Study and Design Considerations of HRSG Evaporators in Fast Start Combined Cycle Plants

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Abstract

Combined Cycle plants with fast startup times are increasingly being used in modern power plants as they save energy and help to meet increasingly stringent emission requirements. These plants are also serving as backup power for renewable energy sources. However, these designs also offer challenges to HRSG suppliers and designers who must evaluate all components in the system to verify the design for operation with fast startup times and the effect on life cycle consumption.

This paper deals with the effect of fast startup on the evaporator design and its impact to the overall design and operation of the HRSG. This paper also offers comparison with a normal or traditional startup. The need to verify the design of evaporators for fast startup is explained. The design issues are analyzed and compared with normal startup and fast startup modes. The issues in evaporator tube bundles, effect of temperature differences across tube rows, downcomer contributions and temperature differences across the drum shell during both normal and fast starts are compared. The details of modeling and startup analysis carried out to obtain data for these analyses are explained. This paper also discusses how the data obtained from startup analysis were utilized in evaluating the mechanical design of evaporators and all its components.

Finally the results of the analyses are concluded with reference to design, operation and the effect on expected evaporator life.
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Introduction

Large heat recovery steam generators (HRSGs) are increasingly required to be designed for cyclic operation and also required to meet faster startup times. The ability of horizontal HRSGs cyclic operation has been discussed and widely reported in literatures and studies. However, the operation and design life of HRSGs becomes more important when the system is operated with fast startup times.

The expected life of HRSG components is governed not only by the stress level during normal operation, but also by stresses resulting from transient thermal and mechanical loadings. In an effort to design units with acceptable creep and fatigue life, designers have done considerable work on the components associated with the highest operating temperature, components of the Secondary Superheaters, and Hot Reheaters. This work focused on creep and fatigue effects in header, header nozzles, and tube to header geometries because the combustion turbine (CT) exhaust gas temperatures and temperature transients are more directly impacted in these HRSG elements.

However, the focus on these critical components does not guarantee that similar effects do not also affect components operating at lower temperatures. The purpose of this discussion is to examine the behavior of the high pressure evaporator. The HP evaporator is of interest because its location in the HRSG makes it more sensitive to CT exhaust gas temperature transients than the lower pressure evaporators. While material creep degradation is not an issue at the operating temperatures of the evaporator, fatigue problems can indeed be of significance. In the past, evaporator material degradation has been minimal due to the slow startup transients experienced by these components located substantially away from the CT. With today’s emphasis to reduce the cost of each plant start by reducing time required to achieve full load operation, knowledge of past evaporator behavior may no longer be applicable. For this reason, a comparison of the impact of accelerated startup on the evaporator system was studied and a comparison between fast and conventional startups is presented in this paper.

HRSG Evaporator System

The natural circulation HP evaporator system, in normal operation, is conceptually very simple. The water in the tubes is heated to boiling. The reduced density, resulting from boiling in the tubes, creates a low density emulsion that drives the circulation. As the emulsion rises in the tubes, water from the drum, descends through the downcomer(s) to reenter the tubes. In this steady-state operation, the
temperature distribution in all of the evaporator tubes is essentially the same because the system operates at saturation conditions.

During startup transients, however, important differences occur. Prior to the CT firing, there is no circulation and all evaporator tubes as well as the downcomers are filled completely with water. Upon CT firing, the rising flue gas temperature will start heating the water in the evaporator tubes. The water in the front tubes will heat faster than in the rear tubes. This will continue until the water in the front tubes starts to boil, initiating circulation. What is significant is that the tube metal temperature will be near the water temperature in that particular tube. In other words, there will be a tube metal temperature variation, high in upstream most tube rows and low in downstream tube rows. That tube metal temperature distribution causes the differential thermal growth of the tube between adjacent tube rows. As the startup progresses, the temperature difference between the front tube rows and rear tube rows diminish until steady operation is achieved and the thermal growth differences are essentially eliminated.

At the next higher level of detail, it must be recognized that the above description of the process is a significant over-simplification. In the heating process, the water is initially in the sub-cooled state. In this state, the heat transfer is governed by the metal to water heat transfer coefficient without significant flow. Once boiling starts, with the subsequent circulation initiation, the heat transfer mechanism changes to saturation conditions with flow.

The HP evaporator in a HRSG is typically structurally different than superheater or reheater assemblies. This is primarily true since all of the evaporator tube elements are connected to a common drum at the top and relatively short pipes at the bottom. By definition and location either outside the gas stream or downstream of all evaporator tube rows, especially in natural circulation units, the downcomer temperature will be lower than the tube temperature in the assembly. These conditions create stress sensitivity to differential thermal growth that is restrained by a relatively stiff structural system.

In the CMI design, the HP evaporator system is made up of a number of parallel modules. These modules are mechanically independent of each other, except they utilize the same steam drum. The heating surface module is comprised of tube bundles of finned tubes. Each module is serviced by a single downcomer. The following diagrams illustrate the generic arrangement used in CMI Energy design evaporators
Aside from the behavior of thermally-induced stress in the tube and piping system of the evaporator, the rising water temperature in the drum causes a temperature gradient through the drum shell wall. This gradient creates shell stresses that are magnified at nozzles and man ways. These stresses will also be magnified as the startup is accelerated. Analysis of these types of stresses and the related fatigue consideration are similar to that applied to superheater headers. For this reason, drum shell stress will not be discussed in detail here.

Analysis approach

Evaporator system design is analyzed in a two step approach. The first step is to perform a transient analysis and the second step is to evaluate the impact on mechanical design due to fast startup from the transient analysis data.

The transient analysis consists of modeling the HRSG system in a transient analysis program and evaluating the effect of tube metal temperatures at various time intervals comparing both normal and fast startups.

The mechanical design analysis for the evaporator system consists of analyzing the redundant loads on the headers and manifold systems. This analysis also evaluates the impact of fast start on estimated design life compared to normal startup operation of the evaporator.

The parameters analyzed in the evaporator are: a) the differential temperature of tube bundle platens; b) elastic system analysis; and c) relative flexibility analysis of header- feeder systems. The differential temperature between the platens is evaluated because during the startup phase, the temperature difference between the
platens will cause fatigue stresses in the connecting manifolds and headers. The elastic behavior and flexibility is greatly affected by this temperature difference and presents a need to evaluate transient conditions and stresses during startup. Hence, these are then evaluated using classical analysis or finite element analysis techniques utilizing the data obtained in transient analysis.

**Effect of fast startup in HRSG design**

During normal operation, the metal temperature of the tube walls and the downcomer pipe will be very similar and, therefore, will not create significant thermal distortion. During startup transients, the hot CT exhaust will raise the tube metal temperature faster than the downcomer metal temperature. This occurs due to the very large fin area in the tubes and heavy wall thickness of the downcomer with its small surface area. This condition causes momentarily greater thermal growth in the length of the tubes than in the downcomer and results in distortion of the evaporator system.

The difference between a normal startup and a fast start are a matter of degree. The largest impact on the evaporator occurs early in the CT startup, at the time that boiling is initiated in the front tubes. The resulting tube metal temperature differences from the front tubes to the rear tubes and from the tubes to the downcomer create the largest loads that stress the tube and evaporator piping system. In a fast start, this point in time occurs slightly earlier than during a normal startup and has the effect of increasing the stresses. Since the peak stresses occur on each startup, the frequency of startups defines the fatigue life the of evaporator system.

The effect of fast startup is analyzed using the transient analysis techniques described below. This analysis provides the data on GT gas start temperature and evaporator tube and downcomer metal temperatures.

**Transient Analysis**

The data required for Transient Analysis has been generated using the commercial HRSG simulation software KED Boiler Dynamic®.

The evaporator model has been built and analyzed in KED Boiler Dynamic® using one of the CMI HRSG design models. The following gives the model details of evaporators built for transient analysis.
Figure 2. Boiler Dynamic Water System model

Figure 3. Boiler Dynamic Evaporator Model

The following composite plots of CT gas temperature at the inlet to the evaporator and evaporator tube metal temperatures show the effect of fast startup on tube metal temperatures compared to normal startup in evaporator.
Figure 4. CT Gas temperature Normal start vs Fast start

Figure 5. Tube metal temperatures in Platens - Normal Start
Figure 6. Tube metal temperatures in Platens - Fast Start

Figure 7. Downcomer metal temperatures fast start vs. Normal Start
**Mechanical Design**

There are two basic approaches for creating sufficient system flexibility to accommodate thermal growth differences occurring in the evaporator. Examples of these approaches are releaser pipes with many bends from the upper headers to the drum or a similar approach for the feeder from the downcomer to the lower evaporator headers.

While these approaches are effective, CMI has chosen a more subtle approach. In an effort to keep the evaporator system compact and to minimize added pipe routing related clutter under the HP Drum, CMI uses an arrangement of relatively straight (stiff) releasers from upper headers to the drum. This permits using the HP Drum as an evaporator support beam. This relatively stiff upper evaporator arrangement requires that the flexibility needed to accommodate the various conflicting thermal growths are provided at the bottom of the assembly. Here some of the feeder pipes can be somewhat smaller in diameter and most of the length of the pipes can be run horizontally, maximizing their ability to absorb vertical thermal growth differences efficiently.

The arrangement of tube bundle platens, downcomers, headers and manifolds in CMI’s design is given below:

![Figure 8. Arrangement of manifolds, headers, feeders and releasers](image-url)
Thermal growth induced stresses in tubes and piping systems are primarily a matter of the mechanical stiffness of these systems. The challenge for the HRSG designer is to provide adequate flexibility in this system without adding to the space and cost required.

In the CMI system, this is accomplished by adjusting the length and diameter of the feeders that connect the downcomer manifold to the lower evaporator headers. By making the feeders sufficiently flexible, the redundant loads that govern the bending in pipes and headers are controlled. The feeder and reliever pipe sizes are also evaluated for performance by circulation studies.

It is interesting to note that during the critical time period in the startup phase, the tube bundles and downcomer will move as shown below as a result of instantaneous thermal growth. Figure 8 shows a complete system. It is noteworthy that it includes 3 bundles that are fully independent of each other except that they are all supported from the same drum. Therefore, for the purpose of the discussion the focus will be on only one bundle.

As can be seen in Figure 9 above, the unrestrained movements of the individual components is not compatible with the other components in the system. This results in some distortion of the system as the different components are forced into compliance. The exaggerated transient distortion diagram (Figure 10) shows how the thermal growth motions are accommodated.
Analysis Results

The following table gives the maximum temperature difference occurring at 1830 seconds in the evaporator structure as determined by transient analysis for a typical case.

<table>
<thead>
<tr>
<th>Location</th>
<th>Temperature T (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Platen</td>
<td>273</td>
</tr>
<tr>
<td>Center Platen</td>
<td>214, 222</td>
</tr>
<tr>
<td>Rear Platen</td>
<td>198, 210</td>
</tr>
<tr>
<td>Downcomer</td>
<td>209, 207</td>
</tr>
</tbody>
</table>

Figure 11. Maximum metal temperature difference at a critical time period (1830 seconds)
Fatigue analysis results, showing the difference between normal and fast start, are given below:

![Fatigue analysis results](image)

**Figure 12. Fatigue analysis results**

When performing this analysis, it was assumed that the system would experience one cold start every three days for 30 years. While the cold start does have the most severe impact on evaporator fatigue stress, the resulting 3660 cold starts is a conservative, although unrealistic case. The life utilization, shown in Figure 12, results from this 3660 cycle assumption. The analysis showed that the maximum fatigue effect occurs in the piping at the bottom of the evaporator, in particular, the feeders that bridge from the manifold to the lower headers. From the previous plot, it is seen that the tube bundle metal temperature is higher in the transient condition during critical time period of fast startup phase compared to normal startup and operation. The fatigue analysis results confirm that the system flexibility is adequate to accommodate the thermal growth motions without creating prohibitive fatigue stresses.

**Conclusion**

Detailed analysis performed on CMI designed evaporators system confirms that for the most severe startup transient, the combination of pipe diameter, wall thickness, length of horizontal pipe run and vertical thermal growth differences are indeed adequate to control fatigue stresses in the HRSG evaporator system. In actual designs, with realistically specified startup cycles and expected years of operation, the life consumption will be less than what is indicated here, but the effect of fast starts will be to increase the fatigue damage. That increase will, however, not limit the planned life of the evaporator.