Condenser, Circulating Water Pump Flow Calculation Using PEPSE®

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ABSTRACT

This paper examines the effects of various circulating water flow rate assumptions on the results from analyzing the performance impact of tube plugging in a condenser. The tube-side water's flow rate has a strong influence in the results of condenser calculations. Affecting flow rate is the pressure drop of the circulating water. This paper advocates accounting for flow rate variations. The equations to account for tube-side pressure drops in the circulating water system are presented, as foundation for this accounting.

The purposes of the paper are to present the development of key equations, to demonstrate application of the method of analysis, and to support the assertion that circulating water flow assumptions (as tube plugging varies) are important. The dependence of flow on tube plugging is calculated by accounting for the hydraulic balance between the tube-side circuit's pressure drop and the pressure head provided by the circulating water pump.

Of principal interest is the condenser's shell side pressure. Comparisons of condenser performance are shown for several different assumptions about flow rate. Example plots are used to illustrate the effects of alternative modeling assumptions. Two models are used. The first is a submodel of a condenser and circulating water pump, along with supply and receiver reservoirs and associated piping. The second is a fossil steam turbine Rankine cycle that includes a condenser and circulating water pump. The method of calculation of the condenser's shell-side equilibrium pressure closely follows the standard published by the Heat Exchange Institute. This method has been a part of PEPSE for a number of years.

Acknowledgement

This work builds upon and is a substantial extension of the 2000 work of Ref 4, authored by Minner and Feigl. A large part of the system data at that time were provided by Tim Feigl of Ameren Energy Generating Company, and these data are used in this paper.

INTRODUCTION

The condenser in a steam electric power generation station is one of the most influential items of equipment in the system as related to performance and cost. The shell-side pressure in the condenser strongly affects the amount of power generation and the heat rate of the station. Standard wisdom holds that the lower the shell pressure of the condenser, the better. There are important limitations of this idea (turbine choking and others), but we need to have a quantitative grasp of how the condenser pressure changes as conditions may change.

The tools to quantify the condenser pressure functionality have been available in the industry, via the HEI - Heat Exchange Institute - publications, via methods programmed in PEPSE (including "design mode" and HEI methods), and others, for some time. See References 1, 2, and 3. This paper provides some examples and a discussion on application of the HEI method of representing the heat transfer in such calculations.

To analyze condenser performance, assumptions are necessary. In the present study, we focus attention on assumptions about the circulating water flow rate, as we use the HEI method to analyze the effect of plugging tubes on the condenser's shell pressure. The circulating water flow rate is directly important because it affects the velocity of the water inside of the tubes, thus the coefficient of heat transfer, and ultimately the shell-side pressure.

To analyze tube plugging effects, the easiest and most commonly made assumption is that the circulating water flow rate is constant as more and more tubes are plugged. Therein the only apparent significant effect of plugged tubes is the change of effective heat transfer area. However, a consequence of this assumption is an implicit increase of tube-side velocity as the number of active tubes is reduced. This unrealistic increase of velocity increases the calculated heat transfer coefficient, tending unrealistically to counteract the effect of the reduced area. The consequence of these counteracting heat transfer effects would be to underestimate performance changes as tubes are plugged. Another assumption that is relatively easy to implement and may be worth considering is that the velocity inside of the tubes remains constant as tubes are plugged.

In reality, however, as more and more tubes are plugged, reductions of circulating water flow rate also occur. The flow rate adjusts to a point where the hydraulic losses and elevation heads in the system are balanced by the pump's pressure rise, according to its "head curve". In order to analyze the condenser under the assumption of this hydraulic balance, it is necessary to account for the pressure losses, the elevation effects, and the pump head curve in the circulating water circuit.

The tube-side pressure drop can be accounted by long-standing fluid-mechanical formulations that are programmed in PEPSE, involving friction factor and form loss factor. These do not necessarily identically match the pressure drop method presented in the HEI document. The examples address the effect of varying amounts of tube plugging as this impacts the calculated shell pressure.

It is reasonable to ask whether assumptions that are made for ease of analysis might contribute to misleading results. In an effort to find out whether these differences are important, PEPSE cases can be run under several different assumptions. Comparisons can then be made between calculated performance results under differing assumptions in separate scenarios. In the first and simplest scenario, the rate of flow of circulating water is held fixed. This scenario is certainly the easier to set up in a model. Therefore, it is a method that is used often by modelers to make a quick estimate of the condenser's performance. The second scenario, also easy to set up, varies the circulating water flow rate to maintain a constant tube-side velocity as more and more tubes are plugged.

Additional scenarios can be run, where the rate of flow is varied, according to the concept of the hydraulic balance discussed above. The method of calculating flow in the latter scenario is to match the circulating water pump's pressure head (which is related to flow rate) against a simulation of the hydraulic pressure drop and elevation changes in the condenser and its piping (which is proportional to flow rate). We can visualize this as finding the intersection of the curves of pressure drop and of pump head versus flow rate.

The pressure losses and elevation heads in the circulating water system are accounted in Type 1 streams and in the condenser component. In order to find the hydraulic balance, PEPSE's special features are implemented. A schedule is used to represent the pump's head curve. The balance between the pump head and this resistance is obtained by use of a PEPSE control. The sensitivity study feature is used to expedite analyzing the variation of tube plugging.

The results of this study provide a refinement of the study of Ref 4 of the 2000 User's Group Meeting. Qualitatively the conclusions from the two studies are the same. Quantitatively, the current study's results are somewhat different and superior to those from of Ref 4.

Numerous assumptions were required in order to apply this method. If these specific assumptions do not apply in some other system, the method of calculation still applies. Only the specific details of application differ.

Fundamentals of Analyses

The equilibrium shell pressure in a condenser is determined by the quantity of heat transferred from the shell-side steam to the circulating water. The heat transfer is a complex function of many variables. A method of calculating condenser performance was established by the HEI Standards, Ref. 1. The current study uses these standard methods. In cases of tube plugging, two primary variables that impact the heat transfer are the change of effective heat transfer surface area and the change of water velocity inside of the tubes. The HEI standard includes these effects in the calculation of condenser pressure.

An earlier paper, Ref 4, presented an application of PEPSE, using the HEI method, to compute condenser performance. Recent modifications of PEPSE (Version 69/GT) have improved both the technical foundation and the ease of use to perform these calculations. This paper explains these improvements and provides example applications.

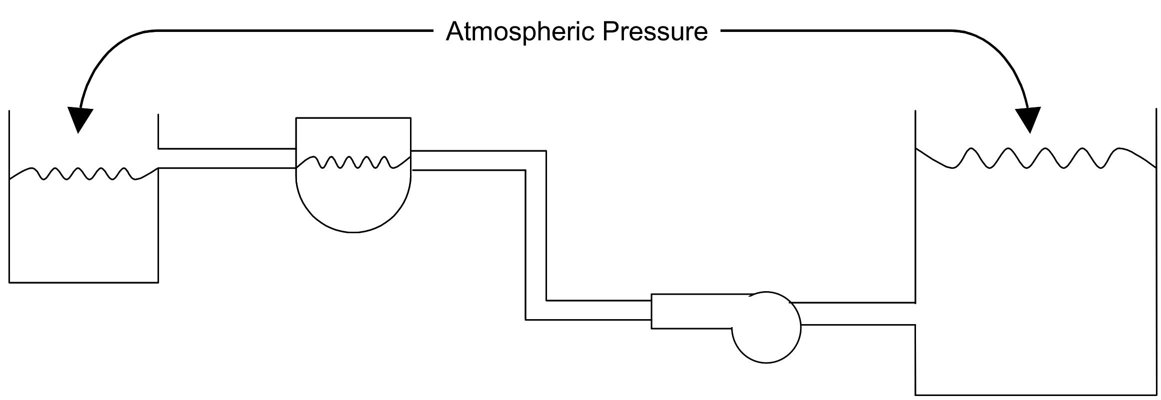
Version 69/GT provides options for direct specification of the fraction (or number) of tubes that are plugged in the condenser. Version 69/GT also includes built in pressure drop calculations for the flow of circulating water in the condenser and the rest of the circuit. Considerable effort by the modeler was required in the work of Ref 4 in using the older GT4 version in order to account for these items.

Tube-side water velocity changes as the flow rate changes, and as the number of active tubes changes. As in the previous paper, the calculation of the flow of circulating water depends on accounting for the pressure drop through the condenser's tube side (as well as the other piping in the circulating water circuit) and for the pressure head of the pump. Both of these are affected by the flow rate.

Basically, a unique flow rate occurs, such that the pump's head overcomes the pressure drop in the system, as well as any elevation head changes. The need for this balance forms the basis of calculating the water flow rate. Therefore, good representations of the pump's head curve versus flow and the system's pressure drop are needed. The pump curve is obtainable from the pump's vendor. The pressure drop in the system depends on the details of the system and on the flow rate. The following sections present the development of the pressure drop equations that are programmed in PEPSE for this accounting.

Analyzing Flow and Pressure Drops

A hydraulic flow circuit is used to analyze flow and pressures throughout the circulating water system.



The flow circuit includes piping, suction from a water source, the pump, the condenser, and the receiving sink. Pressure and elevation must be known at the source and at the receiver.

PEPSE has the capability to calculate pressures throughout this flow circuit. The method uses the head characteristic (curve) for the pump and the standard principles of fluid mechanics (for example, see Ref 5) for each of the flow paths in the circuit. A PEPSE submodel for this purpose is

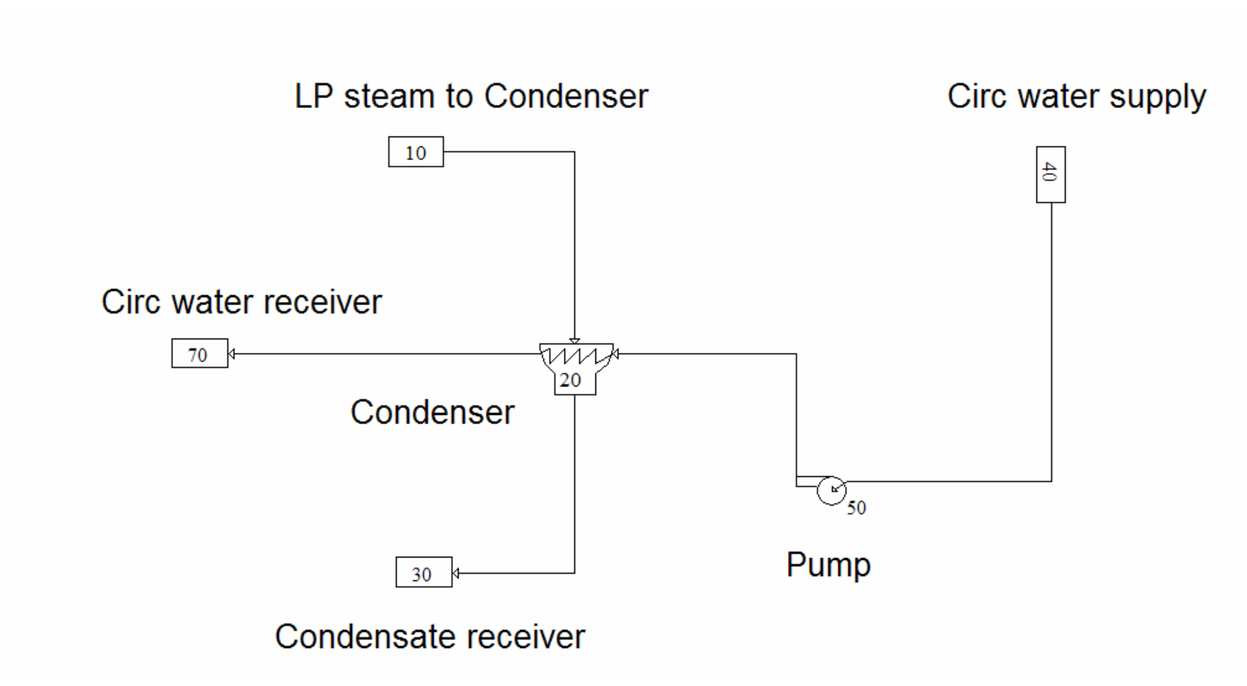


Figure 1 - Condenser Submodel for Tube-Plugging

Development of Equations

The development of equations for calculating pressure and flow effects require many engineering assumptions. Important among these are:

1. All of the assumptions that go into the derivation of the "modified Bernoulli equation". See Ref 5, pgs 339-370.
2. Constant density, "incompressible", flow.
3. Flow in the tubes is uniform, that is, equal velocity in all tubes.
4. Tubes and pipes are long enough to attain fully developed flow.

The basic equations applied for each pipe and for the condenser are:

$$\left(\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + z_1\right) - \left(\frac{p_2}{\rho g} + \frac{V_2^2}{2g} + z_2\right) = \frac{h_\ell}{g} \tag{1}$$

and

$$\frac{h_\ell}{g} = \left(f\frac{\ell}{d} + K \right)\frac{V^2}{2g} \tag{2}$$

where

p is pressure
ρ is density of the water
g is the acceleration of gravity
V is the velocity of the water
z is the elevation, defined positive upward
h_ℓ is the "head loss" due to pipe friction and form losses (also called "minor losses")
f is the pipe-wall friction factor (obtained from Moody chart, see Ref. 5, programmed in PEPSE)
ℓ is the length of pipe or tube
d is the inside diameter of pipe or tube
K is the form loss factor, characteristic of the elbow, contraction, valve, and so forth

subscripts

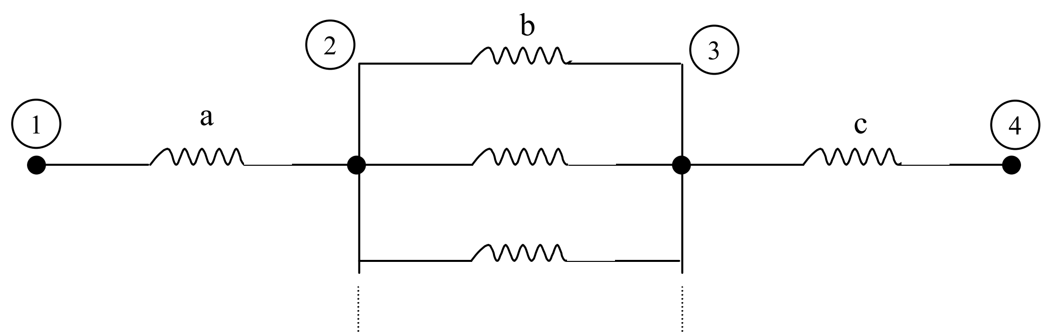
1 is at the inlet of the item analyzed
2 is at the outlet of the item analyzed

These equations are in common usage for calculating pressure drops from one point to another in flow circuits. In the example above, the equations apply for each of the connection lines between components, via PEPSE's Type 1 stream tool. In addition the equations apply to the tube-side flow through the condenser itself, and they are programmed for use with the HEI mode of condenser calculations.

More needs to be said here about the K factor above, representing form loss, also called minor loss. The standard hydraulics literature, e.g. Ref 5, includes tabulations of K factors for many flow devices, such as flow bends, tees, valves, sudden contractions, sudden expansions, and others. It is important to realize that the K factor and the velocity, V, used in calculating minor head loss must be consistent. Typically this velocity is taken at the location of the loss, e.g. at a contraction. For calculations of losses in the condenser, it is not convenient to be required to use local velocities, e.g. at the nozzle entering the water box. For greater convenience, equations are developed here, wherein all of the condenser's form losses and the line losses to and from the condenser are related to the velocity of the water inside of the tubes of the condenser. In this development, accounting is made of the effect of tube plugging.

In the condenser there are several locations of form losses, including entrances and exits to/from the water boxes, entrances and exits to/from the tubes, changes of flow direction, and others. Each of these has its local K factor and its local velocity. As developed below, PEPSE provides for an equivalent form loss, K_{misc}, factor to account for all of these effects in a single term that is related to the water velocity in the tubes.

The following flow schematic for the flow of circulating water through the condenser illustrates key points in this development:



The pressure loss items are as follows:

- a represents the form loss in the inlet piping including pump intake and at water box entrance, approaching nearly to the entrance of the tubes
- b represents each of the parallel tubes with its wall friction loss and the form losses at its entrance and exit
- c represents the exit losses from the water box, near the tube exit through the exit nozzle and including piping to the discharge to atmosphere

The condenser's overall tube-side pressure drop (the product of density and h_ℓ) due to wall friction and form loss is the sum of the losses for these items in series:

$$PD_{hl} = PD_{hla} + PD_{hlb} + PD_{hlc} \tag{3}$$

$$PD_{h\ell} = \frac{\rho}{2}\left[K_a V_a^2 + \left(f_b \frac{\ell_b}{d_b} + K_b\right) V_b^2 + K_c V_c^2\right] \tag{4}$$

Now, using the conservation of mass

$$w = \rho \mathrm{AV} = \rho_\mathrm{a} \mathrm{A_a V_a} = \rho \mathrm{A_b V_b} = \rho \mathrm{A_c V_c} \tag{5}$$

where

A is cross sectional flow area at each loss
A_b is the sum of cross sectional areas of all tubes

Substituting in Eq(2) for V_a and V_c

$$V_a = \frac{A_b}{A_a} V_b \tag{6}$$

$$V_c = \frac{A_b}{A_c} V_b \tag{7}$$

$$PD_{h\ell} = \frac{\rho V_b^2}{2}\left\{\left[K_a\left(\frac{A_b}{A_a}\right)^2 + K_c\left(\frac{A_b}{A_c}\right)^2\right] + \left[f_b \frac{\ell_b}{d_b} + K_b\right]\right\} \tag{8}$$

The first bracketed term [] in the equation above accounts for the condenser's and piping's miscellaneous form losses, and the second term accounts for the losses associated directly with the tubes. As the number of plugged tubes changes, the flow area A_b changes, and thus the miscellaneous losses term changes. At any amount of plugging

$$A_b = \frac{N}{N_{np}} A_{b\,np} \tag{9}$$

where

N is the number of active tubes
N_{np} is the number of tubes with none plugged
A_{bnp} is the total cross sectional flow area of all tubes with none plugged

Using this equation, the pressure loss equation becomes

$$PD_{hl} = \frac{\rho V_b^2}{2} \left\{ \left(\frac{N}{N_{np}} \right)^2 \left[K_a \left(\frac{A_{bnp}}{A_a} \right)^2 + K_c \left(\frac{A_{bnp}}{A_c} \right)^2 \right] + \left[f_b \frac{\ell_b}{d_b} + K_b \right] \right\} \tag{10}$$

The first bracketed term [] is constant, that will be called K_{misc}. It accounts for the miscellaneous form losses at the condition when there are no plugged tubes. Note that, for the case of no plugged tubes, K_{misc} is the equivalent loss factor for the miscellaneous losses, based on use of the water velocity in the tubes.

Finally we have for the head loss pressure drop throughout the circulating water circuit the equation that is useful for computations:

$$K_{misc} = \left[K_a \left(\frac{A_{bnp}}{A_a} \right)^2 + K_c \left(\frac{A_{bnp}}{A_c} \right)^2 \right] \tag{11}$$

$$PD_{hl} = \frac{\rho V_b^2}{2} \left[\left(f_b \frac{\ell_b}{d_b} + K_b \right) + \left(\frac{N}{N_{np}} \right)^2 K_{misc} \right] \tag{12}$$

In the equation above, the term with the b subscripts accounts for the tubes' entrance and exit head losses and for the tubes' wall friction pressure losses. The other term accounts for all of the other, miscellaneous, losses. The latter term changes as the number of active tubes changes.

To understand this changing term, consider a pair of example applications. The first has all tubes active. The second has half of the tubes active (half are plugged). For discussion, consider that the velocity, V_b, is constant from one case to the other. In the two examples, the losses at the tubes are the same because the velocity is the same. But the inlet nozzle losses, turning losses, exit nozzle losses and other miscellaneous losses do change from one case to the other. In fact, the velocities at these other locations reduce by a factor of two (half the tubes at the same velocity, cuts the flow in half). Because these miscellaneous losses are proportional to their local (halved) velocities, and since the velocity term is squared, the miscellaneous losses would reduce by a factor of four. This is easily understood, and it is accurately accounted for by the computing equation above. This discussion should give us confidence that our formulation is correct.

The PD_{hl} result above can be inserted into the general equation for a hydraulic circuit, Eq (1), resulting in the overall computing equation below. This equation is programmed in PEPSE to account for pressure changes from inlet to outlet of the condenser. In application of this equation, the inlet nozzle and outlet nozzle total areas are equal, or nearly so, and this eliminates the velocity-squared kinetic energy terms in the equation.

$$p_{\mathrm{in}} - p_{\mathrm{out}} = \rho g \left(z_{\mathrm{out}} - z_{\mathrm{in}} \right) + \rho \left(\frac{V_{out}^2}{2} - \frac{V_{in}^2}{2} \right) + \frac{\rho V_{\mathrm{tube}}^2}{2} \left[\left(f_{tube} \frac{\ell_{tube}}{d_{tube}} + K_{tube} \right) + \left(\frac{N}{N_{NP}} \right)^2 K_{misc} \right] \tag{13}$$

Then, in applying this equation to account for pressure losses in the condenser's tube side, the challenge is to obtain values for the K's.

Reasonable values of the K factors for the tube entrance and exit losses are 0.34 and 1.0, respectively. We can add these together to give $K_b = 1.34$. Note that condensers with multiple water boxes and multiple passes of tubes would need to use a multiple of this value.

Considering the variability of construction of condensers and the complexity of the circ water flow path, it is not practical to provide a theoretical value of K_{misc}. It would be better to "calibrate" this K by using the computing equation above at a known "reference" condition. There are two possibilities:

1. With known (measured) change of pressure from inlet to outlet and known the flow rate, use the equation to solve for the K_{misc}.

2. Imbed the condenser in the submodel, accounting for all of the circulating water circuit's elevations, the pump's head curve, and all of the piping losses. Use a PEPSE control to adjust K_{misc} to obtain the known pressure at the outlet of the circuit.

THE ANALYSIS TOOL

The latest development version (V69/GT) of PEPSE has been used to run these analyses. Included in this version are the automatic calculations of pressure drop from the tube side inlet to the tube side outlet of the condenser. Inputs are available to allow specifications of elevations, tube K factors and the miscellaneous K factor. Also included in this version as a new feature is the option to specify the fraction or the number of tubes that are plugged. The analyses use the "sensitivity study" feature to quickly and easily run a stack of cases and to show the effects of tube plugging over a selected range. It is possible to run these analyses using older versions. To do so would necessitate doing manual setup of the pressure drop calculations and to specify, literally for each case, individual settings of each value of the tube plugging quantity and running individual cases with these values. Most of these details are discussed in Ref 4. Release of the new version is planned for August, 2004. Also included in V69/GT is Special Option Number 12, which guides you through the data specifications to automate the hydraulic balance that determines circulating water flow rate.

In the model it is important to avoid double-accounting the pressure losses at miscellaneous locations away from the condenser. As developed above, the miscellaneous losses are represented by the Kmisc term at the condenser. When the model is created, these losses should not also be accounted in the several streams between the ultimate source and the ultimate receiver of the circulating water flow. Note that active streams are needed in some parts of the model where elevation head is to be accounted, but these streams should be defined so as to have minimal/zero wall friction and form losses of pressure.

ASSUMPTIONS in Use of the Models

1. HEI method is a good characterization of condenser thermal performance. This includes use of the 5 °F TTD limit, per guidance of HEI.

2. Pump head versus flow curve is a good characterization of the pump's behavior.

3. In the example used here, the circulating water discharges at the elevation of the surface of the circulating water supply. Thus the system is conservative, relative to elevation head. For circulating water systems where the discharge is at a different elevation, e.g. into a cooling tower, the elevation differential can be accounted for easily.

4. The pump draws its circulating water supply from a reservoir at atmospheric pressure, which is assumed to be 14.7 psia.

5. The condenser piping system discharges the circulating water to atmospheric pressure at the same elevation as the intake.

6. The equations above accurately represent the pressure drop through each of the parts of the flow network. The wall friction portion of the head loss is accounted for by the use of the friction factor. Curves of friction factor versus Reynolds number and versus tube roughness are programmed in PEPSE.

7. In the submodel application, it is adequate to maintain a "typical" shell steam side inlet flow rate and thermodynamic condition. In the system model, this assumption is not needed, because the flow rate and condition of steam adjust as changes occur in the condenser itself and throughout the turbine cycle.

SUBMODEL FOR PARAMETRIC ANALYSIS OF CONDENSER

A submodel has been developed using the graphics interface program (MMI) for PEPSE. The model demonstrates the analysis of the condenser in combination with the circulating water pump. The data for this model are illustrative. While the data may be close, they do not necessarily exactly match any existing system. The schematic for this submodel is shown above in Figure 1. The input data file for this model, shown in Table 1 of Appendix A, presents a concise summary of the data inputs to the PEPSE calculation. Refer to PEPSE Manual Volume 1, Ref 2 in order to interpret the data.

As seen in Figure 1 and fully documented in Table 1, the source component with ID = 40 provides the circulating water to the pump. The flow source is at the surface of the circulating water supply (reservoir, lake, river, or ocean) at atmospheric pressure. The pump's intake centerline is located 10 feet below the surface. This elevation difference is accounted in the Type 1 stream that connects the source component to the pump.
As discussed above, several scenarios have been run:

1. Constant circulating water flow rate
2. Constant water velocity in tubes
3. Circulating water circuit hydraulically balanced, varying flow rate, K_{misc} not used
4. Circulating water circuit hydraulically balanced, varying flow rate, K_{misc} used

Scenario 3 above is similar to the "hydraulically balanced" analysis case that was included in Ref 4. You can refer to Eq (11) above, wherein K_b = 13.28 and K_{misc} is set to zero for this scenario. Scenario 4 above uses K_b = 2.68 (= 2 X 1 + 2 X .34 for a 2-pass condenser) and K_{misc} = 10.64 (tuned at the design point). At the design point (no tubes plugged), all four scenarios give the same circulating water flow rate, tube velocity, and condenser pressure.

The control shown in Table 1, line sequence counter 840100, calculates the hydraulic balance point by adjusting the circulating water flow rate at its source component until the calculated discharge pressure (at the receiving reservoir) equals atmospheric pressure. To run the fixed flow case, a "DELETE" command is placed on this control. To run the constant velocity case, a control is used to adjust source component's flow rate until the condenser's tube-side velocity variable, TVELC, equals the selected value (the velocity in the tubes at the design point, no tube-plugging).

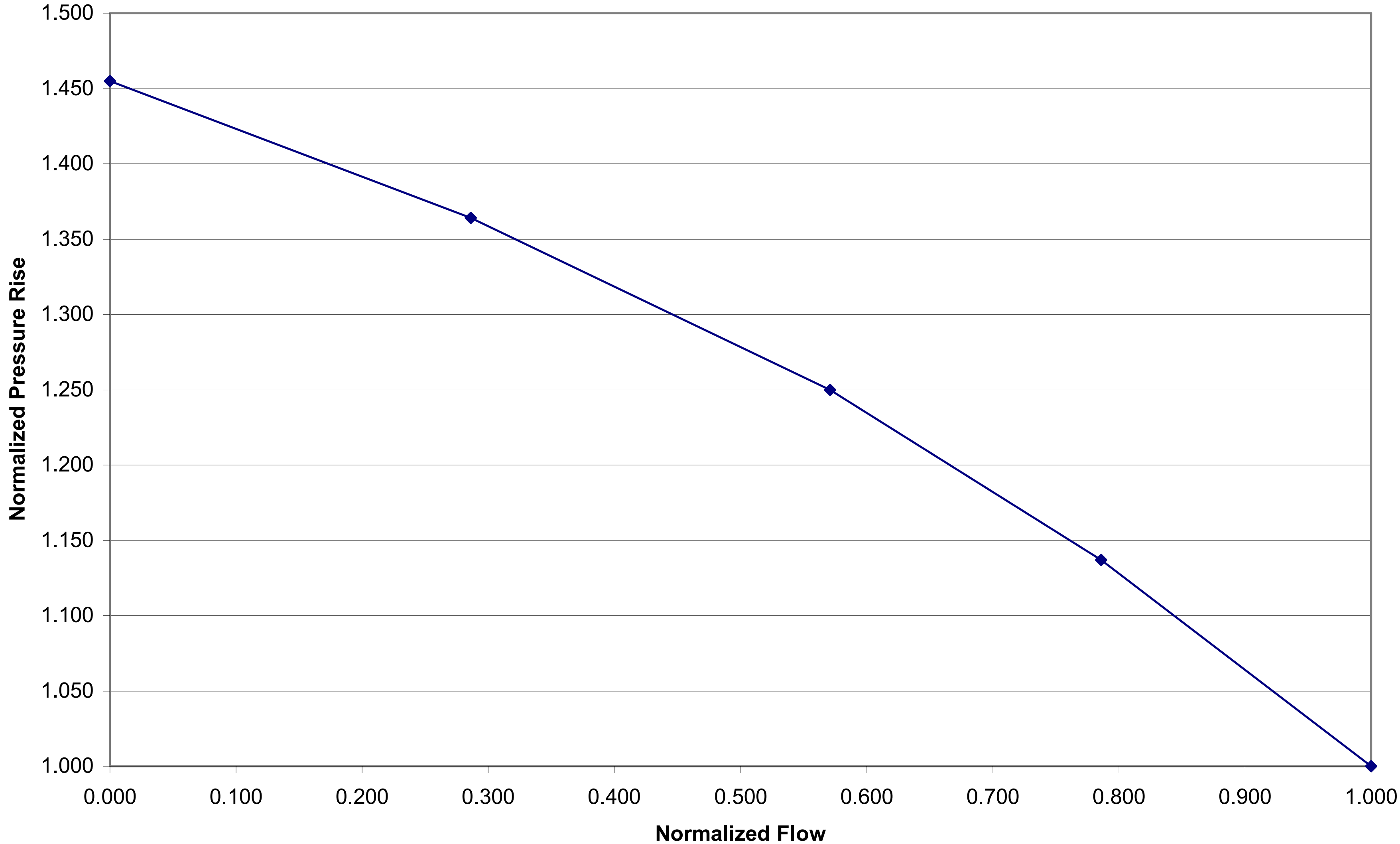
The Type 1 and Type 7 streams in the model have been defined to account for elevation changes in the system only. By artificially setting large stream diameters and short lengths, the wall friction pressure drops in these lines have not been accounted explicitly at the streams. Instead, these pressure drops have all been accumulated in the condenser's K_{misc} term (by the method of tuning at the design point). Finally, the "velocity head" (kinetic energy) at the discharge from the system is lost, and this is also accounted in the tuned K_{misc} term. Examination of the derivation of the equations in a preceding section will verify that these are valid ways of addressing these pressure effects.

In this study, the fraction of tubes plugged, PLGFC1, is used for the tube plugging study. The total number of tubes in the as-designed condenser is 36,374.

The input data for the condenser, component 20, specify a "cleanliness factor" of 85%. This conservatism is used consistently throughout the analyses. Qualitatively, the conclusions of this study would not change if the factor were 100%. It is easy to verify this assertion by changing the input 0.85 to a 1.0 and repeating the run.

Figure 2 shows the curve of normalized pump pressure rise (“head”) as a function of normalized flow rate. A schedule has been used to input this curve to the analysis. The head curve is illustrative, having been extracted and normalized from related applications. This was necessary because the source of information about the condenser provided no pump description. In a real application, it is important to represent the actual pump head curve accurately, and in such a case, it would not be necessary to normalize the curve. The schedule could simply tabulate the head, variable PHEAD, directly.

Figure 2. Normalized Circulating Water Pump Curve



In order to quantify the behavior of the condenser over the range of tube plugging, a sequence of cases was run at discrete values of tube plugging from zero to 50 percent. While it may not be practical to operate up to this amount of plugging, the results highlight the significant difference between constant flow and variable flow rate analysis approaches.

The "sensitivity study feature" of PEPSE was used to create the sequence of cases automatically. To use this feature, in the first case the modeler specifies a starting value of the independent variable x (tube plugging fraction in this case), the number of cases to be run, and the ending value of the independent variable. From this, PEPSE develops all of the other cases in the sequence. In addition, the user provides a list of the dependent variables of interest. In the present case, the dependent variables selected are condenser pressure, circulating water flow, and others. This listing is found in the Table 1 input data file, on the line ID's that start with 93.

The independent variable is the fraction of tubes plugged, which is specified to PEPSE by the input variable, PLGFC1.

Once set up as described, the model is easy to use and to modify for custom or exploratory calculations.

THE RESULTS OF THE ANALYSES USING THE SUBMODEL

Selected results of the sensitivity study for the scenarios are plotted in Figure 3a, b, c, and d.

Figure 3a. Condenser Submodel Shell Pressure Comparison

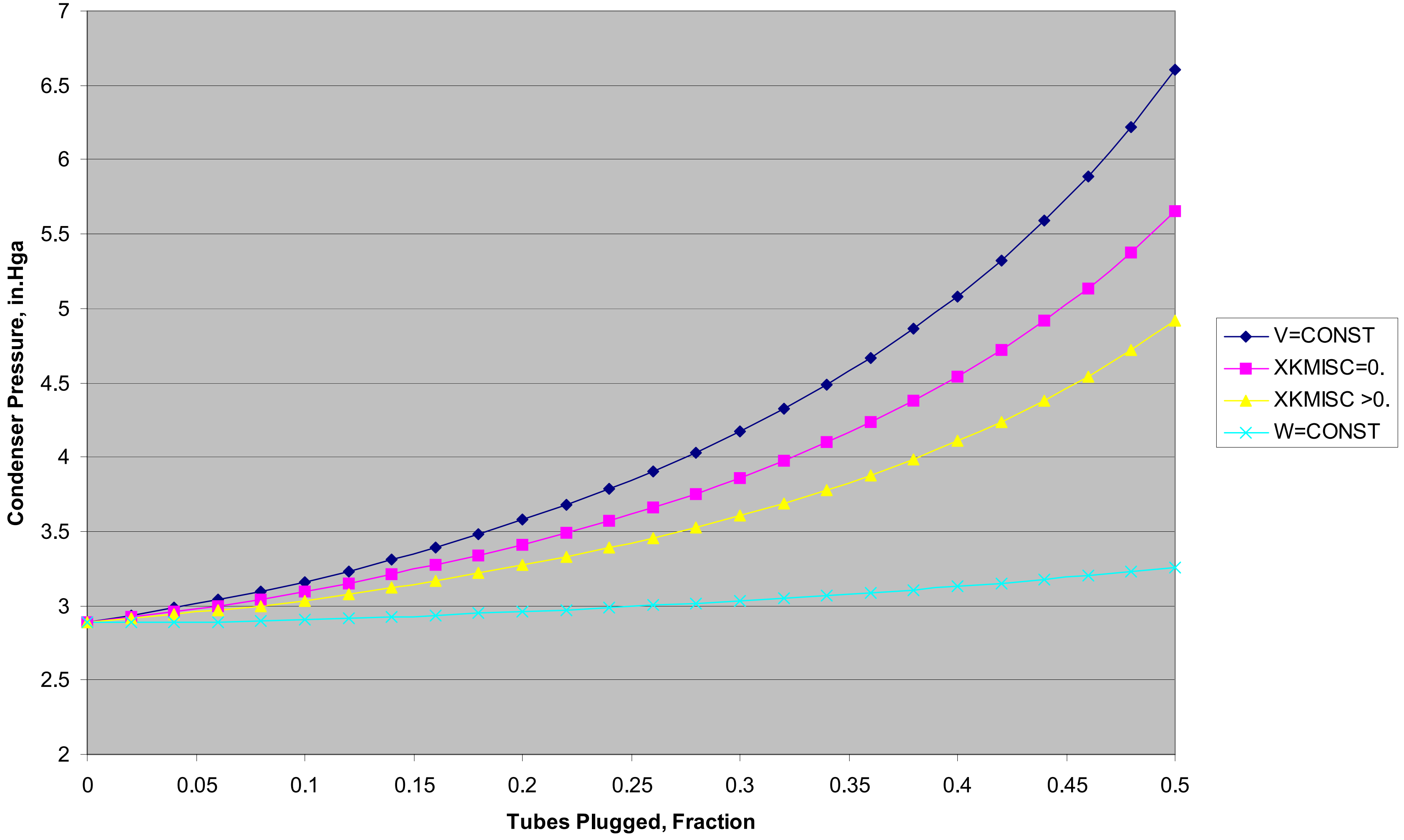


Figure 3b. Condenser Submodel Circulating Water Flow Rate

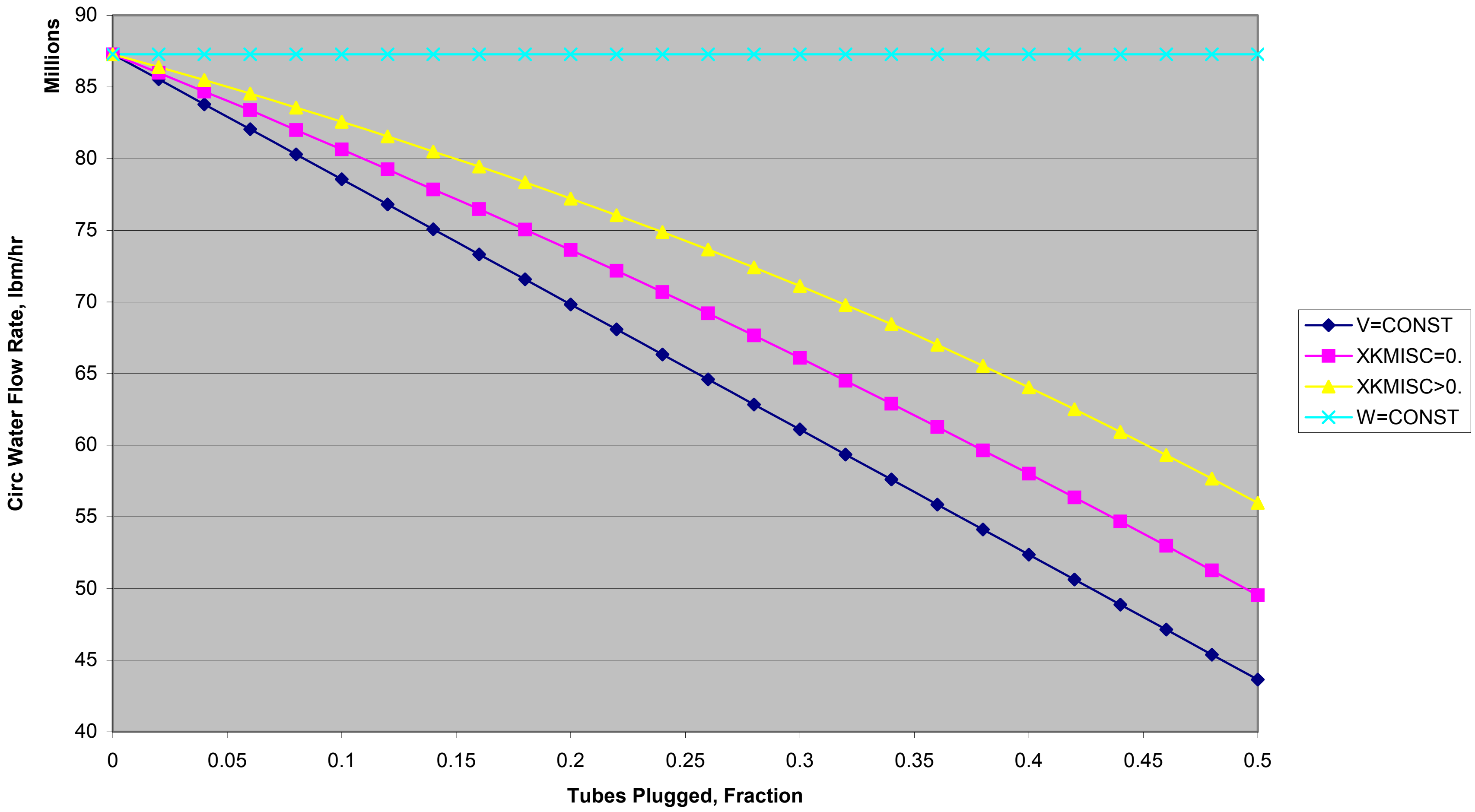


Figure 3c. Condenser Submodel Tube Side Pressure Drop

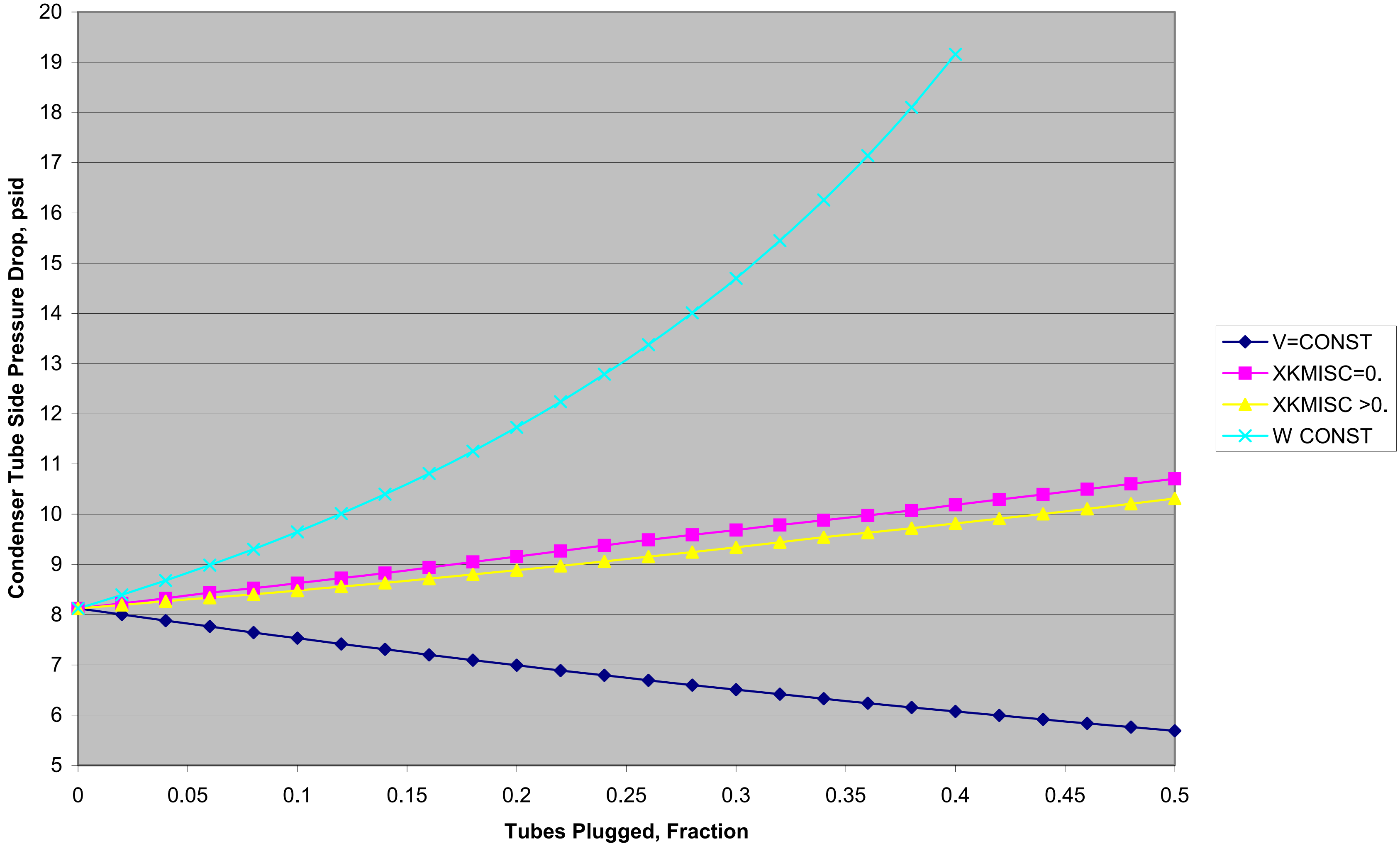
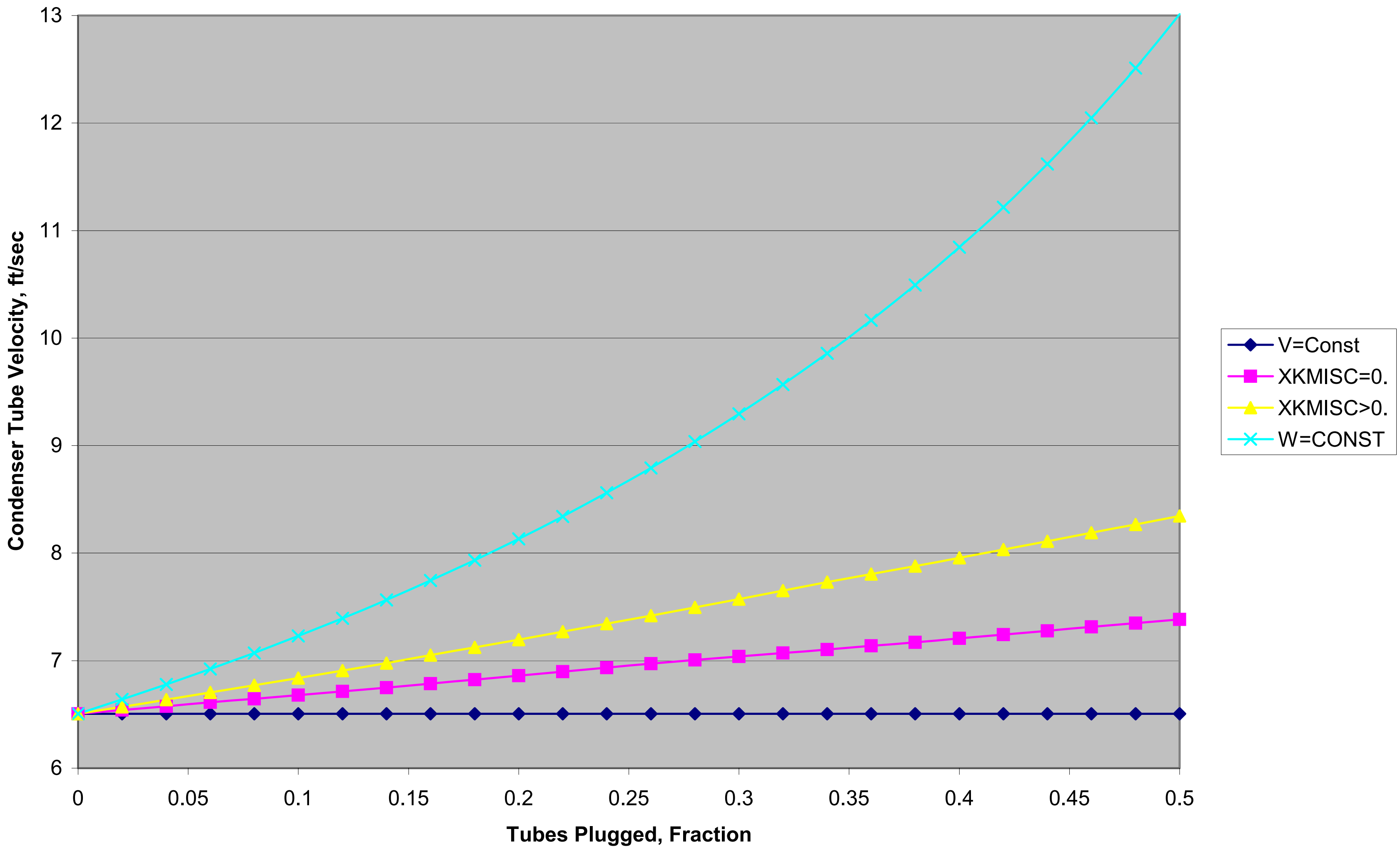


Figure 3d. Condenser Submodel Tube Velocity



The complete detailed results for the hydraulically balanced scenario number 4, as extracted from a full PEPSE output, are shown in Table 2 of Appendix A. A similar set of output occurred for the other three scenarios, but those results are not tabulated here. In the figures we see the condenser's equilibrium shell pressure plotted versus the fraction of tubes plugged. Also plotted are the circulating water flow rate, the condenser component's tube-side pressure drop, and the velocity of the water through the tubes. All cases have been developed based on the same flow rate at the design, no-tubes-plugged condition.

There are substantial differences among the curves for the several scenarios. This indicates that the choice of assumption about circulating water flow rate has an important impact on the results of analyses. For example, over the full range of plugging, the shell pressure, in the fixed flow scenario shows relatively little variation, ranging from about 2.9 in. Hga to about 3.25 in. Hga. In contrast, in the hydraulically balanced scenario (K_{misc} = 0.), the shell pressure varies considerably more, from 2.9 in. Hga to 5.7 in. Hga. This is the same scenario as the one reported in Ref 4. For the hydraulically balanced scenario (K_{misc} > 0.0), the shell pressure curve lies between the constant flow scenario and the other balanced scenario. Notice that the scenario with the assumed constant tube velocity shows the largest effect on shell pressure as the fraction of plugged tubes increases.

The results of the hydraulically balanced case with K_{misc} > 0.0 are preferred over the others that are plotted. The assumptions in this scenario include accounting for diminishing form loss pressure drops, as plugging increases, at the condenser's inlet and outlet nozzles and other locations remote from the tubes. Review Eq (12) to see this effect.
The tube-side pressure drop and the circulating water flow rate are nearly linear with fractional tube plugging over the range considered. Notice that the tube-side pressure drop is a very steep function of tube-plugging for the fixed flow scenario. Indeed the detailed run results reveal that the calculated tube-side pressure drop is so large, above 0.40 fractional plugging, that the discharge pressure would be driven to negative absolute pressure, which is not physically possible. PEPSE resets the pressure drop to zero for these two cases and goes on.

We can conclude that careful representation of the circulating water flow rate appears to be important, at least for condenser pressure and other parameters specific to the condenser, as the amount of tube plugging changes. The hydraulically balanced scenario (K_{misc} > 0.0), with the flow being proportional to the number of open tubes, is more realistic than the fixed flow scenario.

For a related study, Appendix C shows some results calculated using the submodel for a case where there is a shift of the elevation of the surface of the circulating water's supply reservoir. Such shifts may occur as river, lake, or ocean levels change. The elevation is seen to have appreciable effects on the condenser's performance.

STEAM TURBINE RANKINE CYCLE MODEL INCLUDING THE HEI MODE CONDENSER

A PEPSE model of a representative “fossil” steam turbine Rankine cycle has been developed to demonstrate the application of the HEI model in the context of a real system’s simulation and to examine the effects of the circulating water flow rate assumptions. Thereby the impact on power generation can be assessed. This is a single-reheat system that generates approximately 600 MW of gross electrical power. The PEPSE schematic of the turbine-generator system is shown in Figure 4. The input data are shown concisely via the input data file in Table 3 of Appendix B.

The condenser, component 11, is specified in HEI mode for the actual condenser in this unit. It is not the same condenser as the one used in the earlier submodel. Nevertheless, the schematic representation and the logic of the modeling setup are the same as those in the submodel. Thus, the discussion of the details of the setup is abbreviated here. See the discussion above on the submodel.

The circulating water source is component 31 and the circulating water pump is component 603. The curve of normalized pump head versus normalized circulating water flow rate is the same as the one used for the submodel and presented in Figure 2. This curve is specific to this unit, and the absolute levels match the actual pump head curve for the pump used in this cycle.

The logic and the setup of the special features - schedules, operations, control, and the sensitivity study feature - is similar to the setup in the submodel discussed above.

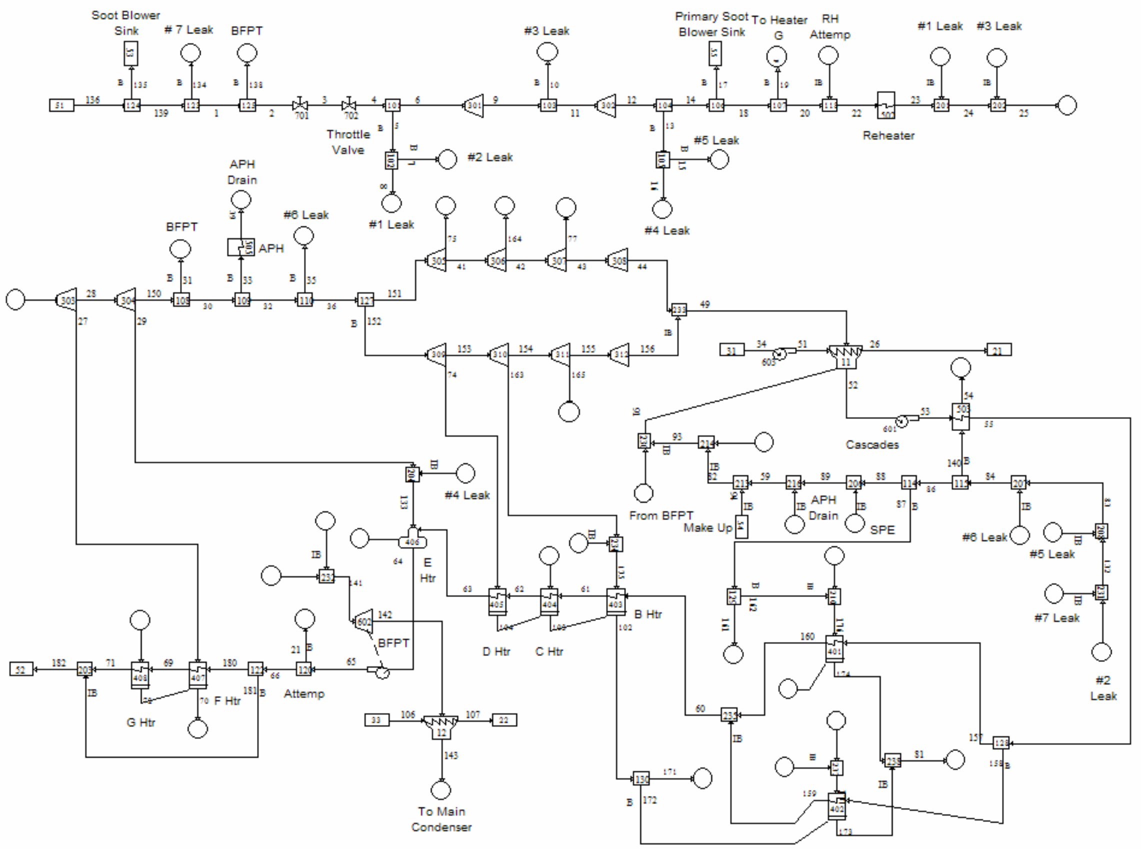


Figure 4. Single Reheat Fossil Steam Turbine Cycle For Analysis Of Tube Plugging Effect On System Performance

THE RESULTS OF THE ANALYSES USING THE SYSTEM MODEL

As for the submodel, the tube plugging study covered a range from zero to 50 percent plugged. Three scenarios were analyzed. These were the fixed flow and the two hydraulically balanced scenarios, one with all of the form loss assigned to the tubes (XKMISC = 0.0) and the other with the K for the tubes taken for two passes and the balance of the K placed in XKMISC>0.0. The system performance was analyzed at full electrical load. So, three separate sensitivity analysis runs were made with this model.

Selected results of the sensitivity study for the hydraulically balanced scenario (with XKMISC>0.0) at full load are shown in Figure 5a and 5b and summarized completely in Table 4 of Appendix B, as extracted from a full PEPSE output. A similar set of output occurred for the XKMISC=0.0 scenario and for the fixed flow scenario, but those results are not tabulated in the Appendix.

Figure 5a. System Gross Power Generation vs Condenser Tube Plugging

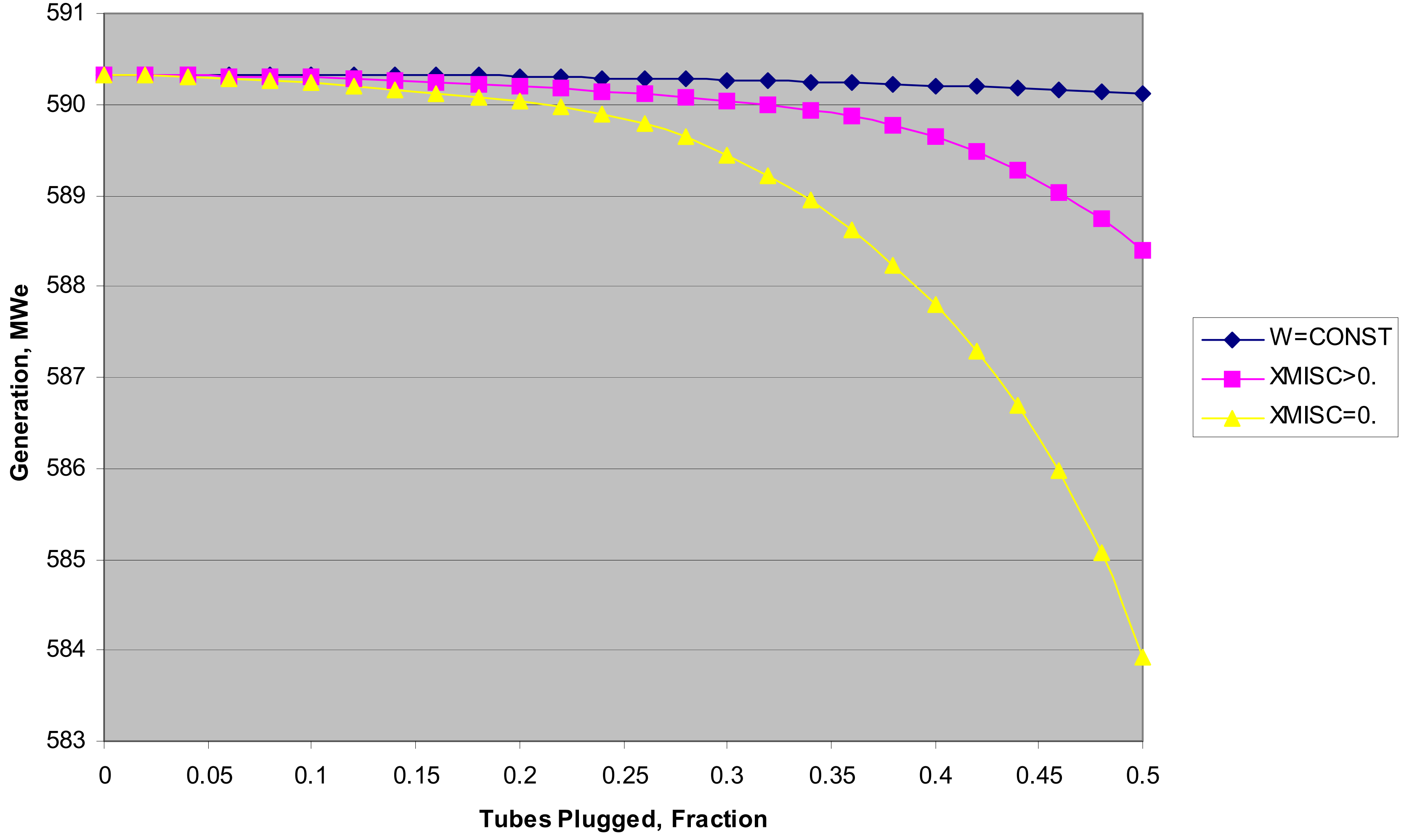
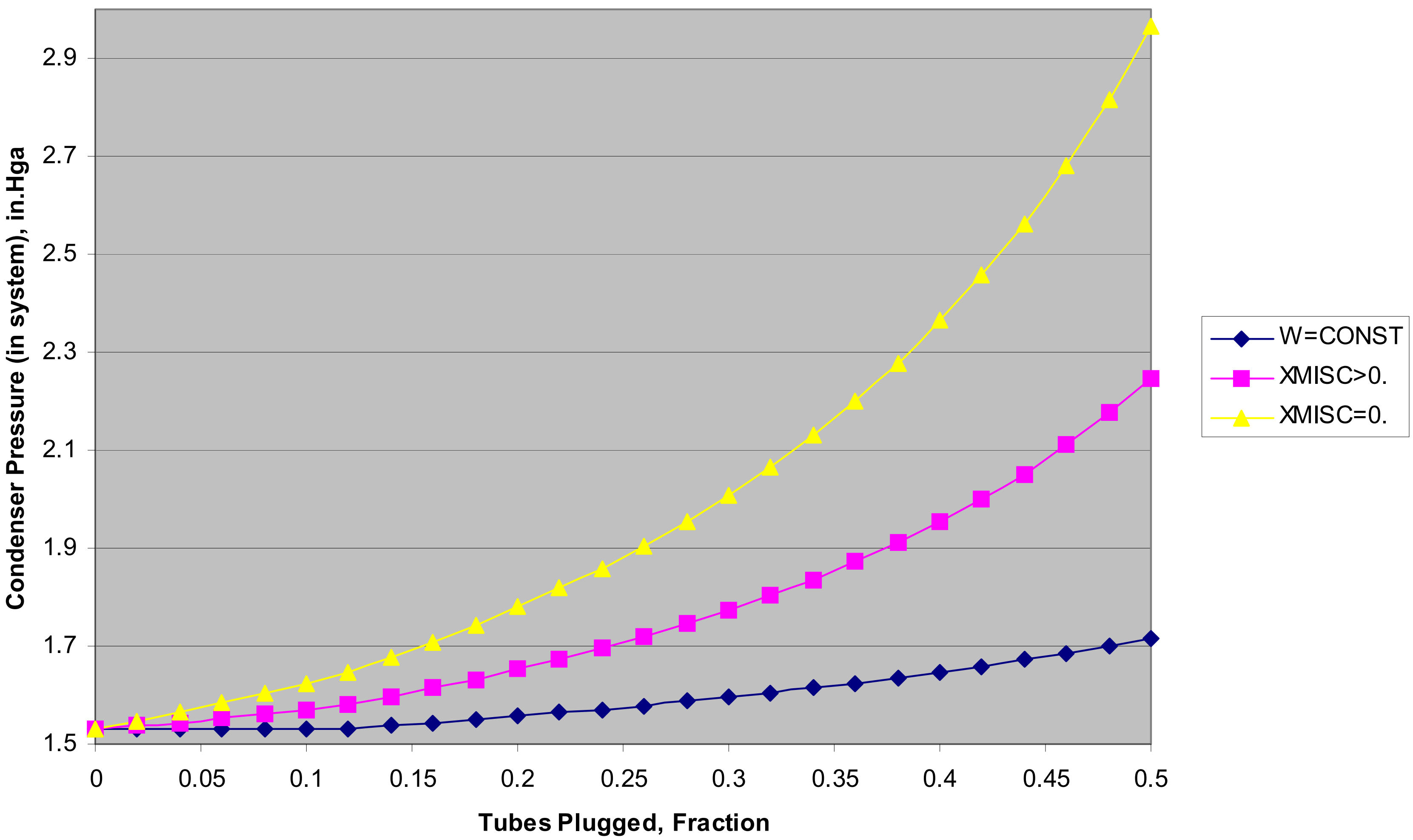


Figure 5b. Condenser Pressure (in system) vs Plugging



In Figure 5b we see the condenser's equilibrium shell pressure plotted versus the fraction of tubes plugged. As was true for the submodel results, the most striking features of the results in Figure 5 are the significant differences among the curves of condenser results for the fixed flow and the hydraulically balanced scenarios. It is important to observe that, while the condenser shell pressure curve for the system model looks very similar to that from the submodel, the overall range of the pressure for the same range of plugging, is smaller than the one from the submodel in Figure 3. The difference between the two models occurs because, as stated above, the condensers are not the same. We could expect that, if the range of pressure had been the same, the calculated power would have shown a larger range also.

The calculated power generation shown in Figure 5a changed scarcely at all for the entire range of tube plugging in the fixed flow scenario. The power changed a small amount for the hydraulically balanced scenario up to about mid-range in the tube plugging study.

The detailed results show that the calculated condenser pressure, for plugging fractions from 0.0 to 0.1, in the system analyses has been overruled by the 5°F limitation of the HEI. This supersedes the "pure thermal" value calculated by the HEI method. See Reference 1 for further discussion of this point.

From the results for both the submodel and the turbine cycle system, we can observe that assumptions made about the flow rate of circulating water have an important impact on the results of analyses. Notable differences appear between the scenarios where flow rate is adjusted versus the scenario where flow rate is maintained at a constant value. We advocate adjustment of the flow rate through use of the hydraulic balance between the circulating water pump's head curve and the pressure drops through the remainder of the circulating water circuit. Viewing the curves also shows that there can be substantial differences in the results from hydraulic balancing, depending on the division of the head loss between those associated directly with tubes and those for other miscellaneous items in the system. Indeed, care is needed to address the impact of elevation pressure changes in order to obtain reliable results.

SUMMARY

The HEI method of calculating condenser pressure, as programmed in PEPSE, has been used to analyze the effect of tube plugging on condenser pressure. The new Version 69/GT capabilities for calculating tube-side pressure drop and for accounting for tube plugging are convenient tools in these analyses. Furthermore, Special Option Number 12 provides a very convenient template for specifying the details of hydraulic balancing to calculate flow.

Several different scenarios have been used to account for the circulating water flow rate. First, the flow rate has been held fixed over the range of tube plugging. Second and third, the circulating water flow rate has been calculated by balancing the pump's head against the hydraulic pressure drop through the tubes, the headers, and the piping of the condenser. In the second scenario, the miscellaneous form losses are explicitly accounted in the term XKMISC>0.0 for the condenser; this is the advocated method of representing circulating water flow rate variations. In the third scenario, the total form loss factor was held fixed, in the term

XKTOOB (no reduction occurs in the inlet and outlet nozzle pressure drop losses as the number of tubes increases), and the XKMISC term was set to zero. This third scenario is similar to the hydraulic balancing scenario that was used in Ref 4. In both hydraulic balancing scenarios, the flow rate reduces as the tube plugging increases and the tube-side pressure drop increases. The fourth scenario maintained a fixed velocity through the tubes as the tubes were plugged. Thus this scenario also involved reduction of total circulating water flow rate as more tubes were plugged. Significant differences occur among the calculated results for the several scenarios.

CONCLUSIONS

It is easy to run PEPSE using the HEI method of calculating condenser performance. The results of this study, using the HEI method, show that accounting for the variation of the circulating water flow rate as tubes of the condenser are plugged has a significant impact on the calculated condenser pressure and tube flow velocity. The specific dependence of condenser pressure on the tube plugging is affected by different assumptions that can be made about this flow rate. However in the analysis, it is necessary to approach considerable and impractical levels of tube plugging before there is a large effect on the turbine cycle's calculated electrical power. In the example model used, at 50 percent plugging, the system power generation has reduced by only 1 percent in the example model.

Four different scenarios have been investigated, covering a range of circulating water flow rate assumptions when analyzing performance effects of tube plugging. These scenarios range from assuming the flow is fixed, to assuming the flow adjusts to attain a hydraulic pressure balance between losses (two different form loss cases) and pump head, to assuming the flow adjusts to maintain a fixed velocity of flow in the tubes of the condenser. The results show that the calculated magnitude of the impact on condenser pressure is least for the fixed flow scenario and greatest for the fixed tube velocity scenario, with the two hydraulically balanced cases falling between these extremes.

The advocated method of analysis uses the hydraulic balancing method of calculating circulating water flow rate. It is important to accurately represent the details of this model, accounting for elevations, for the tube wall friction head loss for the tube entry and exit head losses (for as many tube passes as there are in the condenser) and for the other/miscellaneous minor head losses of pressure in the circulating water circuit. Also, the pump's head curve versus flow rate needs to be scheduled. In order to obtain the K factor for the miscellaneous form losses, it is recommended that an initial calibration run be made (using a PEPSE control) at a fixed/specified circulating water flow rate (either measured or design value).

This study has shown that flow rate of circulating water plays an important role in obtaining reliable results from analysis. This is true for tube plugging. It is also reasonable to conclude that analyses of retubing should consider the hydraulic balance in order to properly represent the role of flow rate. Factors affecting flow rate in retubing studies would be changes of numbers of tubes, changes of inside diameter, changes of length, changes of number of passes, changes of intake and exhaust piping, and changes of surface roughness.

Due to aging of the condenser, pipe lines, and pump, and due to variations of accumulated debris in the pump intake, the results of this design-based study may not match the absolute level of real-world performance on a given day. However, the change of performance predicted in comparing the effect of one amount of tube plugging to another should be reliable.

REFERENCES

1. Standards for Steam Surface Condensers, Ninth Edition, Heat Exchange Institute Incorporated, Cleveland, Ohio, 1995.
2. Minner, et al, User Input Description, PEPSE, PEPSE Manual Volume I, 2004, Idaho Falls, Idaho, 2004.
3. Minner, et al., Engineering Model Description, PEPSE Manual Volume II, Idaho Falls, Idaho, 2004.
4. Minner and Feigl, "Calculations of Condenser Performance Using PEPSE", Proceedings of the 2000 Performance Software User's Group Meeting", Idaho Falls, Idaho, June 20-22, 2000.
5. Fox and McDonald, Introduction to Fluid Mechanics, John Wiley and Sons, Inc., NY, 1973.
6. ASME Steam Properties for Industrial Use, Based on IAPWS-IF97, Professional Version, The American Society of Mechanical Engineers, ASME Press, NY, 1998.

APPENDIX A – Condenser Submodel Tabulations

This appendix contains tables that document the detailed inputs for the condenser submodel and it provides selected output results.

Table 1 - Input Data File for Condenser Submodel

```
010001  80  PRINT
010101   0.0
*
*       DATE: Monday, May 10, 2004
*       TIME: 7:27 AM
*      MODEL: ugm04HEI.MDL
*    JOB FILE: C:\UGM04\ugm04HEI.job
*
=C:\UGM04\UGM04HEI(SET 1)-Circ water system, base case
*
****************************
*  GENERIC INPUT DATA
*****************************
*
* OUTPUT GLOBAL SUPPRESSION CARD
020000 PRINT    PRINT    NOPRNT
020002 NOPRNT   * Geometry Configuration of Model
020004 NOPRNT   * Stream Properties
020005 NOPRNT   * Comparison of Component Port Test Data With Stream Properties
020015 NOPRNT   * Detailed Mixer Performance Output
020016 NOPRNT   * Detailed Splitter Performance Output
020021 NOPRNT   * Second Law of Thermodynamics Performance - Components
020022 NOPRNT   * Second Law of Thermodynamics Performance - Streams
020023 NOPRNT   * Second Law of Thermodynamics Performance - System
020024 NOPRNT   * Material Descriptions Used in the Model
020025 NOPRNT   * First Law of Thermodynamics Performance - Envelope
020030 NOPRNT   * Warning Table of Stream Closures
020032 NOPRNT   * Input Schedule Number N Table of Values
020033 NOPRNT   * Variable Sets Which Reference Schedules
020034 NOPRNT   * Controls Input
020037 NOPRNT   * Definitions of Special Operations Specified
020059 NOPRNT   * Stream Transport Properties
020078 NOPRNT   * Nonzero Operational Variables
012002    3  2  1  0
*
****************************
*  STREAMS
*****************************
*
500400   40   U      50   I
500100   10   U      20   S
500500   50   U      20   T
500220   20   D      30   I
500200   20   T      70   I
*
* Piping from condenser to circ water discharge
600200   1  1000000. 1.00000000E-006  0.0  0.0  0.0  10.  15.  0.0  0.0  0.0
  +  0.0
```

```
*
* Pump Suction Below Reservoir Surface
600400   7 1.00000000E-006 1.00000000E+009  0.016  0.0  10.  0.0  0.0  0.0
  +  0.0  0.0
*
* Pump Discharge to Condenser Water Box
600500   7 1.00000000E-006 1.00000000E+009  0.016  20.  0.0  0.0  0.0  0.0
  +  0.0  0.0
*
*****************************
*  COMPONENTS
****************************
*
* HEI CONDENSER
700200   10  0  5  0.0  -2.5
700205   2  0.0  0.875  432.  36374.  2  -0.85  1  0.0  18  0
710202   0.0  0.0
*
* Circulating water receiver
700700   30
700702   0
*
* Condensate receiver
700300   30
700302   0
*
* ATMOSPHERIC PRESSURE CIRC WATER SOURCE
700400   31  80.  14.7  87283130.  0.0  0.0  0
700402  0  0  0
*
* STEAM SOURCE TO CONDENSER
700100   31  0.95  1.41  2560000.  0.0  0.0  0
700102  0  0  0
*
* CIRC WATER PUMP
700500   41  25.  0.0  0.0  0.0
700501   0.0  0.0  0.0  0.0  0.0  0.0
700506   0
*
*****************************
*  SPECIAL FEATURES
****************************
*
800100 "NORMALIZED PUMP DP VALUES"
* X VALUES
810100   0.0  0.286  0.571  0.786  1.
* Z AND Y VALUES
810110   0.0  1.455  1.364  1.25  1.137  1.
* MULTIPLIERS
820100    10.3  87283130.  0.0
*
```

```
* VARIABLES FOR PUMP PRESSURE VERSUS FLOW CURVE
830100   1  PDPUM  50  WW  40
830102   0
*
* BASELINE NUMBER OF CONDENSER TUBES
871010   36374.
*
* BASELINE FRACTION OF TUBES PLUGGED
871020   0.0
*
* FRAC OF TUBES ACTIVE
880010    ONE  0   SUB   PLGFC1  20   OPVB  1
880015    999  -1
*
* ADJUST INITIAL CIRC WATER FLOW PER NUMBER TUBES
880020    OPVB  1   MUL   WWVSC  40   WWVSC  40
880025    999  -1
*
* CALC CONDENSER PRESSURE DROP
881110    PP  50   SUB   PP  -20   OPVB  111
*
* CONDENSER SHELL PRESSURE, IN.HGA
881240    PP  -22   DIV   PSIHGA  0   OPVB  124
*
890010 "Frac Tubes Plugged"
890011 PLGFC1  20 0.0   U
*
890020 "Tube K factor"
890021 XKTOOB  20 0.0   U
*
890030 "Misc K factor"
890031 XKMISC  20 0.0   U
*
890040 "Tube-side total K factor"
890041 TUBIU  20 0.0   U
*
890050 "Tube Velocity"
890051 TVELC  20 0.0   U
*
890060 "Circ Disch p"
890061 PP  20 0.0   U
*
891010 "Pump Head"
891011 PDPUM  50 0.0   U
*
891020 "Circ Flow Rate"
891021 WW  40 0.0   U
*
891030 "Condenser Shell p, in.Hga"
891031 OPVB  124 0.0   U
*
```

```
891040 "Condenser Shell p Drop, psi"
891041 OPVB  111 0.0   U
*
* CYCLE FLAGS
010200   0  0  0  5  0  0  0.0  0.0  0  0  0  0  0  0  0
010000  ENGLISH ENGLISH
*
* END NOTES
*SET 1-TERMS FOR CONDENSER PRESSURE DROP
*
*  RFNC  XKTOOB  XKMISC  TUBIN  TUBOUT  ELIDS  ELODS
700206  0.  2.64  22.36  0.  0.  20.  15.
*
=C..UGM04HEI(SET 3)-Specd XKMISC-Control Circ Flow
*
* CONTROL CIRC WATER FLOW FOR TUBE OUT P=PATM
840100 WWVSC  40  14.7  0.0  1. PP  20
840105    2  0
840109    1000000.  90000000.
*
*
* END NOTES
*SET 3-TERMS FOR CONDENSER PRESSURE DROP, CALIBRATED XKMISC
*
*  RFNC  XKTOOB  XKMISC  TUBIN  TUBOUT  ELIDS  ELODS
700206  0.  2.64  1.06362E+01  0.  0.  20.  15.
*
=C..UGM04HEI(SET 4)-Tube Plugging Sensitivity Study
*
****************************
*  GENERIC INPUT DATA
*****************************
*
010000  ENGLISH  ENGLISH
*
* SENSITIVITY STUDY
930000 1 NOPRNT  0  0  0.0
930001 "SNSTVT TO TUBES PLUGGED"
930002 PLGFC1 20  0.0  0.5  26
930003
930004
930008
930011 "Condenser Shell Pressure, in.Hga"
930012 OPVB 124
930018
930021 "Circulating Water Flow"
930022 WW 40
930028
930031 "Condenser Tube-Side P Drop"
930032 OPVB 111
930038
```

```
930041 "Pump Pressure Rise"
930042 PDUPMP 50
930048
930051 "Condenser Tube Velocity"
930052 TVELC 20
930058
*
*
******************************
*    END OF BASE DECK
******************************
*
*
.
```

Table 2 – Sensitivity Study Results for Condenser Submodel in Hydraulically Balanced Flow Scenario (XKMISC>0.)

```
V69/GT (67 STEAM TABLES) OF 07 MAY 04 DATE 05/10/04.                  PAGE 14
SENSITIVITY STUDY CASE 26 - PLGFC1( 20)= 5.000E-01
                                                  ** SAVE CASE **

               COMPRESSED TABLE OF SENSITIVITY STUDY RESULTS

   X = PLGFC1  20, NO-UNITS    , SNSTVT TO TUBES PLUGGED
 Y(1) = OPVB   124, OPVB        , Condenser Shell Pressure, in.Hga
 Y(2) = WW      40, LBM/HR      , Circulating Water Flow
 Y(3) = OPVB   111, OPVB        , Condenser Tube-Side P Drop
 Y(4) = PDUPMP  50, PSIA        , Pump Pressure Rise
 Y(5) = TVELC   20, FT/SEC      , Condenser Tube Velocity
```

PLGFC1 20	OPVB 124	WW 40	OPVB 111	PDUPMP 50	TVELC 20
0.00000E+00	3.11180E+00	7.98006E+07	6.53300E+00	1.08653E+01	5.94863E+00
2.00000E-02	3.13934E+00	7.89867E+07	6.59120E+00	1.09268E+01	6.00812E+00
4.00000E-02	3.16733E+00	7.81818E+07	6.65734E+00	1.09876E+01	6.07079E+00
6.00000E-02	3.19819E+00	7.73195E+07	6.71762E+00	1.10527E+01	6.13157E+00
8.00000E-02	3.23027E+00	7.64494E+07	6.78271E+00	1.11184E+01	6.19437E+00
1.00000E-01	3.26845E+00	7.55548E+07	6.84922E+00	1.11860E+01	6.25792E+00
1.20000E-01	3.31609E+00	7.46183E+07	6.91337E+00	1.12568E+01	6.32081E+00
1.40000E-01	3.36652E+00	7.36621E+07	6.98028E+00	1.13290E+01	6.38492E+00
1.60000E-01	3.41776E+00	7.27392E+07	7.06276E+00	1.13987E+01	6.45504E+00
1.80000E-01	3.47423E+00	7.17482E+07	7.13735E+00	1.14736E+01	6.52239E+00
2.00000E-01	3.53455E+00	7.07306E+07	7.21390E+00	1.15505E+01	6.59063E+00
2.20000E-01	3.59910E+00	6.96858E+07	7.29246E+00	1.16294E+01	6.65977E+00
2.40000E-01	3.66864E+00	6.86066E+07	7.37144E+00	1.17109E+01	6.72917E+00
2.60000E-01	3.74518E+00	6.74640E+07	7.44322E+00	1.17818E+01	6.79594E+00
2.80000E-01	3.82811E+00	6.62837E+07	7.51437E+00	1.18550E+01	6.86252E+00
3.00000E-01	3.91728E+00	6.50810E+07	7.58914E+00	1.19296E+01	6.93051E+00
3.20000E-01	4.01408E+00	6.38438E+07	7.66449E+00	1.20064E+01	6.99873E+00
3.40000E-01	4.11920E+00	6.25752E+07	7.74141E+00	1.20850E+01	7.06753E+00
3.60000E-01	4.23371E+00	6.12744E+07	7.81986E+00	1.21657E+01	7.13688E+00
3.80000E-01	4.35884E+00	5.99405E+07	7.89974E+00	1.22485E+01	7.20672E+00
4.00000E-01	4.49606E+00	5.85725E+07	7.98092E+00	1.23333E+01	7.27698E+00
4.20000E-01	4.64350E+00	5.72113E+07	8.07722E+00	1.24177E+01	7.35296E+00
4.40000E-01	4.80901E+00	5.57844E+07	8.16522E+00	1.25062E+01	7.42563E+00
4.60000E-01	4.99239E+00	5.43234E+07	8.25532E+00	1.25968E+01	7.49897E+00
4.80000E-01	5.19645E+00	5.28278E+07	8.34757E+00	1.26896E+01	7.57299E+00
5.00000E-01	5.42445E+00	5.12985E+07	8.44260E+00	1.27845E+01	7.64791E+00

Appendix B – Steam Turbine Cycle Model Tabulations

Table 3 - Input Data File for Single Reheat Fossil Steam Turbine Cycle Performance Study, at Full Load and Hydraulically Balanced Scenario

```
010001  80  PRINT
010101   0.0
*
*
*        DATE: Tuesday, May 11, 2004
*        TIME: 9:51 AM
*       MODEL: ugm04sys.mdl
*    JOB FILE: C:\UGM04\UGM04SYS.job
*
=C:\UGM04\UGM04SYS(SET 1)-UGM00SYS BASE CASE
*
*****************************
*  GENERIC INPUT DATA
******************************
*
* Newton Unit 1 Model
010200   2  3  1  1  1  0  0.0  0.0  0  0  0  0  0  0  0
*
010000  ENGLISH  ENGLISH
*
* Generator Data
011010   1  2  1  0  3600  686000.  0.9  74.7  74.7  0.0
011011   0.0  0.0  0.0
*
* Convergence Data
012000   30  0.0  0.0  0.0  0.0  0.0  0  0.0
*
*****************************
*  STREAMS
******************************
*
501360   51   U      124   I
501390  124   U      123   I
500010  123   U      125   I
500020  125   U      701   I
500030  701   U      702   I
500040  702   U      101   I
500060  101   U      301   I
500090  301   U      103   I
500110  103   U      302   I
500120  302   U      104   I
500140  104   U      106   I
500180  106   U      107   I
500200  107   U      118  IA
500220  118   U      502   T
500230  502   T      201  IA
500240  201   U      202  IA
500050  101   B      102   I
500130  104   B      105   I
500280  303   U      304   I
501500  304   U      108   I
500300  108   U      109   I
```

500320	109	U	110	I
500360	110	U	127	I
501520	127	B	309	I
501530	309	U	310	I
501540	310	U	311	I
501550	311	U	312	I
501560	312	U	233	IB
500490	233	U	11	S
500520	11	D	601	I
500530	601	U	503	T
501330	204	U	406	S
500630	405	T	406	FW
500610	403	T	404	T
500620	404	T	405	T
500600	235	U	403	T
501020	403	D	130	I
501720	130	B	402	D
501590	402	T	235	IB
501770	237	U	402	S
501620	129	B	210	IB
500640	406	D	602	IP
500650	602	UP	120	I
500660	120	U	122	I
501800	122	U	407	T
500690	407	T	408	T
500710	408	T	203	IA
501820	203	U	52	I
501420	602	UT	12	S
501810	122	B	203	IB
500720	408	D	407	D
501060	33	U	12	T
501070	12	T	22	I
501040	405	D	404	D
501030	404	D	403	D
501410	232	U	602	IT
500290	304	E	204	IA
500740	309	E	405	S
501750	234	U	403	S
501630	310	E	234	IA
501740	401	D	238	IA
501730	402	D	238	IB
501580	128	B	402	T
501570	128	U	401	T
500550	503	T	128	I
501760	210	U	401	S
501600	401	T	235	IA
500910	230	U	11	D
500930	214	U	230	IB
500820	213	U	214	IB
500590	216	U	213	IA
500890	206	U	216	IA
500880	114	U	206	IA
500860	115	U	114	I
500840	207	U	115	I
501320	231	U	208	IA
500830	208	U	207	IA
501350	124	B	53	I

```
501340  123   B      231  IB
501400  115   B      503   S
501380  125   B      232  IB
500080  102   U      201  IB
500070  102   B      231  IA
500100  103   B      202  IB
500150  105   B      208  IB
500160  105   U      204  IB
500170  106   B       55   I
500270  303   E      407   S
500190  107   B      408   S
500210  120   B      118  IB
500250  202   U      303   I
500390  505   T      216  IB
500330  109   B      505   T
500310  108   B      232  IA
500350  110   B      207  IB
501510  127   U      305   I
500410  305   U      306   I
500420  306   U      307   I
500430  307   U      308   I
500440  308   U      233  IA
500750  305   E      404   S
501640  306   E      234  IB
500770  307   E      210  IA
501650  311   E      237  IA
500540  503   D      206  IB
500700  407   D      406   D
501430   12   D      230  IA
501710  130   U      401   D
501610  129   U      237  IB
500870  114   B      129   I
500810  238   U      214  IA
500940   54   U      213  IB
500510  603   U       11   T
500340   31   U      603   I
500260   11   T       21   I
*
* Pressure Drop to DC Heater
600290   2  0.02  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*
* Pressure Drop to "D" Feedwater Heater
600740   2  0.02  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*
* Pressure Drop to "F" Feedwater Heater
600270   2  0.02  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*
* Pressure Drop to "G" Feedwater Heater
600190   2  0.05  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*
* Intercept Valve Pressure Drop
600250   2  0.0032  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*
* Pressure Drop to "C" Feedwater Heater
600750   2  0.02  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*
* Pressure Drop to "A1" Feedwater Heater
```

```
600770   2  0.02  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*
* Pressure Drop to "A2" Feedwater Heater
601650   2  0.02  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*
* Pressure Drop to "B" Feedwater Heater
601630   2  0.02  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*
* Stream Spec for APH Drain
600390   5  14.7  210.
*
* Pressure Drop to "B" Feedwater Heater
601640   2  0.02  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*
******************************
*  COMPONENTS
*****************************
*
* Governing Stage
703010   4  1  1  1  1  1
703011   4  0  41.53
703012   0.0  0.0  0.0  0.0  0.0  0
*
* High Pressure Turbine Stage Group
703020   5  1  1  0  1  0.03
703021   1833.  1432.5  3900121.  600.5  352750.
703022   0.0  0.0  0.0  0.0
703027   0
*
* IP Stage Group
703040   6  1  3  1  2  1  0.03
703041   294.  1444.2  3454547.  178.9  236969.
703042   0.0  0.0  0.0  0.0  0.0  0.0  0.0
*
* IP Stage Group
703030   6  1  0  1  2  1  0.03
703031   540.5  1519.1  3569835.  294.  115288.
703032   0.0  0.0  0.0  0.0  0.0  0.0  0.0
*
* LP Turbine Stage
703120   7  1  3  0  3  2  0.0
703121   5.5  1103.3  1263240.5  0.737  0.0  55.6
703122   0.0  0.0  0.0  0.0  0.0
703123   0  0.0  0.0  0  0.0
*
* LP Stage Group
703110   7  1  1  1  3  2  0.03
703111   12.8  1156.7  1347488.  5.5  84247.5  0.0
703112   0.0  0.0  0.0  0.0  0.0
703113   0  0.0  0.0  0  0.0
*
* LP Stage Group
703100   7  1  1  1  3  2  0.03
703101   67.6  1288.5  1403291.  12.8  55802.5  0.0
703102   0.0  0.0  0.0  0.0  0.0
703103   0  0.0  0.0  0  0.0
*
```

```
* LP Stage Group
703090   7  1  0  1  3  2  0.03
703091   178.9  1387.  1489497.5  67.6  86207.  0.0
703092   0.0  0.0  0.0  0.0  0.0
703093   0  0.0  0.0  0  0.0
*
* LP Turbine Stage
703080   7  1  3  0  3  2  0.0
703081   5.5  1103.3  1263240.5  0.737  0.0  55.6
703082   0.0  0.0  0.0  0.0  0.0
703083   0  0.0  0.0  0  0.0
*
* LP Turbine Stage
703070   7  1  1  1  3  2  0.03
703071   12.8  1156.7  1347488.  5.5  84247.5  0.0
703072   0.0  0.0  0.0  0.0  0.0
703073   0  0.0  0.0  0  0.0
*
* LP Turbine Stage
703060   7  1  1  1  3  2  0.03
703061   43.8  1249.8  1403290.5  12.8  55802.5  0.0
703062   0.0  0.0  0.0  0.0  0.0
703063   0  0.0  0.0  0  0.0
*
* LP Turbine Stage
703050   7  1  0  1  3  2  0.03
703051   178.9  1387.  1599841.  43.8  196550.  0.0
703052   0.0  0.0  0.0  0.0  0.0
703053   0  0.0  0.0  0  0.0
*
* Auxiliary Condenser
700120   10  0  2  0.0  0.982
700121   0.0  0.0  0.0  0.0  0.0  0.0
700122   0.0  0.0  0.0  0.0  0.0
*
* Main Condenser
700110   10  1  5  0.0  -1.5
700115   1  0.0  1.  477.624  31660.  2  -0.9  0  0.0  18  0
710112   0.0  0.0
*
* Deaerating Heater
704060   15  1  304  0.0  0.0
704061   0.0  0.0  0.0  0.0  0.0  0.0
704062   0.0  0.0  0.0  0.0  0  0.0  0.0  0
*
* "D" Feedwater Heater
704050   16  0  309  3  0.0  5.  10.
704051   0.0  0.0  0.0  0.0  0.0  0.0
704052   0.0  0.0  0.0  0.0  0.0  0.0  0.0  0
*
* "C" Feedwater Heater
704040   16  1  305  3  0.0  5.  10.
704041   0.0  0.0  0.0  0.0  0.0  0.0
704042   0.0  0.0  0.0  0.0  0.0  0.0  0.0  0
*
* "B" Feedwater Heater
704030   16  1  234  3  0.0  5.  10.
```

```
704031   0.0  0.0  0.0  0.0  0.0  0.0
704032   0.0  0.0  0.0  0.0  0.0  0.0  0.0  0
*
* "1A2" Feedwater Heater
704020   16  1  311  3  0.0  5.  10.
704021   0.0  0.0  0.0  0.0  0.0  0.0
704022   0.0  0.0  0.0  0.0  0.0  0.0  0.0  0
*
* "1A1 Feedwater Heater
704010   16  1  307  3  0.0  5.  10.
704011   0.0  0.0  0.0  0.0  0.0  0.0
704012   0.0  0.0  0.0  0.0  0.0  0.0  0.0  0
*
* "G" Feedwater Heater
704080   18  0  107  3  0.0  -3.  10.
704081   0.0  0.0  0.0  0.0  0.0  0.0
704082   0.0  0.0  0.0  0.0  0.0  0.0  0.0  0
*
* "F" Feedwater Heater
704070   18  1  303  3  0.0  0.0  10.
704071   0.0  0.0  0.0  0.0  0.0  0.0
704072   0.0  0.0  0.0  0.0  0.0  0.0  0.0  0
*
* Steam Packing Exhauster
705030   20  210.
705031   0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*
* Reheater
705020   25  2  1000.
705021   0.1  0.0  0.0  0.0  0.0
705029   0.0
*
* Air Preheater
705050   27  0.0  0.0  0.0  0.0
705051   0.0
705059   0.0
*
* Primary Sootblower SInk
700550   30
700552   0
*
* Seconadary Sootblower Sink
700530   30
700532   0
*
* Auxiliary Condenser Circ Water Outlet
700220   30
700222   0
*
* Condenser Circulating Water Outlet
700210   30
700212   0
*
* Makeup Source
700540   31  64.  32.4  0.0  0.0  0.0  0
700542  0  0  0
*
```

```
* Aux. Cond. Circ. Water Source
700330   31  64.  49.5  15994000.  0.0  0.0  0
700332  0  0  0
*
* Condenser Circulating Water Inlet
700310   31  64.  14.7  -210000.  0.0  0.0  0
700312  0  0  0
*
* Output Comp. - Econ Inlet
700520   32
700522   0
*
* Main Steam
700510   33  1000.  2414.7  3938761.  0.0  0.0  0
700512  0  0
*
* Standard Valve
707010   34  0.0  0.0  0.0  0.0  0.0  0.0  0.0
707011   0.0  0.0  0.0
*
* Throttle Valve
707020   35 -2.0 -2.0 -2.0  0.6  2414.7  1460.4  3938761.
707021   2414.7  1460.4  3938761.
707026   0
707029   0.0  0.0  0.0
*
* Boiler Feed Pump
706020   40  108  2864.  0.982  1059.9  0.63
706021   0.0  0.84  0.0  0.0  0.0  0.0  0.0  0.0
706026   0
706029   0.0  0  0.0
*
*
706030   41  49.5  0.0  0.0  0.0
706031   0.0  0.0  0.0  0.0  0.0  0.0
706036   0
*
* Condensate Pump
706010   41  490.  0.0  0.0  0.0
706011   0.0  0.0  0.0  0.0  0.0  0.0
706016   0
*
* Standard Mixer
702380   50  0  0.0
*
* Standard Mixer
702370   50  1  0.0
*
* Standard Mixer
702350   50  0  0.0
*
* Standard Mixer
702330   50  0  0.0
*
* Standard Mixer
702320   50  0  0.0
*
```

```
* Standard Mixer
702100   50  1  0.0
*
* Standard Mixer
702040   50  1  0.0
*
* Superheat Attemperator Mixer
702030   50  0  0.0
*
* Standard Mixer
702020   50  0  0.0
*
* Standard Mixer
702010   50  1  0.0
*
* Standard Mixer
701180   50  0  0.0
*
* Special Mixer
702310   51  0  0.0
*
* Special Mixer
702300   51  0  0.0
*
* Special Mixer
702160   51  0  0.0
*
* Special Mixer
702140   51  0  0.0
*
* Special Mixer
702130   51  0  0.0
*
* Special Mixer
702080   51  0  0.0
*
* Special Mixer
702070   51  0  0.0
*
* Special Mixer
702060   51  0  0.0
*
* Dual Extracting Mixer
702340   52  310  306  0  0.0
*
* Demand Flow Splitter to BFPT
701250   60  0.0  0.0  0.0  0  0.0
701251   0
*
* Demand Flow Splitter - Leakage #7
701230   60  0.0  0.0  0.0  0  0.0
701231   0
*
* Demand Flow Split (To BFPT)
701080   60  0.0  146724.  0.0  0  0.0
701081   0
*
```

```
* Demand Flow Splitter to Heater G
701070   60  0.0  352750.  0.0  0  0.0
701071   0
*
* Fixed Flow Split (To Sec Soot Blower)
701240   61  0.0  0.0
*
* Superheat Attemperation
701220   61  0.0  0.0
*
* Fixed Flow Split (Reheat Attemp.)
701200   61  0.0  0.0
*
* Fixed Flow Split (To  Steam Pack Exhauster)
701150   61  0.0  2800.
*
* Fixed Flow Split (To Air Preheater)
701090   61  0.0  0.0
*
* Fixed Flow Split (To Prim Soot Blower)
701060   61  0.0  0.0
*
* Fixed Perc. Split Drains from B to A HTR
701300   63  0.0  0.5
*
* Fixed Perc. Split (SSR Overflow to HTRS)
701290   63  0.0  0.5
*
* Fixed Percent Split (1A1 & 1A2 HTRS)
701280   63  0.0  0.5
*
* Fixed Percent Split (A & B Hood)
701270   63  0.0  0.4744
*
* Turbine Shaft Leak Split (L#6)
701100   64  600.  0.0  0.0
*
* Turb. Shaft Pack Leak Split (L#4 & L#5)
701050   64  970.  0.0  0.0
*
* Turbine Shaft Leakage Splitter
701040   64  620.  0.0  0.0
*
* Turb. Shaft Leak. Split. (N2 Pack Leak)
701030   64  500.  0.0  0.0
*
* Steam Seal Regulator
701140   67  123  0.0  17.7  2400.
*
* Throttle Valve Leak. Split. L#1 & L#2
701020   68  0.0  0.0  0.0
*
* Throttle Valve Stem Leakage Splitter
701010   68  0.0  0.0  0.0
*
******************************
*  SPECIAL FEATURES
```

```
*****************************
*
800100 "SCHEDULE OF PUMP DP VALUES"
* X VALUES
810100   0.0  30000000.  60000000.  82500000. 1.05000000E+008
* Z AND Y VALUES
810110   0.0  55.4  51.93  47.61  43.28  38.08
*
* VARIABLES FOR PUMP PRESSUE VERSUS FLOW CURVE
830100   1  PHEAD  603  WW  34
830102   0
830105    5  0
*
* BASELINE NUMBER OF CONDENSER TUBES
871010   31660.
*
* BASELINE FRACTION OF TUBES PLUGGED
871020   0.0
*
* FRAC OF NORMAL TUBES
880010    ONE  0   SUB   PLGFC1  11   OPVB  1
880011    0.0  31660.  0.0
880015    999  -1
*
* CALC CONDENSER PRESSURE DROP
881110    PP  51   SUB   PP  -26   OPVB  111
*
* CONDENSER SHELL PRESSURE, IN. HGA
881240    PP  -52   DIV   PSIHGA  0   OPVB  124
*
******************************
*   SPECIAL OPTIONS
******************************
*
890010 "Frac Tubes Plugged"
890011 PLGFC1  11 0.0   U
*
890020 "Tube K factor"
890021 XKTOOB  11 0.0   U
*
890030 "Misc K factor"
890031 XKMISC  11 0.0   U
*
890040 "Tube-Side total K factor"
890041 TUBIU  11 0.0   U
*
890050 "Tube Velocity"
890051 TVELC  11 0.0   U
*
890060 "Circ Disch p"
890061 PP  26 0.0   U
*
890070 "Pump Head"
890071 PDPUM  603 0.0   U
*
890080 "Circ Flow Rate"
890081 WWVSC  31 0.0   U
```

```
*
890090 "Condenser Shell p, in.Hga"
890091 OPVB  124 0.0   U
*
890100 "Condenser Tube p Drop, psid"
890101 OPVB  111 0.0   U
*
890110 "Generation"
890111 BKGROS  0 0.0   U
*
* OUTPUT GLOBAL SUPPRESSION CARD
020000 PRINT    PRINT    NOPRNT
020002 NOPRNT   * Geometry Configuration of Model
020004 NOPRNT   * Stream Properties
020005 NOPRNT   * Comparison of Component Port Test Data With Stream
Properties
020015 NOPRNT   * Detailed Mixer Performance Output
020016 NOPRNT   * Detailed Splitter Performance Output
020021 NOPRNT   * Second Law of Thermodynamics Performance - Components
020022 NOPRNT   * Second Law of Thermodynamics Performance - Streams
020023 NOPRNT   * Second Law of Thermodynamics Performance - System
020024 NOPRNT   * Material Descriptions Used in the Model
020025 NOPRNT   * First Law of Thermodynamics Performance - Envelope
020030 NOPRNT   * Warning Table of Stream Closures
020032 NOPRNT   * Input Schedule Number N Table of Values
020033 NOPRNT   * Variable Sets Which Reference Schedules
020034 NOPRNT   * Controls Input
020037 NOPRNT   * Definitions of Special Operations Specified
020059 NOPRNT   * Stream Transport Properties
020078 NOPRNT   * Nonzero Operational Variables
*
* END NOTES
*SET 1-TERMS FOR CONDENSER PRESSURE DROP, FIRST GUESS XKMISC
*
*  RFNC  XKTOOB  XKMISC  TUBIN  TUBOUT  ELIDS  ELODS
700116  0.  2.68  50.
*
=C..UGM04SYS(SET 3)-Specd calibrated Kmisc, Calc Flow to bal pump
*
* Control Circ Water Flow for circ discharge = 14.7 psia
840100 WWVSC  31  14.7  0.0  1. PP  26
840105    5  0
840109    -240000.  -100000.
*
* END NOTES
*SET 3-TERMS FOR CONDENSER PRESSURE DROP, CALIBRATED XKMISC
*
*  RFNC  XKTOOB  XKMISC  TUBIN  TUBOUT  ELIDS  ELODS
700116  0.  2.68  3.05157E+01
*
=C..UGM04SYS(SET 4)-Sensitivity to tubes plugged
*
* SENSITIVITY STUDY
930000 1 NOPRNT  0  0  0.0
930001 "SNSTVT TO TUBES PLUGGED"
930002 PLGFC1 11  0.0  0.5  26
930011 "Generation"
```

```
930012 BKGROS 0
930021 "Condenser Shell Pressure, in.Hga"
930022 OPVB 124
930031 "Circulating Water Flow"
930032 WW 34
930041 "Condenser Tube-Side P Drop"
930042 OPVB 111
930051 "Pump Pressure Rise"
930052 PDUPMP 603
930061 "Condenser Tube Velocity"
930062 TVELC 11
*
******************************
*     END OF BASE DECK
******************************
*
.
```

Table 4. Sensitivity Study Results for Steam Turbine Cycle at Full Load and Hydraulically Balanced Scenario (XKMISC>0.0)

```
V69/GT (67 STEAM TABLES) OF 07 MAY 04 DATE 05/11/04.                  PAGE 27
SENSITIVITY STUDY CASE 26 - PLGFC1( 11)= 5.000E-01
                                                 ** SAVE CASE **

               COMPRESSED TABLE OF SENSITIVITY STUDY RESULTS

    X = PLGFC1  11, NO-UNITS    , SNSTVT TO TUBES PLUGGED
 Y(1) = BKGROS   0, MW          , Generation
 Y(2) = OPVB   124, OPVB        , Condenser Shell Pressure, in.Hga
 Y(3) = WW      34, LBM/HR      , Circulating Water Flow
 Y(4) = OPVB   111, OPVB        , Condenser Tube-Side P Drop
 Y(5) = PDUPMP 603, PSIA        , Pump Pressure Rise
 Y(6) = TVELC   11, FT/SEC      , Condenser Tube Velocity
```

PLGFC1 11	BKGROS 0	OPVB 124	WW 34	OPVB 111	PDUPMP 603
0.00000E+00	5.90330E+02	1.52941E+00	1.05022E+08	1.64868E+01	1.64864E+01
2.00000E-02	5.90324E+02	1.53662E+00	1.04347E+08	1.65536E+01	1.65540E+01
4.00000E-02	5.90318E+02	1.54422E+00	1.03647E+08	1.66237E+01	1.66240E+01
6.00000E-02	5.90311E+02	1.55225E+00	1.02920E+08	1.66964E+01	1.66967E+01
8.00000E-02	5.90303E+02	1.56076E+00	1.02165E+08	1.67720E+01	1.67723E+01
1.00000E-01	5.90293E+02	1.56978E+00	1.01380E+08	1.68506E+01	1.68509E+01
1.20000E-01	5.90282E+02	1.58089E+00	1.00563E+08	1.69323E+01	1.69326E+01
1.40000E-01	5.90265E+02	1.59710E+00	9.97143E+07	1.70173E+01	1.70175E+01
1.60000E-01	5.90245E+02	1.61433E+00	9.88309E+07	1.71058E+01	1.71060E+01
1.80000E-01	5.90222E+02	1.63269E+00	9.79116E+07	1.71978E+01	1.71979E+01
2.00000E-01	5.90197E+02	1.65256E+00	9.69325E+07	1.72861E+01	1.72959E+01
2.20000E-01	5.90171E+02	1.67314E+00	9.59632E+07	1.73951E+01	1.73929E+01
2.40000E-01	5.90141E+02	1.69562E+00	9.49207E+07	1.74974E+01	1.74973E+01
2.60000E-01	5.90109E+02	1.71968E+00	9.38397E+07	1.76057E+01	1.76054E+01
2.80000E-01	5.90076E+02	1.74555E+00	9.27135E+07	1.77185E+01	1.77181E+01
3.00000E-01	5.90037E+02	1.77345E+00	9.15398E+07	1.78361E+01	1.78356E+01
3.20000E-01	5.89994E+02	1.80359E+00	9.03164E+07	1.79587E+01	1.79580E+01
3.40000E-01	5.89937E+02	1.83629E+00	8.90410E+07	1.80866E+01	1.80857E+01
3.60000E-01	5.89864E+02	1.87185E+00	8.77112E+07	1.82199E+01	1.82187E+01
3.80000E-01	5.89769E+02	1.91064E+00	8.63246E+07	1.83590E+01	1.83575E+01
4.00000E-01	5.89643E+02	1.95312E+00	8.48785E+07	1.85040E+01	1.85022E+01
4.20000E-01	5.89481E+02	1.99982E+00	8.33703E+07	1.86554E+01	1.86532E+01
4.40000E-01	5.89281E+02	2.05135E+00	8.17973E+07	1.88133E+01	1.87988E+01
4.60000E-01	5.89035E+02	2.11021E+00	8.00835E+07	1.89454E+01	1.89416E+01
4.80000E-01	5.88744E+02	2.17521E+00	7.83214E+07	1.90928E+01	1.90885E+01
5.00000E-01	5.88394E+02	2.24796E+00	7.64867E+07	1.92466E+01	1.92413E+01

PLGFC1 11	TVELC 11
0.00000E+00	6.66035E+00
2.00000E-02	6.75256E+00
4.00000E-02	6.84701E+00
6.00000E-02	6.94366E+00
8.00000E-02	7.04254E+00
1.00000E-01	7.14372E+00

1.20000E-01	7.24724E+00
1.40000E-01	7.35316E+00
1.60000E-01	7.46154E+00
1.80000E-01	7.57243E+00
2.00000E-01	7.68412E+00
2.20000E-01	7.80234E+00
2.40000E-01	7.92067E+00
2.60000E-01	8.04210E+00
2.80000E-01	8.16629E+00
3.00000E-01	8.29327E+00
3.20000E-01	8.42309E+00
3.40000E-01	8.55578E+00
3.60000E-01	8.69138E+00
3.80000E-01	8.82991E+00
4.00000E-01	8.97139E+00
4.20000E-01	9.11583E+00
4.40000E-01	9.26326E+00
4.60000E-01	9.40507E+00
4.80000E-01	9.55189E+00
5.00000E-01	9.70126E+00

Appendix C – Effect of Elevation in Submodel

This appendix demonstrates the impact of elevation on the results of calculations in the condenser submodel of Figure 1. The intent here is to show that accounting for elevation effects is important when using the hydraulic balancing method of computing the circulating water flow rate.

A sensitivity study for the single scenario is analyzed here, the case where XKMISC>0.0 and where the elevation at the surface of the circulating water supply is changed from 10 feet, which appears in the cases in the body of this report, to 5 feet. For purpose of comparison, the results of the original case are presented here in plots. This elevation is important because it impacts the overall head that the pump must overcome in the circulating water circuit. Thus the surface elevation impacts the amount of circulating water that the pump can deliver. The surface elevation, as specified via stream 40 is the only modification from the original data description. The form loss factors here are the same as in the original description. Thus, the system's flow resistance is the same in the two cases presented.

Four plots are included in this appendix as Figure 6a through 6b. These plots are analogous to those shown above in Figure 3.

Figure 6a. The Effect of Elevation on Condenser Pressure, Hydraulically Balanced Case (XKMISC>0.)

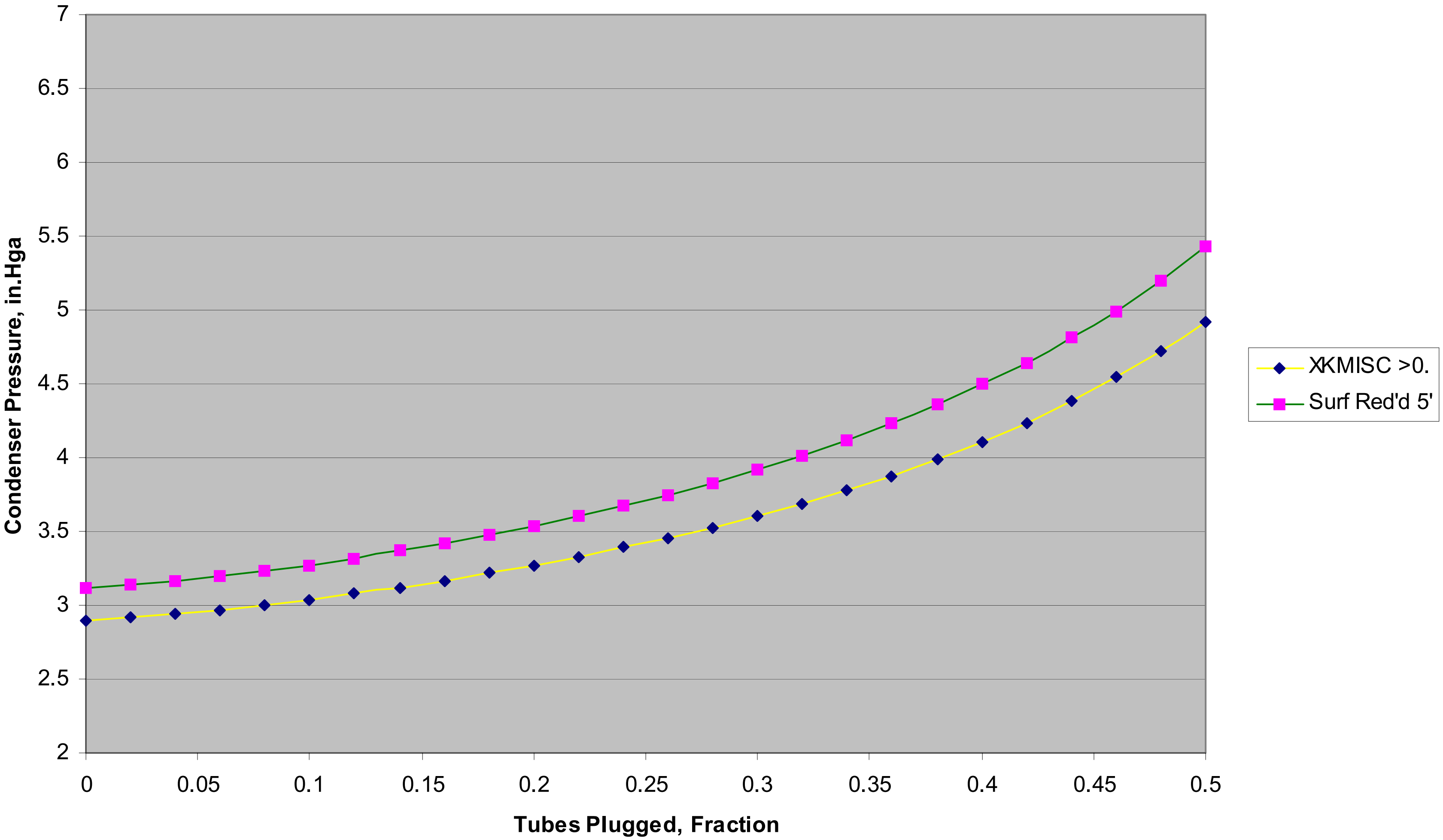


Figure 6b. The Effect of Elevation on Circulating Water Flow Rate, Hydraulically Balanced Case (XKMISC>0.)

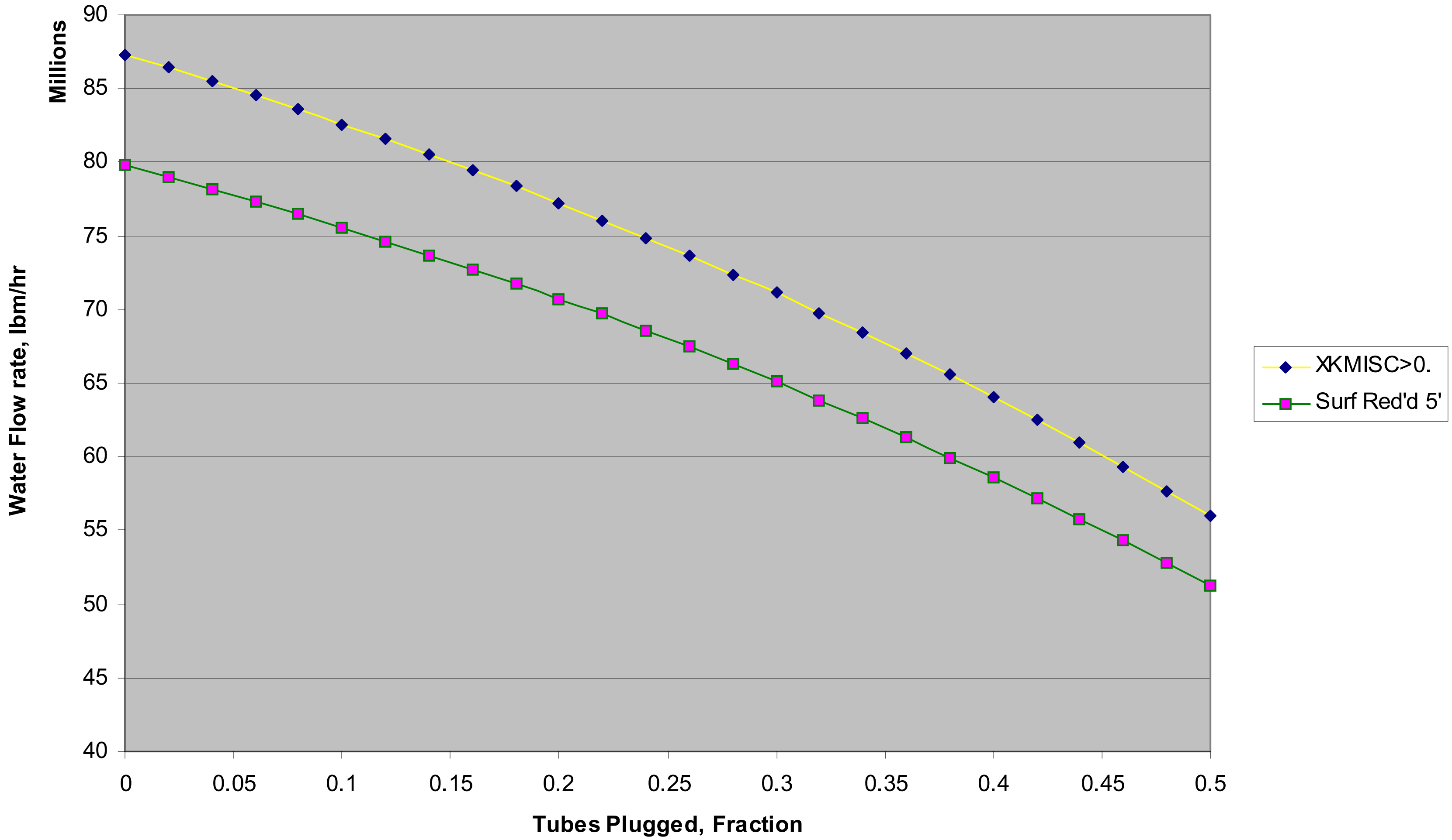


Figure 6c. The Effect of Elevation on Condenser Tube-Side Pressure Drop, Hydraulically Balanced Case (XKMISC>0.)

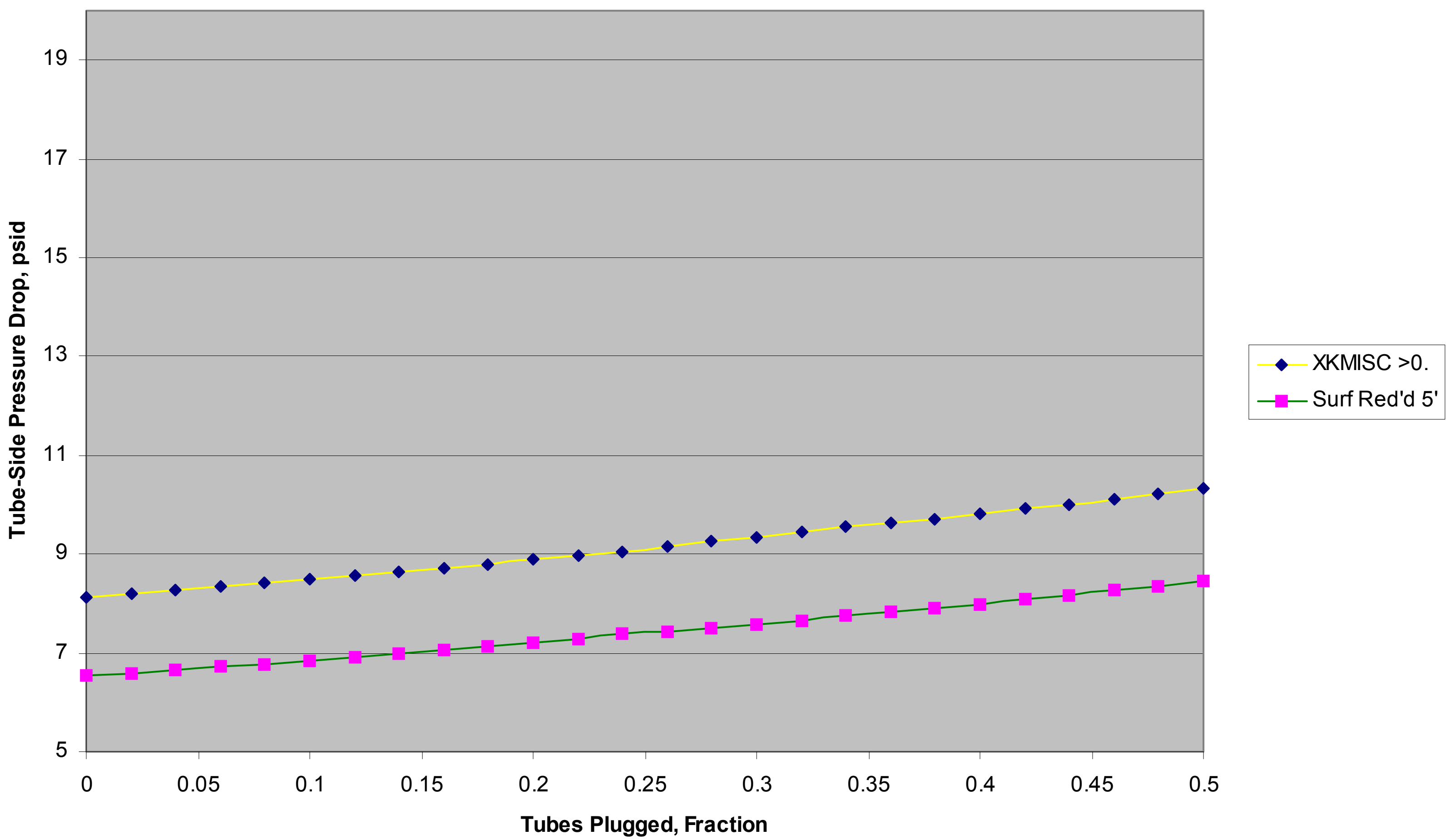
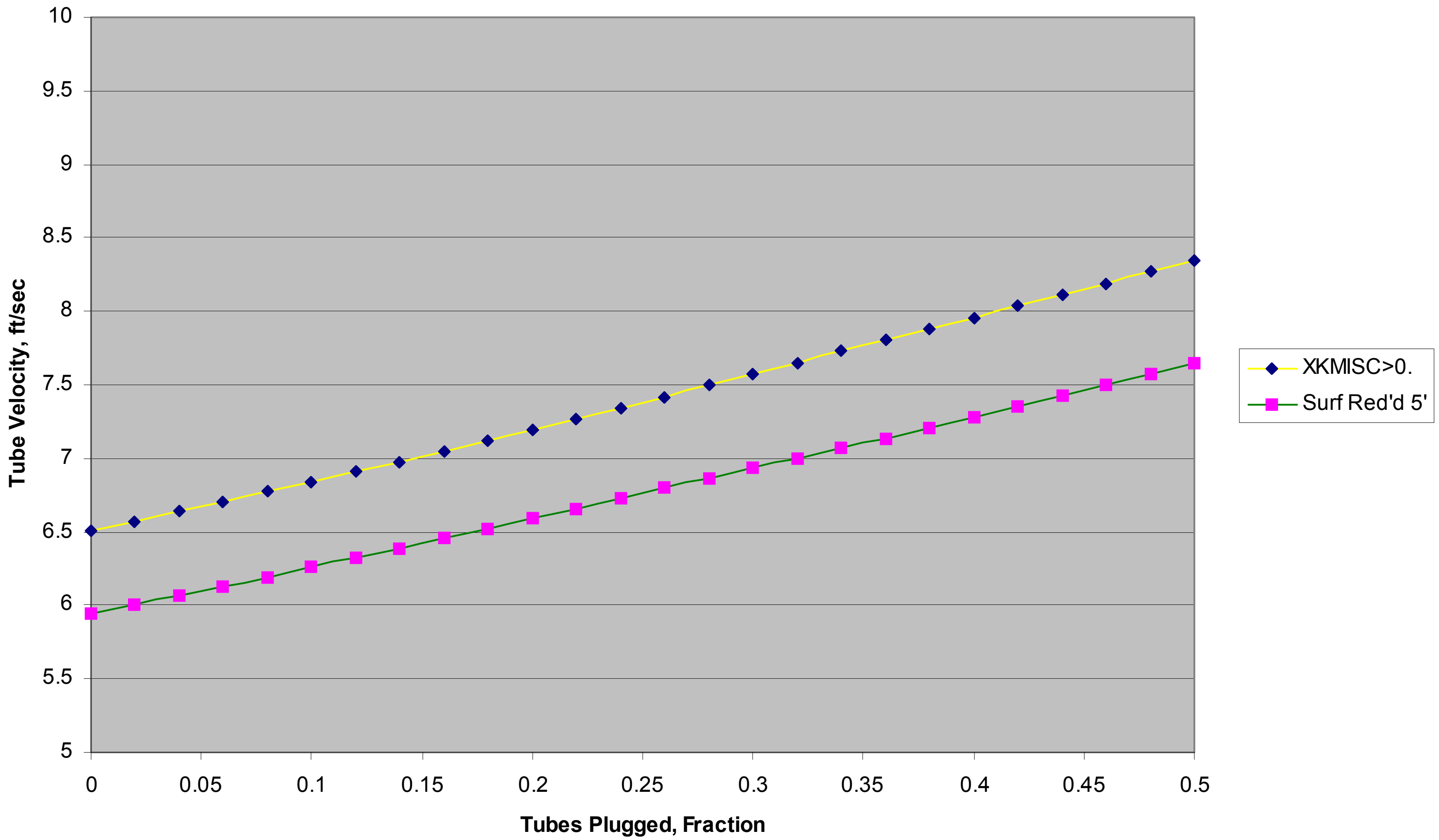


Figure 6d. The Effect of Elevation on Condenser Tube Velocity, Hydraulically Balanced Case (XKMISC>0.)



Comparing the results reveals up to 0.5 in. Hg difference of condenser backpressure for the two different reservoir surface elevations. The circulating water flow rate is about 10% different from one case to the other. The condenser tube-side pressure drop difference is approaching 20%, and the tube velocity difference is about 10% different from case to case.

The differences demonstrated in these plots should serve as a strong recommendation to properly account for elevation changes in each part of the circuit when using the hydraulic balancing method of computing circulating water flow rate.