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Abstract

A heat recovery steam generator (HRSG) with a vertical separator design as part of the high pressure (HP) module natural circulation system has been developed to increase unit availability in a modern, combined cycle plant that is subjected to rapid startup and shutdown conditions and during extreme load change rates. On most large combined cycle plants, the use of a thick walled steam drum is the limiting component in achieving shorter startup/shutdown times and faster rates of load change. Babcock & Wilcox Power Generation Group, Inc. (B&W PGG), among other things, utilizes its patented vertical separator to supplant the steam drum. The vertical separator performs similar functions to the current steam drum, but is configured so that a thinner, smaller diameter vessel system can be used to reduce the thermal stresses and allow for quicker warm ups and faster online operations of the HRSG. One or more vertical separators can be adapted to the HRSG with similar capabilities and capacity as a steam drum. The vertical separator will be offered as an enhancement to the HRSG product line for applications that require very fast startup and transient operation.

This paper discusses the design aspects of the HRSG vertical separator design and the analysis of several HRSG critical pressure part components through finite element analysis (FEA). Discussion of the performance and incorporation of the vertical separator into the circulation system of the HRSG module will be presented. The benefits of the vertical separator include little or no ramp rate limitations, improved fatigue life, and economic cost advantages compared to a comparable steam drum design.

Introduction

As power producers increase their power generation from renewable sources, a major challenge exists in balancing the load demand to the grid. Renewable power from solar or wind can be erratic due to inherent environmental fluctuations they operate within. For this reason, it is important for today's power systems to be flexible in delivering a suitable supply of power for stable grid loading. Power plants will need to be capable of generating efficient power at both base and partial loads, be capable of frequent startups and shutdowns, and most importantly, be capable of starting up rapidly to balance the power needs for an active power grid.

A natural gas-fired combined cycle power plant (CCPP) is one alternative to meet these power demands. The natural gas-fired CCPP units usually have a lower initial cost, can be constructed in a short amount of time compared to other boiler types, and offer a highly efficient power plant with low emissions. To obtain higher efficiency from a CCPP design, gas turbine (GT) manufacturers have increased the gas temperatures and flow rates from the gas turbine, which allows the HRSG to be designed with a higher temperature and pressure steam turbine cycle. This results in a CCPP design that can deliver efficiencies greater than 50%. However, the major drawback with the higher operating pressure of the HRSG is the need for thicker wall pressure vessel components. This in turn has been shown to be a limiting factor in the startup time for the HRSG.

In response to this issue with the higher pressure and temperature HRSG, B&W PGG has developed a new rapid start HRSG boiler. This HRSG boiler is designed with a vertical steam separator that will eliminate the need for the thick-walled steam drum that is typically used on most HRSG designs. This paper will discuss the design aspects of the HRSG vertical separator design and the analysis of several HRSG critical pressure part components through finite element analysis (FEA). Discussion of the performance of the vertical separator on another transient boiler application and incorporating the separator into the circulation system of the HRSG module will be presented. The benefits of the vertical separator include little or no ramp rate limitations, improved fatigue life, and economic cost advantages compared to a comparable steam drum design.

B&W PGG Heat Recovery Steam Generator

B&W has been designing and building steam generation equipment for over 140 years. B&W built its first natural gas-fired waste heat boiler over 50 years ago. In the late 1970s, B&W designed the vertical harp waste heat boiler, which was referred to as the turbine exhaust gas (TEG) boiler. B&W continued to design and market TEG boilers throughout the 1980s, and in the 1990s, it was redesigned and modularized as a bottom-supported HRSG. Since the 2000s B&W has offered HRSGs through licensees and is now developing its newly designed rapid startup, vertical separator HRSG.

There are two choices for an HRSG boiler design: 1) once-through, and 2) natural circulation with a steam drum. Operational issues exist with each design. For the once-through HRSG, thermal fatigue problems have been experienced due to temperature differentials within the final evaporator and the lack of proper distribution of the two-phase flow from the first evaporator. For the natural circulation HRSG with an HP steam drum, an additional amount of startup time is required to allow the drum to absorb heat so that the drum's through-wall temperature gradient is not exceeded before full gas turbine operation is allowed. In most cases, the operational guidelines for drum heat absorption must be followed even for base loading, fast starting, or load cycling. Among other things, through the use of one or more vertical separators (Figure 1) in lieu of the steam drum, the heat absorption limitation can be reduced so that the gas turbine can be allowed to startup without the need for a hold time. This feature is a standard for B&W PGG's rapid load change HRSG boiler design that utilizes the benefits of a traditional natural circulation HRSG, but with the elimination of the HP drum.

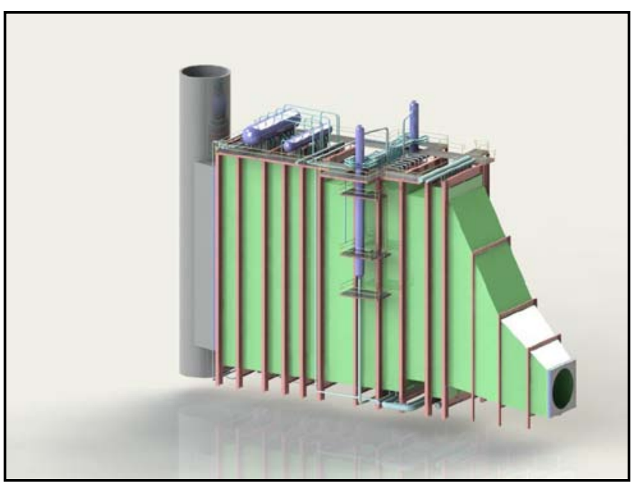

Fig. 1 B&W PGG rapid start HRSG with vertical separators.

Several key aspects of the HRSG design require special attention. The ability to withstand temperature gradients during startup is probably the most important. Other design features to consider include the condensate drain system, the distribution of flue gas from the turbine outlet to the first rows of heat transfer surface in the HRSG, and the thick pressure components, such as the high pressure superheater and reheater header manifolds and vertical separator.

A discussion of these design considerations is provided based upon a typical set of startup conditions for the HRSG.

Startup Time

The startup time required for an HRSG begins with the ignition of the gas turbine and ends when the gas turbine reaches its base load and the steam produced from the HRSG is generating power from the steam turbine. The benefits of a fast startup include:

- maintaining flexibility to offset unpredictable alternative power sources,
- minimizing emissions, and
- increasing efficiency

A typical gas turbine ramp rate is shown in Figure 2. This startup ramp rate is used as the basis for B&W PGG's evaluation of the thick-walled pressure part components, i.e., superheater header modules, reheater header modules, steam drum and vertical separator that are critical to the HRSG cycle life. Fatigue analysis of these major components is performed so that two shift operations during the design plant life do not exceed the components' fatigue life. For the B&W PGG HRSG, finite element analysis was conducted to provide a suitable design of the tubes, headers, harp and module interconnections and vertical separators which could accommodate these startup requirements. B&W PGG also applied these dynamic operating parameters to the circulation and condensate drain system, and elevated drum/separator swell to permit reliable system operation.

A set of typical HRSG startup conditions for a 300 MW combined cycle unit is provided in Table 1. The definition of the start type (i.e., hot start, warm start, or cold start) is determined based upon the time that the plant has been idle

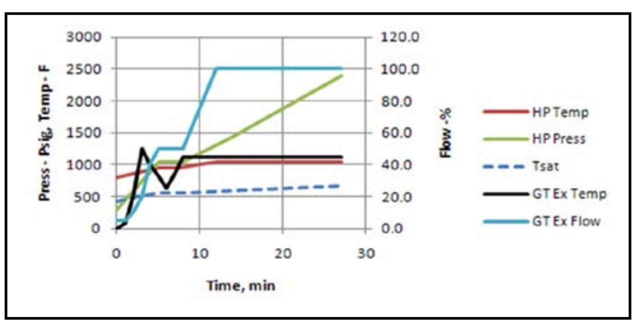

Fig. 2 Typical gas turbine ramp rate for hot startup.

Table 1 Fuel Ultimate Analysis				
Start Type		**Cold**	**Warm**	**Hot**
Time to MCR	Minutes	100	96	27
Drum	Press., psig	2430	2430	2430
	Temp., F	665	665	665
SSH Out	Press., psig	2400	2400	2400
	Temp., F	1050	1050	1050
Lifetime Cycles (30 years)		200	1170	4680

without the turbine operating. The following are typical durations for each start type:

- Hot start ≤ 8 hours
- Warm start > 8 hours and ≤ 72 hours
- Cold start > 72 hours

Features of B&W PGG's Rapid Startup HRSG

General description

B&W PGG's rapid start HRSG (Figure 1) is a top-supported, horizontal gas path design, with three pressure levels and reheat to maximize cycle efficiency. It includes a vertical separator, single row harps in the final superheater (SH) and reheater (RH), and an advanced drain system for effective and reliable condensate removal. A duct burner may be added for peaking purposes or for stand-alone HRSG operation (fresh air firing option would be necessary). For peaking operation when the electrical grid demands the CCPP to increase load, the HRSG pressure parts are designed around the duct burner firing capability to allow the plant to operate at both base load and full duct burner load.

B&W PGG minimized gas-side pressure drop by optimizing pressure part configuration and inlet flue design through computational fluid dynamics (CFD) flow modeling. See Figure 3. These two design features allow for lower back pressure on the GT, which results in improved efficiency.

Emissions are mitigated by integrating a carbon monoxide (CO) catalyst and a selective catalytic reduction (SCR) system into the HRSG. As the combusted flue gas passes through the SCR system, the nitrogen oxides (NO_X) are converted to N_2 and H_2O and CO is converted to CO_2 and H_2O through chemical reactions within each catalyst.

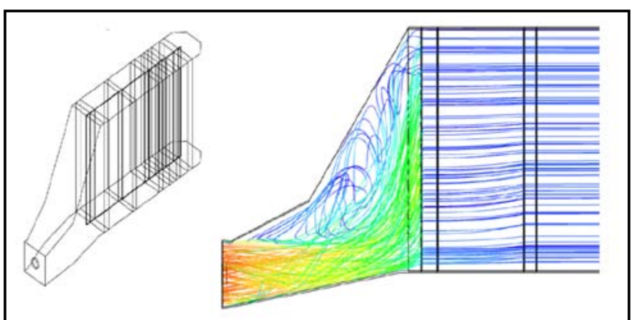

Fig. 3 CFD modeling of the HRSG entrance flue.

SH/RH design

B&W PGG's HRSG utilizes single tube row harps with high alloy steel as a means of providing smaller, thinner walled headers for the final superheater and reheater. See Figure 4. These two heat transfer components are connected to intermediate headers that transfer the steam to the main SH/RH steam outlet header. In analyzing this design through a transient FEA, the header-to-tube wall temperature gradient was reduced due to the thinner walls of the intermediate header which results in less thermal fatigue under rapid startup conditions.

The single row SH and RH harps consist of T91 material grade tubes typically with an outside diameter (OD) of 1.5 to 2.0 in. and wall thickness from 0.12 to 0.2 in. The mini headers used in the single row harps are connected to intermediate headers. The connections between the mini headers and the intermediate headers allow further reduction of stress and evens out the expansion between the single row harp headers and the intermediate headers. The intermediate headers consist of P91 material, typically ranging from 4 to 6 in. OD, with a 0.4 to 0.95 in. wall thickness. The intermediate headers are connected to SH and RH outlet headers. The outlet headers are constructed of P91 or P92 grade material, typically with 8 to 14 in. OD, and thickness from 0.6 to 1.4 in. Sizes of reheater headers can be larger based

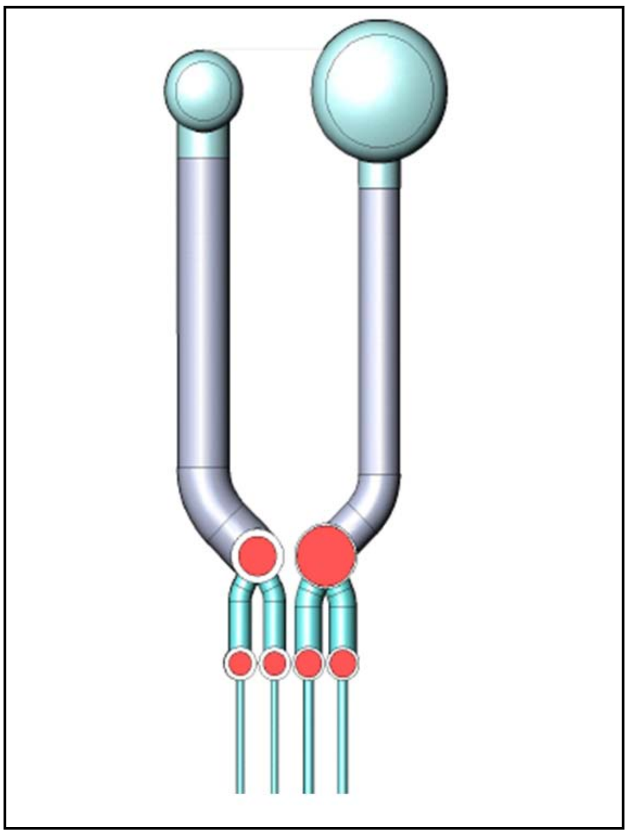

Fig. 4 Single row harps in final SH and RH.

on steam-side performance and pressure drop conditions. All components used in the SH and RH design are based on the specific pressure and temperature range of the HRSG design, so variations may occur as the design parameters change.

Details of the FEA results are provided later in the paper. The thinner wall components were found to minimize the thermal gradients in the overall design reducing the potential for failures in the thick-to-thin joints during rapid startup and cycling. The higher alloy materials in the SH and RH allow a thinner component design which facilitates fast start/cycling conditions.

Drain system

During GT purges and light-offs, the condensation generation rate can be significant, especially within the first couple of tube harps of the SH and RH. The condensation that is formed must be drained and the drain system must be fully functional and capable to keep up with the rate of condensate formation as the GT load ramps up. Inadequate condensate removal is a common industry problem, leading to failures in the tubes and tube-to-header welds. B&W PGG's drain system is based upon a review of past issues and recommended guidelines [Reference 1] and meets the needs of a fast startup/cycling condition.

Each HRSG design will incorporate a unique drain layout based on the specified performance of the unit. The final SH and RH modules, typically where the majority of the condensate forms, consist of connections at the center and both ends of the header, as well as a set of connections on the lower interconnecting steam piping. These connections drain to a blowdown tank using a single run of pipe for each component. All drain piping is carefully sized to provide adequate flow capacity and maintain flexibility. An appropriate drain slope is used to direct flow into the blowdown tank. The use of martyr valves, main control valves, and drain pots are implemented into the system. These components work with temperature detection devices so that only condensate leaves the drain system at the appropriate temperatures and times. A typical drain system is shown in Figure 5.

Vertical separator

The limiting factor in the startup ramp rate of a typical HRSG is the high pressure steam drum because of the heat absorption time necessary to minimize the temperature gradient of the steam drum metal. As a result of the thickness of the HP drum, HRSG suppliers will specify a minimum

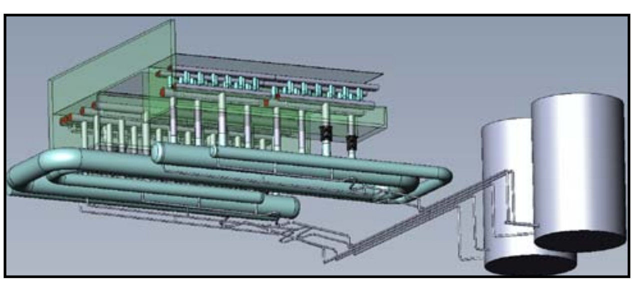

Fig. 5 Typical HRSG condensate drain system.

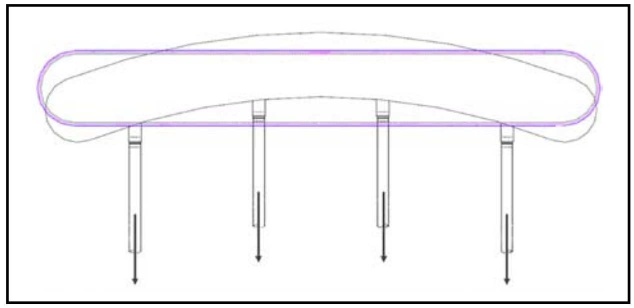

Fig. 6 Schematic of drum humping.

hold time for the gas turbine at a low load during startup to allow the HP steam drum to slowly increase in temperature to minimize the top-to-bottom metal temperature differences. Failure to minimize the HP steam drum temperatures results in lower metal temperatures along the bottom water-wetted surface and higher metal temperatures along the upper steam cooled surface. This temperature difference results in bowing of the drum, referred to as drum humping. (See Figure 6.) This effect can limit the life span of the HRSG.

Drum humping places significant stress on the heavy riser and downcomer connections of the drum and can also result in exceeding the stress/fatigue limits of the drum shell itself. To determine the amount of damage being done to the connections or shell material, HRSG suppliers will often recommend monitoring the number of fast start events, and recording and documenting the damage being done to the components.

B&W PGG's patented vertical separator (see Figure 7) eliminates the need for an HP steam drum, most of the drum internals, and the startup limitations associated with

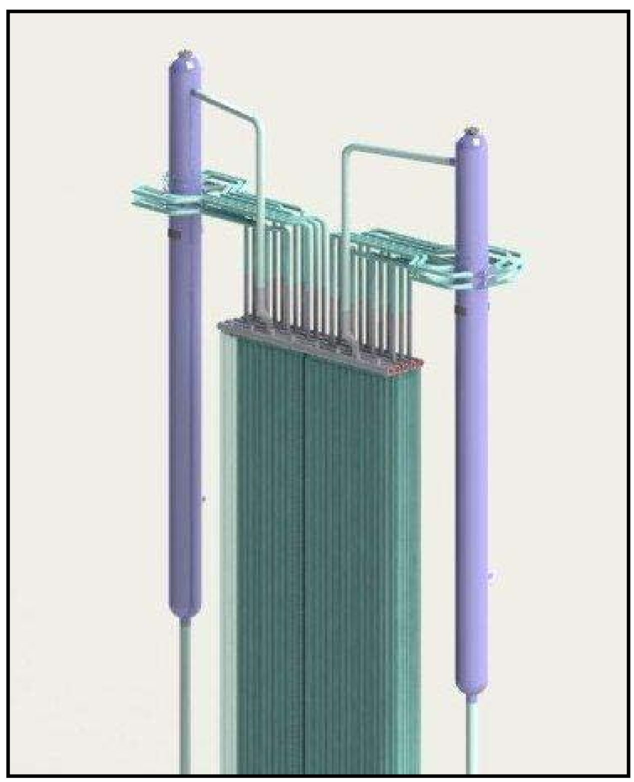

Fig. 7 Vertical separator on B&W PGG's HRSG.

the drum. Startup rates that could only be achieved with a more costly once-through HRSG are now available with this new design. Unlike the once-through design in which extra generating bank surface is needed and downward circulation and distribution of 2-phase flow is a concern, the vertical separator replaces the HP drum without any modifications to the existing pressure parts, and retains the benefits of a simple natural circulation circuit.

The vertical separator is supported at approximately the same elevation as the upper tube bundle headers. The thermal expansion of the vertical separator and downcomer thus approximates the expansion of the bundle. This parallel expansion minimizes stresses at supply and riser connection points. Unlike a horizontal steam drum, the full cylindrical area of the vertical separator below the normal water level can be utilized for feedwater storage to the desired hold time. The amount of water holding capacity is designed to contract requirements.

The tangential entry of the riser piping into the vertical separator results in an integral primary steam/water separator. With the addition of secondary mechanical chevron-type separators, the same steam purity as a traditional steam drum is achieved. The high quality steam exits the top of the vertical separator and is routed to the high pressure primary superheater. (See Figure 8.) The use of the B&W PGG vertical separator design results in the same fast start benefits of a once-through design with the ease of operation and cost benefits of a natural circulation design.

Water level control within the vertical separator is designed to meet the cyclic conditions expected for a CCPP. As a result of these extreme conditions, the circulation design of the HP module is analyzed for a wide range of water levels within the separator. The design is thoroughly analyzed for highest and lowest water levels points within the separator. The lowest point is designed to be just above the point where the feedwater enters the drum, which can be several feet below the upper outlet headers of the evaporator circuits.

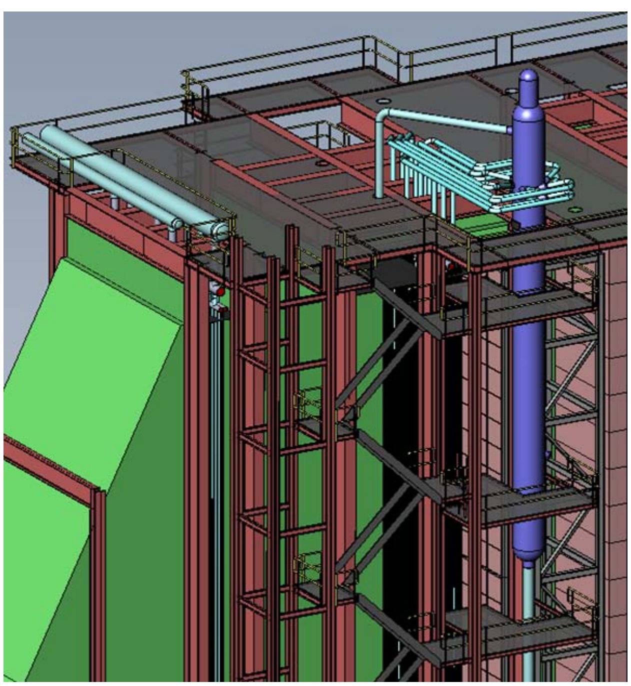

Fig. 8 Arrangement of vertical separator on HP module of an HRSG.

HRSG Circulation Analysis

B&W PGG's design provides the proper circulation system for the design conditions the boiler is expected to experience during typical operation. Through circulation design analysis, the boiler components can be sized properly and more economically for the expected operational conditions.

B&W PGG has developed an extensive set of design requirements for HRSGs to meet the demanding conditions required for today's combined-cycle power generation operation. In addition to the typical steady-state circulation analysis, transient operation of the boiler was also investigated. The analysis led to a design that reduced the need for special and costly features, like additional water-holding capacity for the unit through the use of larger steam drums. Analyzing for flow excursions (Figure 9) during load changes and transient operation can be used to optimize the supply and riser connections to the heat generating surface. An optimized circulation system design provides a reliable HRSG, which eliminates most of the operational issues that result from an improperly designed unit.

B&W PGG's boiler circulation analysis computer program utilizes advanced techniques for calculation of heat transfer and single- and two-phase fluid flow parameters. With this computer program, a circulation model of each individual circuit of an entire boiler is evaluated. Circuits within the HRSG are subject to a variation in heat transfer across its width and depth. The computer program manages this by allowing the designer to divide each circuit into zones. The designer is then able to determine the balanced water and steam flow in each zone by solving the energy, mass and momentum equations. At the balanced flow condi-

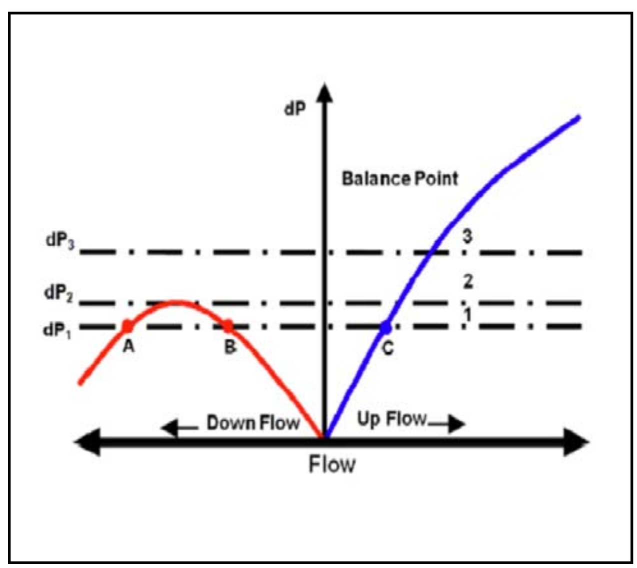

Fig. 9 Typical flow stability/excursion check.

tion, design criteria are examined allowing the designer to determine whether circulation characteristics are adequate.

For each condition, adjustments are made to individual circuits, when necessary, to bring their flow characteristics within acceptable limits. These limits are based on B&W PGG's experience, both in the field and through research center testing. Adjustments to improve circuit circulation can include, but are not limited to, determining the appropriate number of steam separators in the steam drum or incorporating a vertical separator; adding orifices at the entrance or within individual circuits; altering the number of supplies and/or risers; and lowering feedwater temperature entering the steam drum. Each circulation analysis is unique and the requirements to achieve acceptable circulation characteristics are case-specific to the boiler and operating conditions being examined.

HRSG design considerations include exit quality from each outlet header, velocity within the tubes and circulation connections, sensitivity of the evaporator tubes to heat variation and load change, static and dynamic flow stability of the evaporator system, departure from nucleate boiling (DNB), Figure 10, and drum/vertical separator steam separation performance.

Fatigue life assessment using finite element analysis

Life assessment of critical HRSG components requires fatigue analysis. The fatigue life analysis results for a secondary superheater outlet header (SSHOH), HP drum and vertical separator for a typical HRSG design are discussed in this section. The main objective was to study the effect of transient conditions brought on by fast startup and shutdown rates, along with high design temperature and pressure on the fatigue life of the various HRSG components using FEA techniques. SSHOHs are connected to the single tube row harp which is located near the inlet flue and are exposed to the hot turbine exhaust gases resulting in some of the highest temperatures within the HRSG components.

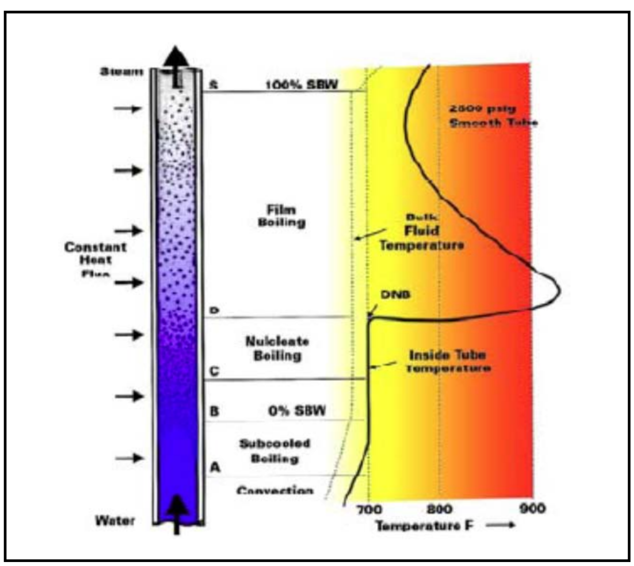

Fig. 10 Characteristics of departure from nucleate boiling.

The FEA investigated the state of stress resulting from heat transfer-induced thermal differentials between the tube stubs and vessels/headers. To optimize computational resources, only segments of the components were modeled by utilizing the symmetry boundary conditions. The temperature-dependent material properties were used for the FEA. The thermal boundary conditions were applied in the form of surface film conditions for the different startup cycles (cold, warm and hot). Quadratic hexahedral twenty-node and quadratic tetrahedral ten-node heat transfer and structural stress elements were used for the heat transfer and stress analyses respectively. The sequentially coupled thermal stress transient analyses were performed to observe the stresses in the components due to thermal differentials brought on by the transient thermal conditions. ASME Section VIII, Division 2 guidelines were followed to calculate the fatigue life usage factor for all components. For combined (multi-axial) stress states, the stress intensity provides a convenient basis to compare to the usual uni-axial material properties and is the underlying basis for fatigue analysis.

Highly flexible high pressure superheater harps

B&W PGG has extensively analyzed the design of the harps of the HRSG for both high cycling applications and fast start operating scenarios to maximize operating life. For challenging applications like fast start and high cycle applications, single row harps for both the high pressure superheater (SH) sections and the reheater (RH) sections of the HRSG are recommended. The single row harps provide the flexibility needed in the tube-to-header connection, and permit the use of smaller diameter upper and lower headers. As with the high pressure drum, fast start conditions in thick-walled headers can result in the same bending and high localized stresses at interconnecting piping and tubes. The small diameter header used with a single row harp can use a thinner material which also allows for faster ramp rates without exceeding the allowable stresses on the components.

Figure 11 shows meshes utilized for the high pressure SSHOH models. The multi-tube harp header model is shown on the left, and the single row harp model is on the right.

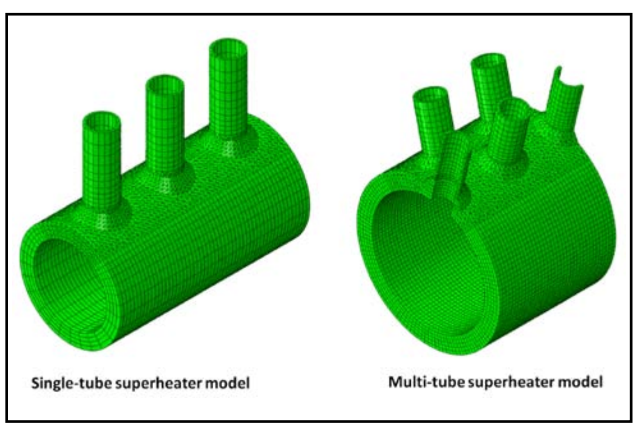

Fig. 11 FEA mesh for superheater headers.

For the regions of interest in the components the mesh was appropriately refined locally. The details of the weld region were modeled as these locations have been observed to greatly affect the fatigue life of the HRSG components. For the structural boundary conditions, the symmetry boundary conditions were enforced at both ends of the header with appropriate restraints applied to simulate the effects of a continuous header. From the standpoint of pressure and thermal stresses in the vessel, incorporation of internal components was deemed to be unnecessary. The top-to-bottom temperature differentials at the startup and shutdown cycle result in drum/header humping with large additional stresses. The structural boundary conditions were selected to include the effects of vessel humping in the models.

The temperature contour plot representing a time in a startup-shutdown cycle of a single row harp arrangement is shown on the left in Figure 12, and the contour plot for the multi-tube harp arrangement (only portion of the model) is shown on the right. Figure 13 shows the von Mises stress contour plot of a SSHOH at a particular time in a transient startup-shutdown cycle for single and double row harp arrangements. The maximum stresses in the component occur at the bore hole, which is prone to fatigue damage as highlighted by the red contours. The high localized stresses result in initiation of the crack in the component and successive cyclic loading enlarges the crack and eventually leads to fatigue failure of the component.

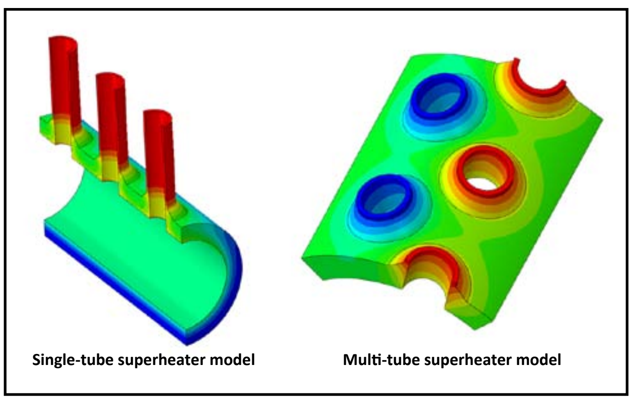

Fig. 12 Temperature contour plot for superheater headers.

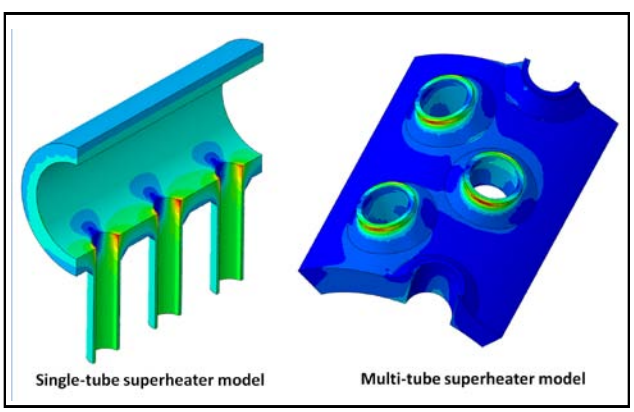

Fig. 13 von Mises contour plot for superheater headers.

Fig. 14 Steam drum.

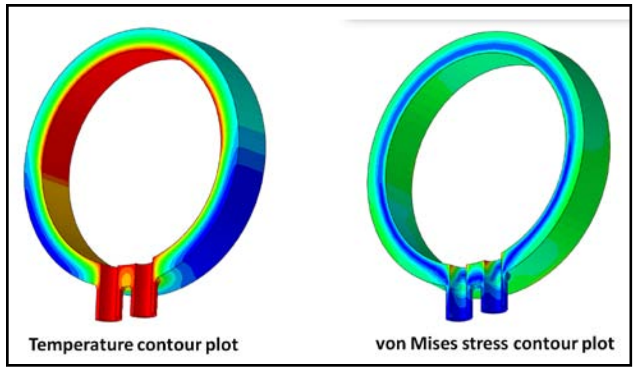

Fig. 15 Temperature and von-mises contour plot for HP drum.

Vertical separator and high pressure drum

Figure 14 shows a manufactured drum with stubs, manway door (top-left corner) and other attachments ready to be shipped. The left side of Figure 15 shows the thermal profile of the HP drum segment at a particular time of a typical cold startup cycle, and the right side shows the von Mises stress contour plot at the same time. The red colored contours indicate high temperature and high stress regions.

Figure 16 is a typical vertical separator during installation. Figure 17 shows a segment from the vertical separator that was modeled for the FEA. The left side of Figure 17 shows thermal profile contours for the vertical separator segment at a particular time in a typical cold startup cycle. On the right is the resulting von Mises stress contour plot at that same time. The red color highlights the regions of high temperature in the temperature plot and the associated high stresses in the von Mises contour plot.

Fig. 16 Vertical separator.

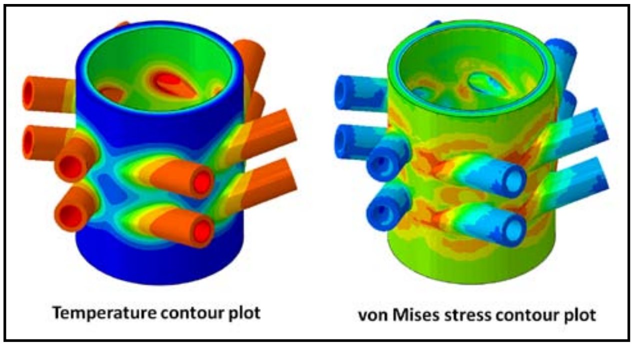

Fig. 17 Vertical separator temperature and von Mises contour plot.

Table 2 shows a typical result for the SSHOH fatigue life usage comparing the single row and the multi-tube harp arrangement for the cold startup cycle. Test results indicate that the multi-tube harp arrangement sustains large fatigue damage in the cold startup cycle in comparison to the small fatigue life usage for single row harp arrangement. Similar observations and results from different FEA models for various startup-shutdown cycles confirmed B&W PGG's recommendation of using the single row harp arrangement for the high pressure superheater and reheater sections of the HRSG.

Table 3 lists the fatigue life usage factor for the HP drum and the vertical separator for the cold, warm and hot startup-shutdown cycles. Test results indicate that fatigue life usage for the vertical separator is superior to the HP drum under the rapid changes in transient temperature and pressure boundary conditions. The thicker drum under-performs in fatigue life when compared to the relatively thin vertical separator under the rapid startup-shutdown transient conditions. Under these startup-shutdown cyclic transient conditions, the estimated drum fatigue life would be about 16.5 years. Thus, the fatigue life estimates point to the need for regular drum monitoring and inspection and may require expensive drum repair and/or replacement through the life span of the HRSG.

Table 2
Fatigue Life Usage for Secondary Superheater Outlet Header (SSHOH)

Cycles	SSHOH	
	Single-row	Multi-tube
Cold	1%	35%

Table 3
Fatigue Life Usage for Vertical Separator vs HP Drum

Cycles	Vertical Separator	HP Drum	Design Cycles
Cold	1%	10%	200
Warm	6%	32%	1170
Hot	18%	140%	4680
Total	25%	182%	6050

Conclusions

B&W PGG has introduced a new concept for a rapid start HRSG by, among other things, incorporating the use of one or more vertical steam separators for a HP steam drum. The technology that has been incorporated into this design is expected to provide enhanced performance compared to the current HRSG designs and has been developed based upon the demands and needs of our customers. The operational flexibility offered by this HRSG design will enhance the fatigue tolerance of the design for dispatching and cycling the combined cycle plant.

With the vertical separator, thinner pressure part components, advanced drain system, state-of-the-art circulation system, proprietary heat transfer modeling program, and detailed finite element analysis, B&W PGG's HRSG is designed to accommodate rapid load changing demands.

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