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REPLACEMENT FEEDWATER HEATER PERFORMANCE MODELING AND RATING CALCULATIONS

Gerald Weber
Midwest Generation EME, LLC

Michael C. Catapano
Powerfect Inc.

ABSTRACT

It is not uncommon to expect that feedwater heaters will require replacement over their Unit's service life. In some cases, Unit upgrades, changes in the full range of operation, and the absence of root cause failure analysis can lead to unsuitable replacements. Neglecting these considerations can result in the continuance of similar failures as heaters are either replaced in-kind or not to the extent necessary as dictated by the changes in load and/or how they are operated. The heater technical specification must not only address the obvious issues related to changes in tube material, quality control, and references to the current state-of-the-art heater standards, but also the full range of current and projected modes of operation. An important factor in obtaining a heater that will last reliably for many years is to specify one that will be versatile enough to handle not only the normal base load operation, but will also safely withstand higher loads, higher heat inputs, and other modes of operation reasonably expected. The replacement heater specification must define the full range of projected load impositions to allow the Vendor to consider and adapt his internal layouts and physical geometries to accommodate them safely and conservatively.

This paper shall illustrate how performance modeling and predictive rating calculations can be valuable tools in helping to identify the full range of conditions to be considered by the Vendor so as to optimize the specification of the new heater. A variety of hypothetical cases can be examined in order to help determine the optimal design and its effects on the entire heater system as well as projected resultant differences in Unit load and heat rate or efficiency. Constructing a performance mode model, such as the PEPSE example utilized herein, for single heater analysis is quick and relatively easy. The feedwater and drain inlet conditions (temperature, pressure and flow), the heater shell pressure, and the required Terminal Temperature Difference (TTD) and Drains Cooler Approach (DCA) are inputs to the model which then calculates the required steam flow demand and the heater outlet conditions. Using this tool, the initial design, current minimum and full load (from plant historical data or PI data), future full load, abnormal/overload conditions and any other pertinent analysis may be accomplished. The key output data delivered by the model is the required steam and drain flows obtained by the energy balance. This information is then specified to the heater Vendors as it applies to the rating and physical sizing of the replacement. This information can be crucial to ensure that the replacement heater(s) will be capable of providing long, reliable life for even the worst load potentials.

REPLACEMENT HEATER PARAMETERS OF MAJOR INFLUENCE

The replacement heater specification must reflect the current Unit performance, which is typically not the same as it was originally. Quite often, a new design guarantee point must be defined in the replacement specification based on the Unit's present day PI data. The new guarantee point becomes the basis for the Vendor's performance warranty as it is used to rate the replacement. A discussion of some of the major parameters influencing the rating and design of an example three-zone HP heater follows.

Feedwater flow

If the maximum generation point of the Unit has been increased since initial design, as the Unit ages or experiences cycle modifications, the efficiency may reduce tending to increase the feedwater flow for the same load point. Increase in feedwater flow increases inlet tube velocities. The various tube materials utilized have specific maximum tube side velocities identified by the HEI guidelines. They should not be exceeded and should have enough conservatism to allow some margin for future plugging. Tube side design pressure drop should be specified at 10 psi maximum if possible. This will tend to limit the overall length of the replacement.

Drains inlet flow and conditions

If downstream heater conditions have changed, then cascade drainage will be different. Extraction steam demand will be biased by the energy of the incoming drains.

Steam inlet flow and conditions

If the feedwater flow increases, the required steam flow also increases. In addition, if the shell pressure or feedwater inlet temperature has changed, the steam flow will correspondingly change. The overload considerations will further compound the increase potentials.

Shell side velocities

Changes in steam flow, the cumulative drains outlet flow, tube pitch, baffle design and spacing may result in higher shell side velocities within the respective desuperheat and drains cooler zones (DSH and DC zones), and if excessive, tube vibration may result. The specification should provide limiting criteria to be met by the Vendors design at the worst overload condition.

Performance requirements

In some instances, it may be advantageous to consider changes to the specified TTD or DCA temperatures for the replacement heater. Sometimes it is due to physical size increase limitations, i.e., shell OD, heater length, etc. In other examples, the history of problems for specific applications may indicate the need for more subcooling margin in the DC zone to minimize the potential for flashing drains. There may be a certain benefit for going to a negative TTD on a second point heater that has a high degree of superheat available in the extraction steam. This will not only affect the surface area requirements for the replacement heater but will also impact the performance of the heaters upstream and downstream in the cycle. Therefore a system performance model should be utilized to quantify the change in performance of the other heaters in the system and the effect on Unit load and heat rate. These issues are usually not totally addressed and resolved until the final design review stage with the selected Vendor.

Full range of operation

The specification performance schedule must tell the FWH Vendor(s) the minimum conditions for low-load cyclic operation, as well as the worst abnormal overload of maximum feedwater flow and/or minimum depressed feedwater inlet temperature. Both of these scenarios can be quantified based on the Unit's historical performance data during those modes of operation. In some cases where data is not available, off design heater projections must be estimated using the effectiveness method of performance prediction before using the results in the system energy balance model.

Materials of construction

Changes in tube material for improved corrosion resistance usually results in a decrease in thermal conductivity and demands a larger heater with more tube surface, resulting in considerations for physical external limitations at the heater location in the Plant.

The following illustrates an actual Utility plant replacement heater case study where performance modeling was used to analyze the current requirements of the feedheating system. The results of the performance runs provide the necessary performance data and information to generate the new design guarantee point, as well as the potential low-load and overload guidelines. The results are tabulated into a Performance Schedule attachment to the replacement Technical Specification document.

CASE HISTORY BACKGROUND INFORMATION

The Unit used in the analysis example is an 850 MW turbine with dual boilers capable of independent operation. The Unit has two heater strings, each with three stages of high pressure feedwater heaters for each boiler. The first two heaters, Nos. 5 and 6 in each string are suffering from stress corrosion cracking. The tube leakage incident frequency is increasing and eddy current results and tube samples have indicated the heaters are near end of reliable life. Historical information regarding failure chronology and root cause analysis usually provides the first basis for the generation of the replacement specification. The determinations of the full range of current modes of operation are equally as important to the specification.

PERFORMANCE MODEL

The first step is to construct a performance mode model for each heater and then combine the individual heater models into the system model. It should be understood that there are a number of computer performance modeling programs available in the industry, in this example, the PEPSE model software was employed.

An energy balance model is constructed for each heater considered. To allow the program to simulate reality, the extraction steam originates from an infinite source and is regulated by a demand splitter which iterates to the correct amount of extraction steam necessary to satisfy an energy balance. The energy balance is achieved when the demanded extraction steam energy matches the input TTD and DCA. The inputs to the model are the extraction steam temperature and pressure, feedwater inlet flow, pressure and temperature, TTD and DCA. The model is executed and iterates to solution. The important outputs are the steam and drain flows.

Using the same concept described above for a single heater, a group (or string) of heaters can be analyzed. In this case each individual heater can be input into the system feedwater heater submodel where all the effects on modifying the individual performance system can be analyzed to incorporate actual operating conditions and simulate overloads. This is presented in Figure 1 where each heater iterates to solution.

FIGURE 1 - PEPSE PERFORMANCE MODE MODEL FOR HEATER SYSTEM

The unit in this example has incurred cycle modifications since original acceptance testing. The modifications have increased the #5 heaters extraction pressure and consequently increased the temperature rise and corresponding heat duty. This has caused the required steam flow to increase by 34%. The increase in the #5 heat duty has decreased the #6 feedwater temperature rise and heat duty by about 15%. The data is presented in Table 1 and 2 as the new full load guarantee design point with 2 boilers in service. These tables will ultimately become the Performance Schedules for the Replacement Specifications

ABNORMAL / OVERLOAD OPERATION:

Now that we have determined the base case design performance, it is important to consider potential problems that may result due to abnormal operation. Some of these potentials are discussed in detail in Appendix B of the HEI Standards for Closed Feedwater Heaters. This could include operating with a depressed feedwater inlet temperature which will raise the required extraction steam flow and cause a corresponding increase in the shell side steam and condensate velocities in the desuperheating and drain cooling zones. Since the #5 heater is the first heater above the dearator (DC heater), the overload condition chosen is a 20 deg F reduction in feedwater inlet temperature. The model results for this case are also presented in Table 1 as the thermal overload case with 2 boilers in service. The #6 heater is also analyzed with a 20 deg F reduction in inlet temperature in order to simulate a derated condition (such as an internal feedwater bypass) in the #5. This data was input to the model and executed with the results presented in Table 2.

Other potential cases for overload were also considered. One mode considered was to operate the #6 with the #5 completely out of service. This was judged to incorporate more margin than realistically necessary because based on the system feedwater piping, the #5 cannot be removed from service by itself. The whole string must be removed. Therefore it was decided that a realistic overload condition was to consider the #5 operating in a derated condition instead of being taken out of service. These overload states for both heaters represent about 40% more steam flow than the re-rated design value for #5 and about 50% more for the #6. As a heater ages and more tubes are plugged, proactive measures to lengthen the life are taken. These could include cutting a hole in the pass partition plate to reduce the feedwater velocity and overall heat duty in the heater. Although this helps the aging heater, it can over burden the downstream heater if it is not designed for the increased heat duty and shell-side velocities due to decreased feedwater inlet temperature. Therefore, although it may not always be necessary to size a heater to operate safely without the upstream heater in service, it may be useful to build some conservatism into the design in case the heat duty does increase. Note that the heater is not expected to maintain the design TTD and DCA in the overload condition. The only requirement guaranteed is the full load with design flows. However, sizing for a realistic overload costs slightly more but can increase the service life significantly. It is important to note that compensation for abnormal overload conditions <u>does not</u> require an increase in tube surface, with a proportional increase in heater purchase price. This is a commonly misunderstood point. This defining information provided in the performance schedules of the technical specification simply requires the Vendor to check his mechanical design, physical internal geometries, and construction issues to insure that the replacement heater can safely and conservatively withstand the projected full range of load imposition and provide continuous, undamaging operation all the way up to the worst abnormal potentials.

TABLE 1 - HEATER NO. 5 MODEL RESULTS

Heater #5 Design Ratings and Overloads		Original Design Data	New Design Guarantee Point	Abnormal Case 1 Low Load Max. FW Flow Single Boiler	Abnormal Case 2 * Degraded FW Inlet Temperature ~ 20 °F Lower
Gross Load MW	MW	850	850	390	850
Feedwater Flow	lb/hr	2,883,134	3,000,000	3,000,000	3,000,000
Feedwater pressure	psia	3215	3215	2800	3215
Feedwater Inlet Temp	deg F	322.8	325.7	271.6	305.7
Feedwater outlet temp	deg F	359.7	372.5	319**	371.5**
Steam Flow	lb/hr	87,693	117,639	112629**	161689**
Steam Press	psia	162.2	189.9	94.5	189.9
Steam Temp	deg F	724.5	728.0	727.8	728
Saturation temp	deg F	364.6	377.5	323.8	377.5
Drain Inlet Flow	lb/hr	361,060	349,316	303,758**	352,666**
Drain Inlet Temp	deg F	369.6	382.5	328.8**	382.5**
Drain Inlet Enthalpy	Btu/lb	342.6	356.3	299.6**	356.3**
Drain Outlet Flow	lb/hr	448,753	466,955	416307**	514355**
Drain Outlet Temp	deg F	332.8	335.7	281.6**	316.7**
TTD	deg F	4.9	5.0	5**	6**
DCA	deg F	10	10.0	10**	11**
FW Pressure Drop	psi	12.9	10.0 max.	TBP	TBP
DSH Pressure drop	psi	1.8	TBP	TBP	TBP
DC pressure drop	psi	2.9	TBP	TBP	TBP

TBP = To be predicted by heater manufacturer

* Hypothetical overload data is approximated as 140% of design steam flow entering heater

** Assumed data

Another operation scenario that was modeled is operation with only one of the two dual boilers in service. When this occurs the feedwater flow for the boiler in service is the same as full load flow as with both boilers operating, 3000 klb/hr, but the unit is only at half load. Since the unit is at half load, the dearator heater operating pressure is lower which corresponds to a reduced feedwater inlet temperature. The shell operating pressure of the heaters is also lower, corresponding to less heating. However, even though the unit is at half load, the one boiler full load flow of 3000 klb/hr causes the model to predict almost the same steam flow as full load with both boilers in service. This is because the heaters are still operating at full capacity. Normally, the feedwater flow and required extraction steam flow would be reduced at half load and an overload potential would not needto be considered. Note that this is not a common relationship in most plants unless they have dual independent boilers. However, this particular application serves as an excellent example of analyzing the specific operating requirements of the heater system and specifying the heater requirements accordingly.

Note that in the specification analysis, the objective is to consider all modes of operation reasonably expected and to consider how long the heater may be operating in that mode. The model analysis results listed in Tables 1 and 2 for the overloads are based on an estimate of the TTD and DCA that we predict based on either operating experience in that mode, or if necessary, the performance is estimated by using the NTU-effectiveness method calculations[7]. We then input that predicted TTD and DCA into the model and iterate to the required steam flow. The data that is calculated for the overload modes is based on these results and/or assumptions. They provide a reasonable flow estimate with which to calculate the shell and tube side velocities and other parameters required to ensure the heater life is not significantly shortened by operating this way. The heater Manufacturer may be able to refine these calculations with their own heater rating programs.

DISCUSSION OF REPLACEMENT HEATER SPECIFICATION

The heater Vendors solicited are instructed to submit their bids based on the performance schedules presented in Tables 1 and 2. The bids are then technically evaluated for specification compliance at the new design point and the worst overload(s) conditions identified. Information requested in the proposals will allow checks and calculations of important parameters and compares them to the HEI and EPRI recommended guidelines referenced in the specification for compliance. Some of the major areas checked are as follows:

TABLE 2 - HEATER NO. 6 MODEL RESULTS

Heater #6 Design Ratings and Overloads		Original Design Data	New Design Guarantee Point	Abnormal Case 1 Low Load Max. FW Flow Single Boiler	Abnormal Case 2 * Degraded FW Inlet Temperature ~ 20 ^{o}F Lower
Gross Load MW	MW	850	850	390	850
Feedwater Flow	lb/hr	2,883,134	3,000,000	3,000,000	3,000,000
Feedwater pressure	psia	3215	3215	2800	3215
Feedwater Inlet Temp	deg F	359.7	372.5	318.8	352.5
Feedwater outlet temp	deg F	406.6	410.7	351.6**	409.0**
Steam Flow	lb/hr	116,874	99,750	80,073**	149,484**
Steam Press	psia	266.3	278.9	137.5	278.9
Steam Temp	deg F	844.4	869.4	878.7	869.4
Saturation temp	deg F	406.6	410.7	351.6	410.7
Drain Inlet Flow	lb/hr	244,186	249,565	223,685**	255,128**
Drain Inlet Temp	deg F	416.6	420.7	361.6**	419**
Drain Inlet Enthalpy	Btu/lb	393.1	397.9	334.3**	396**
Drain Outlet Flow	lb/hr	361,060	349,316	303,758**	404,613**
Drain Outlet Temp	deg F	369.7	382.5	328.8**	377.5**
TTD	deg F	0	0.0	0**	2.0**
DCA	deg F	10	10.0	10**	10**
FW Pressure Drop	psi	14.5	10.0 max.	TBP	TBP
DSH Pressure drop	psi	2.3	TBP	TBP	TBP
DC pressure drop	psi	2.9	TBP	TBP	TBP

TBP = To be predicted by heater manufacturer

* Hypothetical overload data is approximated as 150% of design steam flow entering heater

** Assumed data

Baffle Details
The baffle types, configurations, percent cuts, and spacing selected for the desuperheating and drain cooling zones impact the heat transfer capability and pressure drop of the respective zone and the details as such are utilized to calculate shell-side mass flow rates and linear velocities. The baffle layouts define the available net flow areas as the steam or condensate flows into each zone, across the tube field array within the specific baffle spacing, and longitudinally through baffle window openings.

Tube Pitch
The tube pitch is the center-to-center distance between the tubes and obviously impacts the net free flow area available for the cross mass flow rates calculated. Increasing the pitch is one way heater rating Engineers can lower the shell-side velocities within the desuperheating and drain cooling zones. By specifying a maximum tube side pressure drop at the new design point, and limiting heater length and zone cross flow velocities at the overload parameters in the specification, the Vendor is forced to open the tube pitch as it is more desirable to have replacement heaters proposed as shorter and fatter as opposed to longer and skinnier.

Maximum Unsupported Tube Span
The two main parameters affecting the vibration potential in the DSH and DC zones are the cross velocities and the maximum unsupported tube spans. If excessive, the tubes may actually collide or rub at the midspan and/or cause excessive wear and fretting at baffle/support locations. Tube leaks can occur very quickly under these dynamic impositions.

Vibration Potential
Based on the above parameters, there are industry accepted empirical calculations that are utilized, as indicated in the EPRI references, the HEI and TEMA. To determine the potential for damaging vibration, important parameters such as tube static deflection (by Sebald), fluid elastic whirling, critical cross flow velocity ratios (by Connors), and natural and vortex shedding frequency comparisons (by Chen) are some of the typical calculation checks performed at design and checked at the worst overload conditions to assure non-damaging potentials across the full load range to be imposed.

Desuperheating Zone "Wet Wall" Margin
Under all modes of operation, particularly during cyclic low-load operation, one must ensure that the tube wall metal temperature at the exit of the DSH zone is at least 1 deg higher than the shell side saturation temperature corresponding to the

pressure at that location. If not, localized condensation can develop, causing entrained water droplet impingement damage on tubes, supports and baffles. Vendors must verify their proposed design to comply with this requirement.

Drains Cooler and Desuperheat Zone Bypasses

Limitations imposed by the Specification based on the performance predictions help in some cases to define the thresholds of when system modifications are necessary to give the Unit Operators greater flexibility during abnormal operations. The inability for the Vendors proposed designs to comply with the specification due to the sizing restrictions, provide the justification to incorporate external DC and/or DSH zone bypasses because the replacement heater simply cannot safely compensate for the overload imposition. Rather than allow the heater to destroy itself trying to satisfy thermodynamic equilibrium during overloads, Operators will have predetermined instructions for the safe bypass and alleviation of excessive steam and drainage flows during certain specific modes of operation. “Wet-wall” conditions at the DSH outlet during cyclic/low-load operation, (discussed later herein) is another area of similar concern. These considerations for modifications to the piping system have recently been acknowledged in the newest edition of the HEI published in 2004. External feedwater bypasses can also afford significant counter impact on possible overloads, however this is usually more costly since it is related to much heavier wall piping and valving than the shell side systems.

Shell Inner Diameter and Nozzle Sizing

Shell sizing must be based on the overload potentials to insure that conservative flow areas between the bundle outer tube limit and the shell ID exists that promote longitudinal distribution of the steam and lower penetrating velocities across the bundle as it condenses. Some or all of the shell nozzle sizes may also increase based on HEI guidelines at the overload specification, and the shell sizing is also a function of those nozzle sizes. As the inner diameter increases, the shell-side velocities decrease. For Vertical Channel Down replacement heaters, shell size is also a function of obtaining the required capacitance, (area of available condensate volume per inch of level), and is usually limited within the constraints of the physical room available surrounding the existing heater installation. The Specification should identify the maximum size limitations for the replacement heater.

Based on these parameters and the results of calculations, the heater bids may be compared and evaluated on an equal basis for specification compliance and the requested heater design durability.

In addition to the heater mechanical integrity checks, the heat transfer of each zone should be checked and verified that it produces the required energy balance and that the respective heat transfer coefficients are reasonable. This check can also be accomplished using a performance model where the energy balance through the simplified design mode is a useful verification.

Level Control

Improved level control is often desired for new heaters, especially those in vertical orientation. New vertical heaters are often larger diameter to provide more internal space to maintain the liquid level. This is often a function of available physical space.

CONCLUSION

This paper has offered an actual Utility plant case study to illustrate how performance modeling can be used to analyze the requirements of a current heater system so as to support the need to generate a proper replacement heater specification. The results of performance runs and predictive calculations provides the necessary performance data and information to generate the new design guarantee point, as well as the potential low-load and overload guidelines. The solicited heater Manufacturers now have the required information in a tabularized Performance Schedule of the replacement Specification for optimum heater rating and sizing. Identifying the full range of load imposition allows them to check and verify their respective design to be safe and non-failing over the full potential of future operations, thus ensuring longer heater life.

Once the new heater is delivered and installed, a performance acceptance test should be conducted utilizing ASME PTC 12.1 as a guideline, in support of verifying performance specification compliance.

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