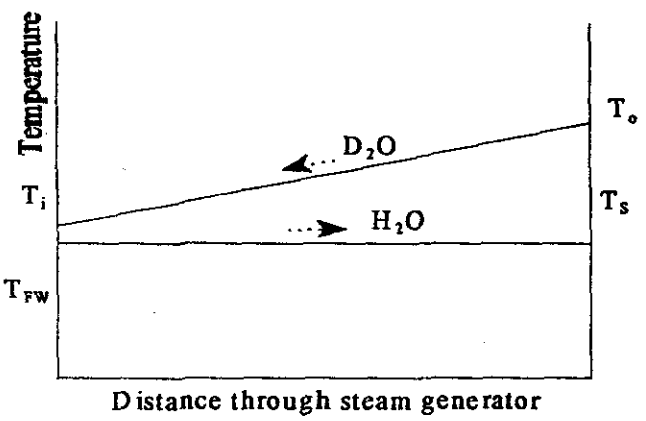

Figure 3.3 Simplified Steam Generator Temperature Distribution

Thus, equation 4 becomes

$$Q = UA\,\frac{(T_{OUT} + T_{IN})}{2} - UAT_s \quad (5)$$

But, T_{OUT}, the steam generator outlet temperature, is the same as the reactor inlet temperature. Also, the steam generator inlet temperature is the same as the reactor outlet temperature. Hence equation 5 becomes

$$Q = UA\,(\frac{T_o + T_i}{2} - T_s) \quad (6)$$

This can be related to enthalpy by noting that

$$h \approx C_pT + CONSTANT \quad (7)$$

where C_p is the heat capacity of water. Equation 6 then becomes

$$Q = \frac{UA}{C_p}\,[\frac{h_o + h_i}{2} - h_s] \quad (8)$$

if we assume the same properties for H_2O and D_2O and where h_s is the enthalpy of the saturated liquid H_2O at temperature T_s.

3.4 Primary Side Flow

A final primary heat transport system relation is needed to complete this approximate picture. The primary side flow is determined by a balance between the head generated by the primary pumps and the circuit head losses due to friction.

$$\Delta P_{pump} = \Delta P_{circuit} \qquad (9)$$

The pump curve (head vs. flow) relationship is supplied by the pump manufacturer. It can be approximated by a power series:

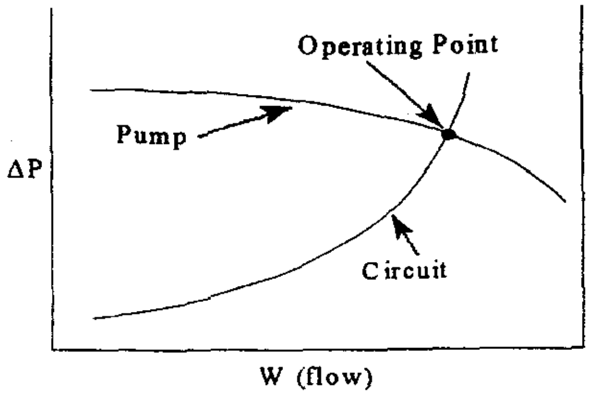

Figure 3.4 Circuit Losses and Pump Head vs. Flow

$$\Delta P_{pump} = A_o + A_1 W + A_2 W^2 + ... \qquad (10)$$

The circuit losses obey the classical velocity squared relationship to a first order approximation:

$$\Delta P_{circuit} = K\, W^2 \qquad (11)$$

where K can be a complex function of material properties and pipe geometric details.

Typical shapes for equation 10 and 11 are shown in figure 3.4. The intersection of the two curves is the operating point, equation 9.

3.5 Secondary Side Flow

The secondary side steam flow can be calculated by an energy balance on the secondary side of the boiler (similar to that done for the reactor):

$$Q = W_{steam}\,(h_{steam} - h_{feedwater}) \qquad (12)$$

The feedwater temperature (hence enthalpy) is given by the turbine manufacturer. The steam temperature (hence enthalpy) is set by the controlled steam pressure. Thus the steam flow is:

$$W_{steam} = \frac{Q}{(h_{steam} - h_{feedwater})} \qquad (13)$$

This neglects second order auxiliary flows usually present on steam generators such as reheater drains and boiler blowdown.

3.6 Approximate Solution

The primary heat transport approximate conditions are set, then, by the simultaneous solution of the energy balance at the core, the energy balance at the steam generator and the momentum balance around the circuit. The secondary side is quantified by an energy balance at the steam generator secondary side.

In summary:

$$Q = W\,(h_o - h_i) \tag{2}$$

$$Q = \frac{UA}{C_p}\,[\frac{h_o + h_i}{2} - h_s] = UA\,[\frac{T_o - T_i}{2} - T_s] \tag{8}$$

$$\Delta P_{pump} = \Delta P_{circuit} \tag{9}$$

$$Q = W_{steam}\,(h_{steam} - h_{feedwater}) \tag{12}$$

Equations 2 and 8 can be rearranged to give an expression explicit in h_i as follows:

Equation 2 gives

$$h_o = \frac{Q}{W} + h_i \tag{14}$$

Substituting into equation 8:

$$\frac{Q}{W} = \frac{UA}{C_p W}\,[\frac{Q}{2W} + h_i - h_s] = \frac{UA}{W}\,[\frac{Q}{2C_p W} + T_i - T_s] \tag{15}$$

Solving for h_i gives:

$$h_i = \frac{Q}{W}\,[\frac{C_p W}{UA} - \frac{1}{2}] + h_s = \frac{QC_p}{UA} + h_s - \frac{Q}{2W} \tag{16}$$

$$T_i = \frac{Q}{W}\,[\frac{W}{UA} - \frac{1}{2C_p}] + T_s \tag{17}$$

Thus we see that since all parameters, Q, W, C_p, A, U, etc., are positive quantities, the reactor inlet enthalpy (and hence the inlet temperature) will rise up as flow rises, will rise as secondary side temperature and enthalpy rise and may go up or down as power changes.

The reactor outlet enthalpy, h_o, is directly related to h_i by equation 2. Thus:

$$T_o = \frac{Q}{W}\left[\frac{W}{UA} + \frac{1}{2C_p}\right] + T_s \tag{18}$$

$$\begin{aligned} h_o &= \frac{Q}{W} + h_i = \frac{Q}{W} + \frac{Q}{W}\left[\frac{C_pW}{UA} - \frac{1}{2}\right] + h_s \\ &= \frac{Q}{W}\left[\frac{C_pW}{UA} + \frac{1}{2}\right] + h_s \end{aligned} \tag{19}$$

The average enthalpy in the core and the steam generator is:

$$h_{aver} = \frac{h_o+h_i}{2} = \frac{Q}{W}\left(\frac{C_pW}{UA}\right) + h_s = \left(\frac{QC_p}{UA}\right) - h_s \tag{20}$$

$$T_{aver} = \frac{T_o+T_i}{2} = \frac{Q}{UA} + T_s \tag{21}$$

The result is worth remarking since it shows that T_{aver} is not a direct function of flow. Given T_s, C_p/UA as fixed for a given secondary side temperature and steam generator geometry, T_{aver} is a simple linear function of the reactor power, Q.

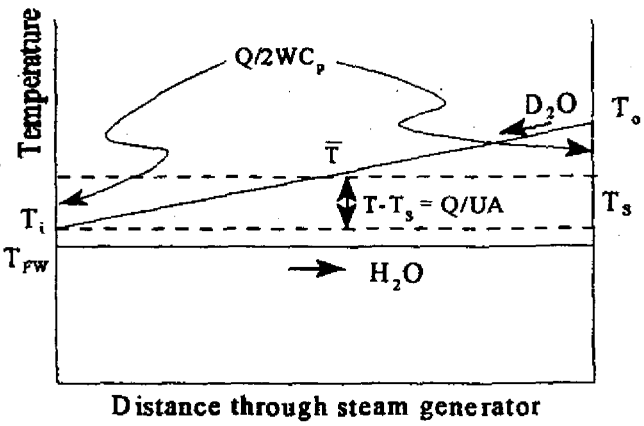

Figure 3.5 Temperature Variations

Figure 3.5 illustrates this point and also shows the spread or variation in T about T_{aver} given by:

$$T_o - T_{aver} = \frac{Q}{W}\left(\frac{W}{UA} + \frac{1}{2C_p}\right) + T_s - \frac{Q}{W}\frac{W}{UA} - T_s$$
$$= \frac{Q}{2WC_p} \tag{22}$$

Similarly

$$T_{aver} - T_i = \frac{Q}{2C_{pW}} \tag{23}$$

From equation 18, we see that the primary side enthalpy floats on top of the secondary side with just enough ΔT to transfer Q kW of power.

Also given a rough estimate of flow for the calculation of U (not a strong function of flow since W is large and turbulent - most of the resistance to heat transfer is due to conduction through the tubes and crud layer) we can calculate T_{aver} and estimate the spread in T_{aver} ($T_{aver} \pm Q/2WC_p$). This gives a good first estimate of the temperatures and enthalpies and indicates whether boiling will occur in the primary circuit or not.

With this enthalpy, temperature and hence density estimate, the circuit losses can be calculated and compared to the available pump head at that flow.

The flow estimate can be updated and the whole procedure repeated until convergence is reached. A sample calculation follows.

3.7 Sample Heat Balance for CANDU 600

Parameters:

- $Q \approx 2000$ MW(th) $= 2\text{x}10^6$ kW(th) (given)
- $W \approx 8000$ kg/s total core flow (guessed)
- $T_s \approx 265°C$ (given) $\Rightarrow h_s \approx 1150$ kJ/kg
- $C_p \approx 5$ kJ/kg °C (guessed)
- $U \approx 5$ kJ/s°Cm^2 $\Rightarrow (C_pW / UA) \approx 0.625$
- $A \approx 3200$ m^2 / steam generator
- $P_{ROH} = 10$ MPa (given)

Thus from equation 16

$$h_i = 250\,[0.625 - 0.5] + h_s = h_s = 1181.25\ kJ/kg \tag{24}$$

and

$$h_o = h_i + \frac{Q}{W} = h_i + 250 = 1431.25\ kJ/kg \tag{25}$$

The saturation enthalpy at the outlet header is roughly 1370 kJ/kg. Hence our prediction of the primary outlet conditions is that the D_2O should have some boiling. In fact, the detailed design calculations give the outlet quality at 4% with an enthalpy of ~ 1415 kJ/kg.

It is instructive to look at the system sensitivities. From equation 15:

$$W = \frac{Q}{2(\frac{QC_p}{UA} + h_s - h_i)} \tag{26}$$

Therefore

$$\frac{\delta W}{\delta h_i} = \frac{Q}{2(\frac{QC_p}{UA} + h_s - h_i)^2} = \frac{Q}{2(\frac{Q}{2W})^2} = \frac{2W^2}{Q} \tag{27}$$

and

$$\frac{\delta(\frac{W}{W_o})}{\delta(\frac{h_i}{h_{io}})} = 9.0 \tag{28}$$

Thus if we had chosen h_i to start our iterative calculation, and our guess was in error by 25% the flow will subsequently be in error by 9.0 x 25% or 225%. Thus huge swings in estimated flow will accompany the search for the right h_i.

If, instead, we guess at flow and are out by 25%, the h_i calculated will be out by only 2.8%. Convergence will, thus, be much better behaved. Figure 3.6 illustrates the calculational procedure.

The proper iterative procedure, then, would take full advantage of these sensitivities. The key parameters are fixed or guessed: Q is usually given, W is guessed from, say, a single phase circuit loss calculation at any reasonable enthalpy, U is calculated based on empirical correlations, A is usually given and T_s is usually given. The enthalpies can then be readily calculated. Depending on the nature of the correlations used for U, the iteration may involve an inner loop on U and h to converge on a self-consistent heat transfer given the flow. The flow, then, is updated based on the circuit loss calculation until convergence is reached.

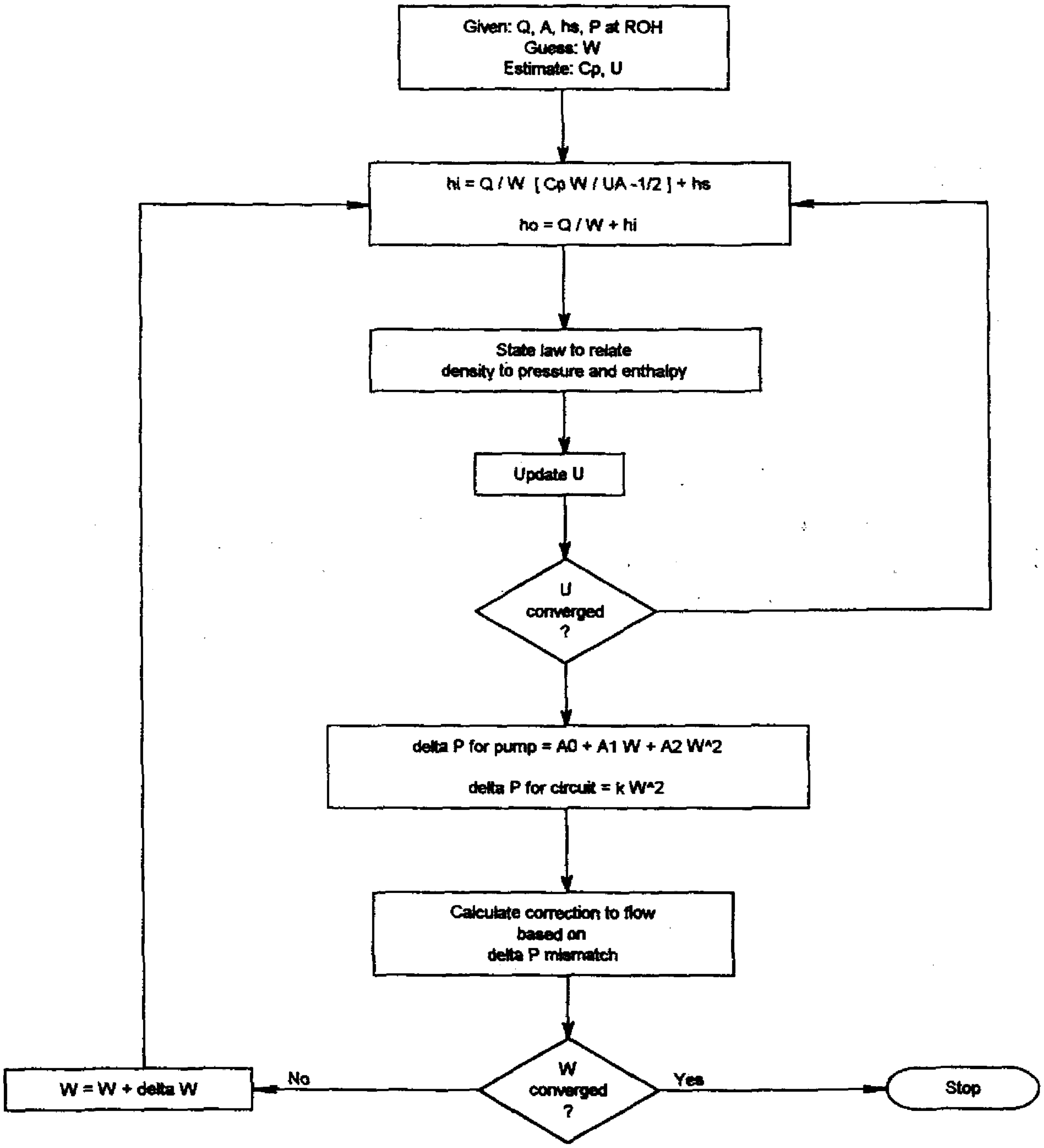

Figure 3.6 Flow Chart for HTS Calculations

3.8 Steam Generator with Preheater: Simple Analytical Solution

To illustrate the mechanisms behind the variation in RIH temperature as a function of power, the heat balance equations around the reactor and the steam generator are examined.

For the reactor, we have:

$$Q = W\,C_p\,(T_o - T_i) \qquad (29)$$

where:

- Q = reactor power ≈ steam generator power
- C_p = D_2O heat capacity ≈ constant
- T_o = ROH temperature
- T_i = RIH temperature

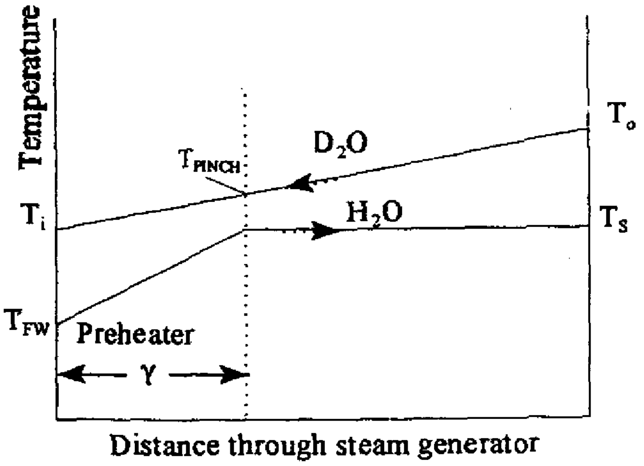

Figure 3.7: Steam Generator Temperature Distribution

For the steam generator, we have:

$$dQ = U\,dA\,(T_{PRIMARY} - T_{SECONDARY}) \qquad (30)$$

where:

- U = overall heat transfer coefficient
- dA = incremental heat transfer area
- $T_{PRIMARY}$ = temperature of D_2O in S.G. tubes
- $T_{SECONDARY}$ = temperature of H_2O in S.G. shell.

Since both $T_{PRIMARY}$ and $T_{SECONDARY}$ vary throughout the steam generator, equation 30 cannot be directly integrated. Thus, we assume linear variations, as shown in figure 3.7. Thus:

$$Q = UA(1-\gamma)\left[\frac{(T_o + T_{PINCH})}{2} - T_s\right] + UA\,\gamma\left[\frac{(T_i + T_{PINCH})}{2} - \frac{(T_s + T_{FW})}{2}\right] \qquad (31)$$

where:

- γ = the fraction of the steam generator associated with preheating the feedwater
- T_{PINCH} = D_2O temperature at the pinch point

T_s = temperature of saturated H_2O
T_{FW} = feedwater inlet temperature.

From figure 3.7 and equation 29:

$$\begin{aligned} T_{PINCH} &= T_i + \gamma\,(T_o - T_i) \\ &= T_i + \gamma \frac{Q}{C_{pW}} \end{aligned} \qquad (32)$$

Substituting equation 32 into equation 31 gives (after some cancellations):

$$Q = UA\left[\left(\frac{T_o + T_i}{2}\right) - T_S + \frac{\gamma}{2}(T_S - T_{FW})\right] \qquad (33)$$

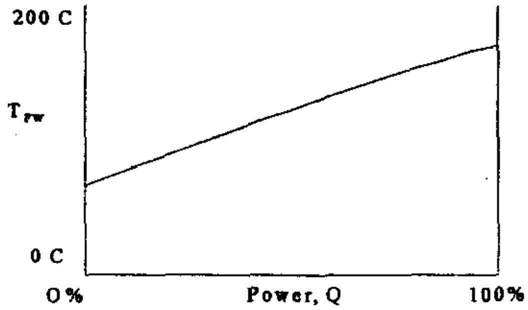

Figure 3.8 Variation of feedwater temperature with power

But, again, from equation 28:

$$T_o = \frac{Q}{W C_p} + T_i \qquad (34)$$

Thus equation 33 becomes (solving for T_i):

$$T_i = \frac{Q}{W C_p}\left[\frac{W C_p}{UA} - \frac{1}{2}\right] - \frac{\gamma}{2}[T_S - T_{FW}] + T_S \qquad (35)$$

and

$$T_o = \frac{Q}{W C_p}\left[\frac{W C_p}{UA} + \frac{1}{2}\right] - \frac{\gamma}{2}[T_S - T_{FW}] + T_S \qquad (36)$$

To examine T_i variation with Q, the behaviour of the other parameters in equation 35 must be addressed.

<u>T_s vs. Q.</u>

The secondary side saturation temperature is held constant by holding the pressure constant except for Pickering G.S.

<u>T_{FW} vs. Q</u>

The variation in feedwater temperature is shown in figure 3.8.

W, C_p, A, U vs. Q

These parameters have a second order variation or are constant. The most rapidly varying parameter is U.

γ vs. Q

The power required to bring the feedwater up to saturation is:

$$Q_{PREHEATER} = W_{FW}\, C_{P_{H_2O}} (T_{FW_{SAT}} - T_{FW}) \tag{37}$$

But, from equation 31:

$$Q_{PREHEATER} = UA\,\gamma \left[\left(\frac{T_i + T_{PINCH}}{2}\right) - \frac{(T_S + T_{FW})}{2}\right] \tag{38}$$

Thus:

$$\gamma = \frac{W_{FW}\, C_{P_{H_2O}} (T_{FW_{SAT}} - T_{FW})}{UA\left[\frac{(T_i + T_{PINCH})}{2} - \frac{(T_S + T_{FW})}{2}\right]} \tag{39}$$

The parameter that varies the most on the right-hand side of equation 39 is W_{FW}. From a secondary side heat balance:

$$Q = W_S\, h_S - W_{FW}\, h_{FW} + 2^{nd} \textit{ order terms} \tag{40}$$

Since $W_S \approx W_{FW}$, $h_s \approx$ constant, and $h_{FW} \approx$ constant, then

$$W_{FW} \propto Q \tag{41}$$

Thus, to a first approximation, from equations 39 and 41,

$$\gamma \propto Q \tag{42}$$

or:

$$\gamma = \frac{\gamma_{100}\, Q}{Q_{100}} \tag{43}$$

where:

γ_{100} = preheating fraction at 100% F.P.
Q_{100} = Q at 100% F.P.

Putting equation 43 into equation 35:

$$T_i = \frac{Q}{W C_p}\left[\frac{W C_p}{UA} - \frac{1}{2}\right] - \frac{Q\,\gamma_{100}}{2\,Q_{100}}\,[T_S - T_{FW}] + T_S$$
$$= \frac{Q}{Q_{100}}\left[\frac{Q_{100}}{W C_p}\left[\frac{W C_p}{UA} - \frac{1}{2}\right] - \frac{\gamma_{100}}{2}\,[T_S - T_{FW}]\right] + T_S \tag{44}$$

$$T_o = \frac{Q}{Q_{100}}\left[\frac{Q_{100}}{W C_p}\left[\frac{W C_p}{UA} + \frac{1}{2}\right] - \frac{\gamma_{100}}{2}\,[T_S - T_{FW}]\right] + T_S \tag{45}$$

Thus we see that the RIH temperature is the same as the saturation temperature of the steam with a correction due to primary side effects and a second correction due to feedwater temperature effects. Both these effects are roughly proportional to power.

Thus, at 0% F.P.:

$$T_i = T_S \tag{46}$$

$$T_o = T_S \tag{47}$$

To evaluate numerically the size of the correction terms, we have, for the CANDU 600:

$Q_{100} = 2.064\times10^6$ KJ/s
$U = 4.5$ KJ/s°C m^2
$A = 3200$ m^2 per steam generator (12800 m^2 total)
$W = 8250$ Kg/s
$C_p = 4.25$ KJ/Kg°C
$\gamma_{100} = 0.15$
$T_{FW} = 177$°C @ 100% F.P.
$T_S = 260$°C.

Thus:

$$T_i = \frac{Q}{Q_{100}}\{58.86\,[.60 - .50] - 6.22\} + 260$$
$$= \frac{Q}{Q_{100}}(6.32 - 6.22) + 260 \tag{48}$$

$$T_o = \frac{Q}{Q_{100}}(64.75 + 6.22) + 260$$
$$= \frac{Q}{Q_{100}}(58.53) + 260 \qquad (49)$$

Thus, even at 100% F.P., the net correction to T_i is less than 0.1°C. Even allowing for large variations in U, etc., the effect on T_i is expected to be small over the full power range. This has been confirmed by detailed calculations.

T_o at 100% F.P. = 318.5°C, which is greater than the saturation temperature of 310°C at 10 MPa at the ROH. Thus, the assumption of no boiling at the ROH is not true.

We can estimate the amount of boiling using:

$$Q = W C_p \left[T_{oSAT} + \frac{x h_{fg}}{C_p} - T_i\right] = W C_p \{T_{oSAT} - T_i\} + \frac{W C_p x h_{fg}}{C_p}$$
$$= Q_{1\phi} + Q_{2\phi} \qquad (50)$$

The power at which boiling starts is given by equation 49:

$$\frac{T_o - 260}{58.53} = \frac{310 - 260}{53.53} = \frac{Q}{Q_{100}} = \frac{50}{53.53} = .854 \qquad (51)$$

or 85.4% F.P.

$$\therefore \frac{Q}{Q_{100}} = \frac{Q_{1\phi}}{Q_{100}} + \frac{Q_{2\phi}}{Q_{100}} = \frac{W C_p}{Q_{100}}\{T_{SAT} - T_i\} + \frac{W x h_{fg}}{Q_{100}} \qquad (52)$$
$$= .854 + .146$$

$$\therefore x = \frac{.146 \times Q_{100}}{W h_{fg}} = \frac{.146 \times 2.064 \times 10^6 \text{ KJ/s}}{8250 \text{ kg/s} \times 800 \text{ KJ/Kg}} \tag{53}$$

$$= 0.045$$

or 4.5% Quality at the ROH

We have assumed in the above that the value of 85.4% for onset of boiling as calculated by 53 remains valid as the power goes up beyond the onset of boiling. That is, we have assumed that the parameters which determine the onset of boiling, W, C_p, U, A, T_S and T_{FW} do not significantly change when boiling starts in the P.H.T. This is only approximately true: W and U are affected by the presence of 2ϕ flow. But this is good enough to illustrate the point.

We have now enough information to sketch out the heat duty diagram as a function of power.

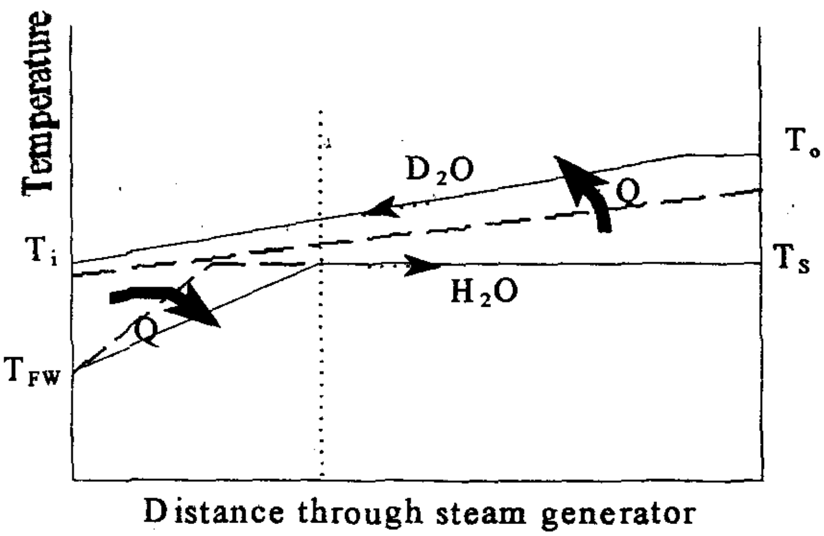

Figure 3.9 Temperature profile as a function of power

3.9 Steam Generator with Preheater: Numerical Solution

Consider the steam generator to be a countercurrent heat exchanger. For any small segment, dz, in the heat exchanger, the heat transferred is:

$$dq = U\,dA\,(T_p - T_s) \qquad (54)$$

where the primary and secondary temperatures will vary with position. An energy balance on the secondary side gives:

$$W_s \times dh_s = dq \qquad (55)$$

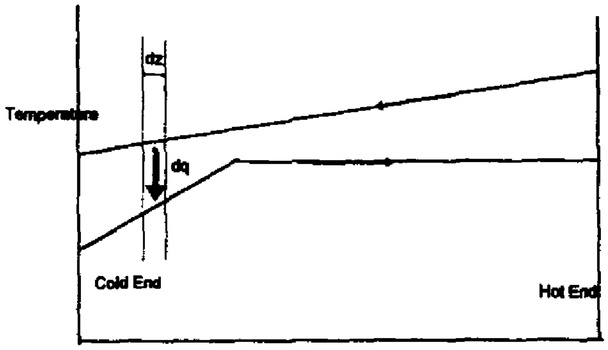

Figure 3.10 Heat duty diagram: heat flow in segment dz

Similarly for' the primary side:

$$W_p \times dh_p = -dq \qquad (56)$$

where the minus sign indicates a heat flow form the primary to the secondary side, i.e., the primary fluid is losing enthalpy. For single phase for either side:

$$dh = C_p\,dT \qquad (57)$$

Therefore:

$$dT_p = -\frac{U\,dA\,(T_p - T_s)}{C_p\,W_p} \qquad (58)$$

$$dT_s = \frac{U\,dA\,(T_p - T_s)}{C_p\,W_s} \qquad (59)$$

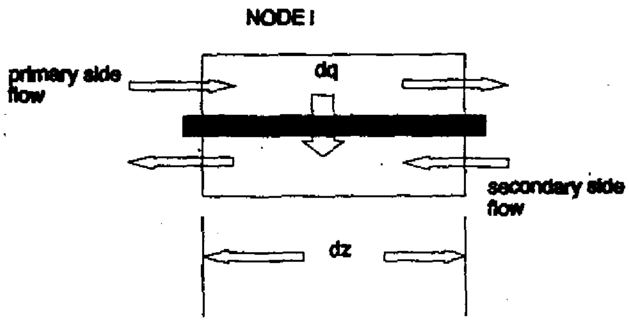

Figure 3.11 Heat flow in segment dz

If we divide the boiler into N segments, dA = A/N. The numerical algorithm is simply to start at one end of the heat exchanger with known or assumed temperatures and flows at that boundary and to repeatedly apply equations 58 and 59 in a marching fashion to the other end of the heat exchanger. If we start at the cold end (feedwater entering, primary fluid exiting), we are assured of single phase flow on both sides. At each successive nodal point, i:

$$T_{p,i+1} = T_{p,i} + \frac{U\,A}{C_p\,N\,W_p}\,(T_{p,i} - T_{s,i})$$
$$T_{s,i+1} = T_{s,i} + \frac{U\,A}{C_p\,N\,W_s}\,(T_{p,i} - T_{s,i}) \quad (60)$$

At each nodal point, i, the calculated temperature should be compared to the saturation point. Once saturation temperature is reached, the temperature remains at the saturation temperature, of course.

The result is the temperature profiles for both the primary and secondary sides for the given flow rates, area, heat transfer coefficient and cold side temperatures. Equation 54 is used to accumulate the total heat transferred by the heat exchanger. If the heat transferred was above or below the desired heat transfer, then an iteration on the whole process is required. Typically, it is desired to know what the primary side temperature profile is for given secondary side conditions, given primary side flow and given steam generator geometry and heat transfer coefficient. In this case, the primary side inlet temperature is varied until the target Q is met; once again, the primary side "floats" on the secondary side.

The effect of power is seen via W_s which is proportional to Q. For low Q, T_s will rise rapidly to the saturation temperature. This lowers the effective temperature difference between the primary and secondary sides. Hence T_p will not rise as quickly compared to the high power case.

The more general solution is dynamic. We shall develop the transient equation in a subsequent chapter.

3.10 Summary

This explains in very simple terms the main features of the CANDU heat transport system (HTS). The main actors in the interplay of processes in the HTS are:

HTS Flows
HTS Temperatures (Quality)
Circuit Resistances
Pump Head
Boiler Heat Transfer
Power

These govern the steady state operation of the HTS. If the quality is non-zero, it is important to know by how much since it influences U and K to a large degree. Also the relationship between the quality and void fraction is important for determining the swell and shrink during transients.

The transient behaviour is important because flow, temperature and pressure swings can be damaging to the components. Accurate models of the system are required so that detailed analysis of normal and abnormal events of plant operation can be analyzed and accounted for in the design of the plant. The accuracy required depends on the design margin. Tight margins require high accuracy while crude models will suffice for robust designs.

Accurate assessments of pressure drops, two-phase flow behaviour, heat transfer details, pump head curves, etc., are required for design. Detailed equations for mass, energy and momentum balances are required throughout the system and they must be solved simultaneously in the steady state and the transient. Empirical correlations must be found to account for complex processes like pressure drop in pipes under single and two-phase conditions, heat transfer (boiling and non-boiling) etc. These topics are covered in the other chapters. Detailed assessments of layout, maintenance and man-rem considerations, economy, technical feasibility, component life, stress analysis, and controllability must all be considered before a design is finalized; these topics are <u>not</u> covered in this course.

Although the HTS is very simple in concept, the details make it quite complex indeed. It's size, use of expensive D_2O, and necessary provision for cooling to the fuel <u>at all times</u> make it expensive. The system is designed to very high standards because the first line of defence to ensure safety in the CANDU system is the integrity of the primary boundary (pipes) and the proper design of the processes within that boundary.

Subsequent chapters discuss in varying degrees the details involved in satisfying the above.