CYCLIC SERVICE FEATURES FOR HEAT RECOVERY STEAM GENERATORS

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ABSTRACT

In the recent past much has been learned about features of Heat Recovery Steam Generator's, HRSG's that make them susceptible to premature failures from cycling. The recent trend has been to convert from baseload operation to cyclic mode of operation. This has created concern for owner-operators who worry the equipment originally designed to last twenty five to thirty years may only last a few years without major mechanical revisions or updating. This article outlines some of the areas of concern in procuring new HRSG's or updating existing units, what features should be considered in the design if cycling is required and why these feature can provide a robust unit capable of handling the demands of today's market.

For components such as reheater and HP Superheater coils, tube to tube temperature differences can create high internal thermal stresses. The ability of coils to absorb these temperature differences without creating the potential for low cycle fatigue is a necessary design feature. The details necessary to minimize or eliminate these internally generated stresses are discussed.

Through thickness temperature gradients are considered important when determining start up and shut down ramp rates. Keeping the headers that are susceptible to creep as thin as possible helps to minimize the stresses associated with start up and shut down. Several techniques for calculating component thicknesses are presented.

For HRSG's that are required to cycle daily, condensate management becomes a real challenge. Condensate quenching will damage boilers tubes, pipes and other hot sections of the boiler faster than almost any other mechanism known. When the boiler is kept pressurized and hot and then restarted, large amounts of condensate are generated in the high pressure superheaters and reheaters. This often floods lower headers and piping. How this condensate is removed is important for boiler design when cycling.

Finally, several other recommendations that can increase equipment longevity such as condensate pots for desuperheaters, feedwater recirculation systems, auxiliary equipment to hold boiler pressure and temperature, and the problems with certain types of piping layouts are all briefly discussed.

INTRODUCTION

Nearly everyone knows that cycling reduces life expectancy of hot components in gas turbines. Turbine manufacturers have for years designed the equipment to withstand the damage created by the highly cyclic nature of operation [1]. However, until recently not much attention had been given to designing the HRSG for cyclic service. For many years most plants operated as baseload with few starts or stops. With market conditions changing and with the increase cost of fuel it has become the norm for plants to start and stop daily. Another reason for this lack of attention to cyclic service has been the design codes. For the most part ASME Section I Power Boiler code and the British BS 1113 do not have rules or guidance for how to design boilers for cyclic service. Some of the European design codes such as TRD 301 and EN 12952 have provided practical methods to evaluate the boiler components for both creep and fatigue [2]. This information is essential to operating boilers in ways that will improve life expectancy.

Most major boiler manufacturers have learned much in the last ten years about features for Heat Recovery Steam Generators, HRSG's that are absolutely necessary to insure the equipment will last its intended life. In addition to the design, there has been much discovered in boiler operation that is equally important to understand. This article will discuss some of these features and operating considerations that should be understood and addressed when designing new equipment or switching from baseload operation to cyclic service

COIL FLEXIBILITY

It is absolutely essential to eliminate or minimize low cycle fatigue stresses. Codes such as EN 12952 and TRD 301 give rules for designing boilers for high cycle fatigue but do little to prevent premature failures as a result of low cycle creep-fatigue [3]. For HRSG's, it is almost always due to unresolved thermal expansion. Therefore, non-corrosion related failures in tubes, pipes and headers are typically caused by low cycle thermal fatigue.

For older units, it has not been as important to provide flexibility in the right places to avoid low cycle thermal fatigue. Experience has shown that these units have performed well in a market environment where cycling was limited. However, when older units have been taken from a generally baseload operation and to one that is cyclic, low cycle fatigue often develops rapidly. There are two important aspects of coil flexibility to consider:

- Tube to tube temperature differences
- Piping layouts

Tube to tube temperature differences

All high temperature superheaters and reheaters have different tube metal temperatures as the steam is heated from inlet to outlet. In most natural circulation boilers, the tubes closest to the Gas Turbine, GT, will be hottest and decrease in temperature toward the stack. Various configurations of these components are seen throughout the industry depending upon the manufacturer but all have the same problem. Each row of tubes will be at a different temperature relative to the other. Tubes with different temperatures expand at different rates. At start up, these differences are normally at their highest and decrease to some normal operating equilibrium condition as full steam flow is established.

Figures 1 and 2 shows two different types of coil configurations and means of dealing with row to row temperature differences. In Figure 1, the steam enters the inlet header and is heated by the exhaust gas. The tubes near the GT, row 1, being hottest and the tubes toward the stack, row 4, being the coolest. Since the steam is superheated each row will be ever increasing in temperature. Correspondingly, the tube metal temperatures will also increase. In this configuration, the inlet and outlet headers at the top of the coil are used for support and the lower headers are allowed to move vertically unrestrained. All the temperature growth differences from row to row must be absorbed internally within the coil. This is accomplished through tube flexing, header rotation and axial compression or tension of the tubes. During thermal transient conditions, such as start up, the internal stresses created by these differences can be very high. High thermal stresses lead directly to high thermal fatigue damage. If the upper headers are both fix against vertical movement this type of configuration would not be desirable for cyclic operation. However, by adding spring supports to one header or the other, allowing vertical movement, these stresses are reduced to negligible levels.

General rule: It is always better to allow components to move freely relative to each other instead of relying upon tube or header flexibilities to absorb thermal movements. Stress levels will be orders of magnitude less when allowed to move.

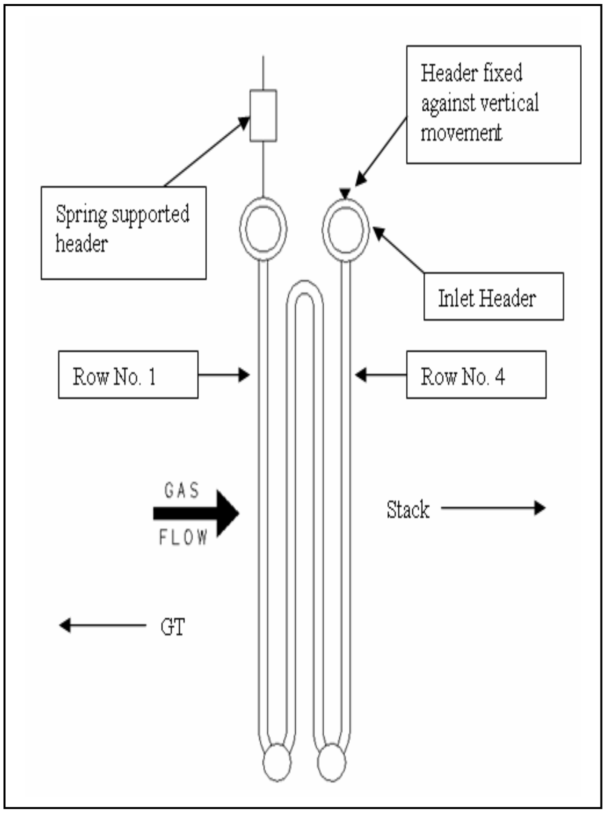

Figure 1
Superheater/Reheater with Spring Supported Headers

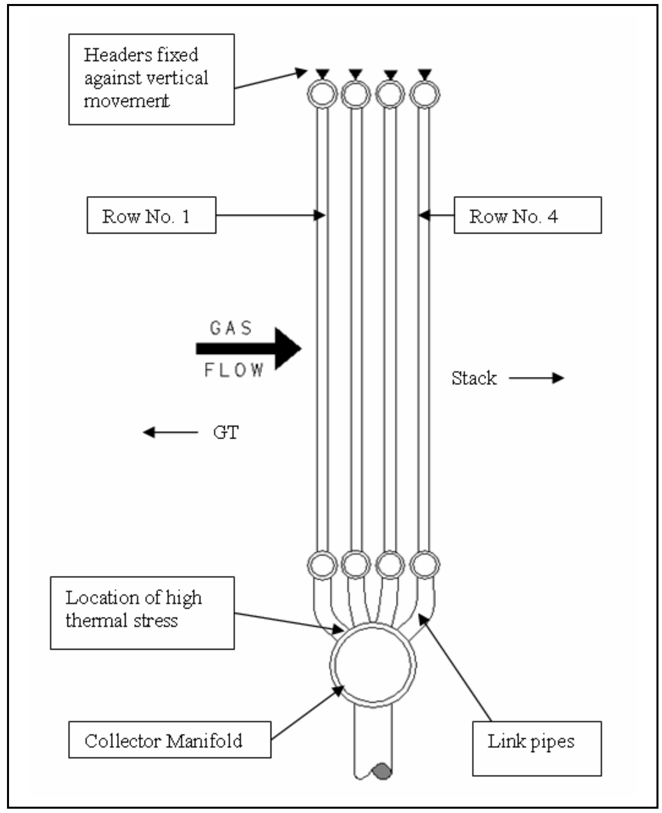

Figure 2
Superheater/Reheater with Fixed Upper and Lower Headers

Figure 2 is another superheater or reheater configuration commonly seen in the industry. Again tube row No. 1 closest to the GT will be hottest and tube row No. 4 coldest. Although each tube row is support by individual headers at the top, the bottom headers are not allowed to freely expand relative to each other. Each lower header in linked to an outlet manifold which ties all rows together. This arrangement relies on the flexibility of the link pipes and the ability of the manifold to rotate to absorb the differential temperature movements between the rows. The maximum stress in this configuration will be at the link pipe bend to manifold connection. This configuration is an example of a poor layout for cyclic operation because it does not allow components to move freely relative to each other but instead depends entirely on the coils internal flexibilities.

In summary, a good design for superheaters and reheaters is one that allows tube rows of different temperatures to move freely relative to one another without relying heavily upon internal coil flexibilities. The coil arrangement shown in Figure 1 is an example of a design that allows tube rows to expand feeling minimizing or eliminating restrained thermal stress. The coil layout shown in Figure 2 is an example of a coil design which relies on internal coil flexibilities to absorb differential tube movements. Some additional examples of poor and good coil layouts for superheaters and reheaters are shown in Figure 3a and 3b respectively.

In figure 3a there are three examples of layouts that restrain the thermal expansion difference from row to row. In the first two examples to the right in Figure 3a the upper and lower headers tie the rows together. These types of layouts are used very successfully for evaporators where the row to row tube temperatures are very small but work poorly for reheaters and superheaters.

The same is true for the third example because the lower manifold ties all the tube rows together preventing free relative movement.

The three examples in Figure 3b provide either free relative tube to tube movement or large flexibility from row to row. In the example to the far left in Figure 3b the outlet header is supported on springs which allows the header to move up or down depending on the tube temperature difference. The other examples have large horizontal pipe runs which allow the lower headers to move easily relative to each other compared to the examples in Figure 3a.

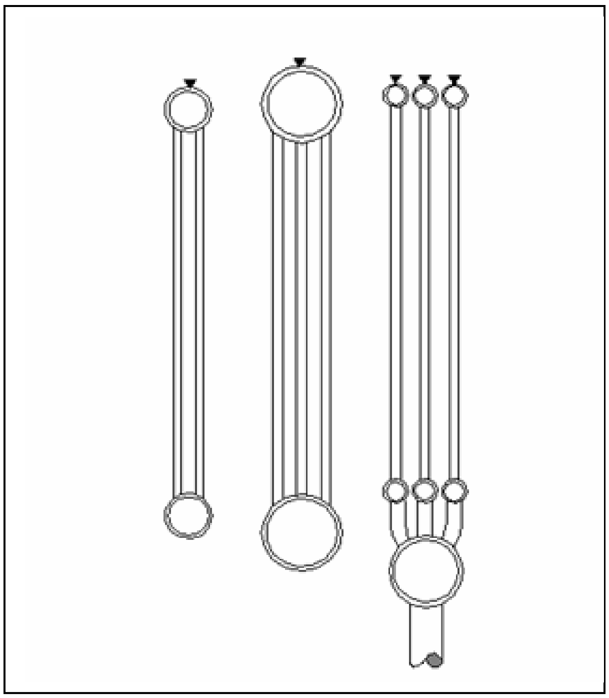

Figure 3a
Some examples of Superheater/Reheater coils with poor tube to tube flexibilities

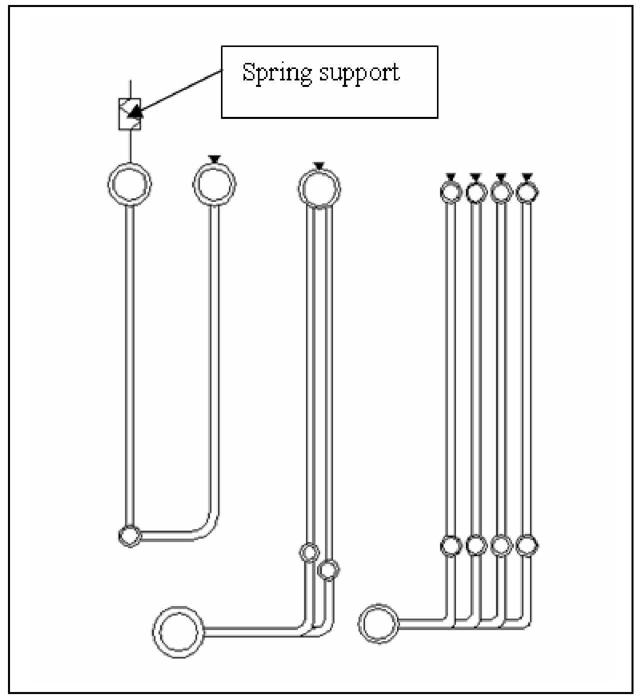

Figure 3b
Some examples of Superheater/Reheater coils with good tube to tube flexibilities

PIPING LAYOUTS

One area that is often overlooked is piping layouts. During start up, it is not uncommon for piping routed external to gas flow to be hundreds of degrees cooler in temperature than the coils they are attached to. At normal operation there can be some difference but these differences are usually small. Therefore, it is important to consider the transient temperature difference when routing piping. An example of this is shown in Figure 4. Here the outlet of one superheater is routed from the top to the bottom of the second superheater. In this example, the inlet for the second superheater is at the bottom. During normal operation the temperature differences might easily be accommodated in the piping flexibilities. However as the unit starts up, the superheater tubes will heat up rapidly. Since steam flow has not been established, the interconnecting piping will be ambient, setting up very high temperature differences between the piping and the coils. After steam flow is established, these differences greatly decrease. This is especially important to consider for superheater and reheater interconnecting piping.

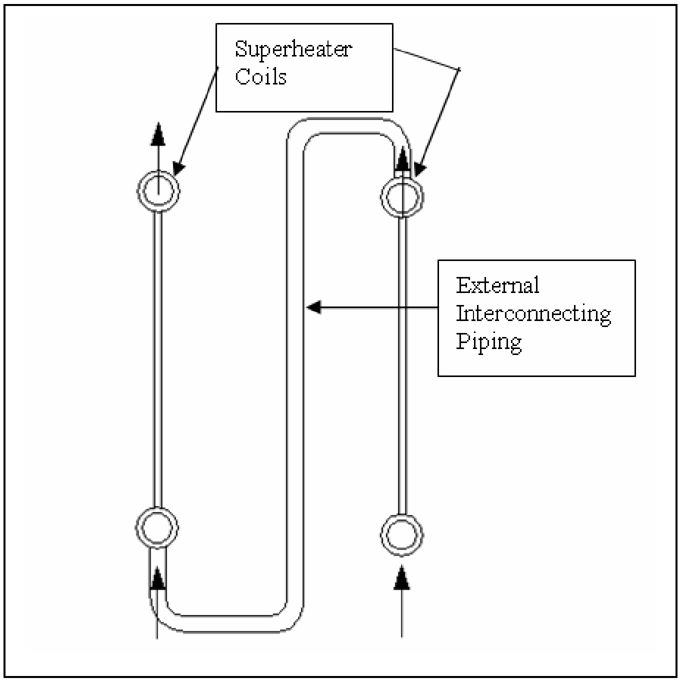

Figure 4
Example of external pipe routing with potentially high thermal stresses

Similar arrangements are seen on water filled components such as evaporators and economizers. These components exhibit fewer problems because they are filled with water. The water keeps the temperature of the boiler parts closer in temperature during the transients. There has been some concern on evaporators. During start up the tube rows closes to the GT will heat up somewhat faster than the tube rows at the rear. The entire coil will heat up faster than the downcomer. It is these temperature differences that are the concern. Typically the difference in temperature is around a hundred degrees. Piping flexibility is sufficient for the design of these water fill components. It is always good practice to assume some conservative temperature difference and design these parts to insure they will be adequate.

COMPONENT THICKNESS

Owner-operators often require the HRSG to be designed such that it does not limit the start up speed of the plant. Assuming that all low cycle fatigue problems have been resolved, the next area of concern is the fatigue damage caused by pressure and through thickness thermal gradient cycling. Of the two, fatigue damage caused by through thickness temperature gradients is the most important. Thermal gradients through the thickness are a direct function of the component thickness. The thinner the component the smaller the gradient and stress. It is therefore considered good design to keep the controlling parts such as superheater and reheater headers as thin as possible. This is also true for the high pressure steam drum as it can often control the start up rate.

In order to consider these conditions, it is necessary that owner-operators define how the HRSG and the plant will be operated. It is essential to conservatively estimate how many of each type of cycle the plant will experience. How this is done is beyond the scope of this article but it is mentioned here because to accurately calculate the start up ramp rates or allowable thermal gradients the manufacturer or designer needs this information. Without it, most manufactures will assume some default value for design purposes which may of may not reflect reality.

One technique used to keep hot headers as thin as possible is to use single row harp construction with multiple inlet and outlet nozzle branch connections, see Figure 2. With only one tube row per header the diameter of the header can be as small as possible. Since the header thickness is a function of the diameter, the thickness will be minimized. Unfortunately, this type of construction requires multiple inlet and outlet nozzles to handle the steam flow.

A second technique allows the use of larger headers. Tubes enter a header in a uniform pattern. Most design codes allow the thickness to be calculated using a ligament efficiency approach. With this method the header must provide all the material necessary to keep the primary membrane stresses below the acceptable limits. An alternate to this approach is to provide tube stubs that are thickened so that part of the hole reinforcement is provide in the stub. This allows the header thickness in some cases to be thirty percent less. See Figure 5 for a typical detail.

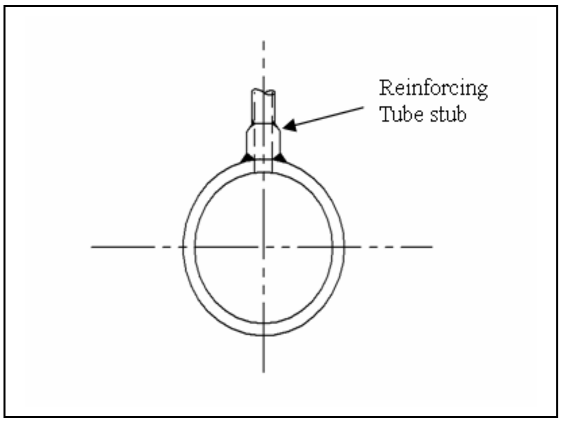

Figure 5
Stub reinforced tube to header attachment

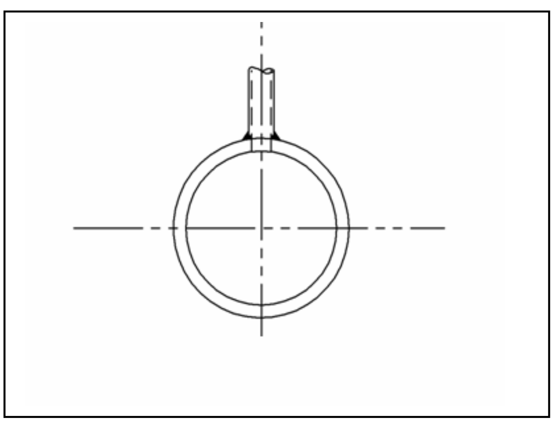

Figure 6
Conventional full penetration tube to header attachment

TUBE TO HEADER CONNECTIONS

Within the industry there is numerous tube to header connection details. This topic has been the subject of much discussion. In the European community it is widely accepted that the use of full penetration tube attachments such as shown in Figure 6 are the best for cyclic service. This conclusion has been challenged as of late because for many manufacturers the desired quality of attachment is much more difficult to achieve with this detail and results in too many leaks. In the United States the use of partial penetration weld attachments as shown in Figure 7 has proven to be much more reliable in practice resulting in fewer leaks.

Studies of different joint geometries have shown that during transient conditions the maximum stresses do not occur at the inside gap as thought to be the case for the partial penetration joint. When a detail fatigue analysis is performed for both the full penetration and partial penetration joint detail the results are very similar results [4].

It is known however, that during thermal transients a thicker stub relative to the tube helps minimize the temperature gradient between the tube and the header. The thicker stub attached to the header provides an improvement in heat transfer and hence lower temperature gradients. In addition, using stubbed headers allows for additional NDE for improve quality. It is therefore, recommended that even though the partial penetration weld is acceptable when compared to tube full penetration weld, it is not as good under high cyclic conditions when compared to a thickened stubbed full penetration tube to header attachment.

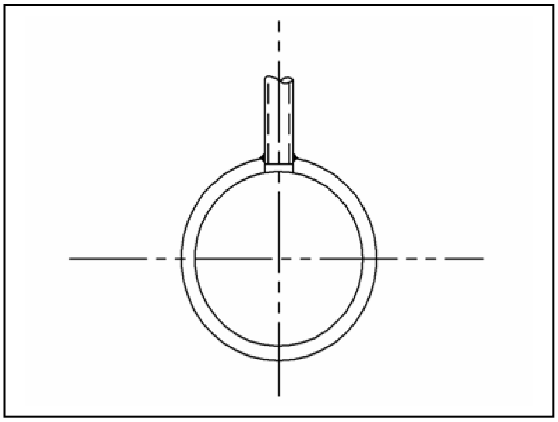

Figure 7
Conventional partial penetration tube to header attachment

MATERIALS

For high temperature components such as HP Superheaters and Reheaters it is important to keep component thicknesses small as was previously discussed. In addition to the design techniques described under component thicknesses, the use of higher strength materials also plays an important role.

If the HRSG will be coupled to gas turbines with exhaust temperatures exceeding 1100°F, such as the 7FA or 9FA class machines, superheater and reheater outlet headers and steam piping should use the modified 9% Chromium (Cr) steel, known as P91 [1]. The use of this material will allow header thicknesses to be minimized. In addition this material has excellent fatigue and creep characteristics.

DESUPERHEATERS

It has long been recognized by steam turbine manufacturers that desuperheaters provide an opportunity for water induction into hot components. When this occurs damage results in a very short period of time, often one cycle. ASME TDP-1 [5] states that design, control and operation of all systems, including desuperheaters that have a potential for allowing water to enter the turbine should prevent any unusual accumulations. However, since malfunctions do occur, the recommendations for preventing turbine damage due to water induction include one of the following:

- Detection of the presence of water either in the turbine or, preferably, external to the turbine before the water has caused damage;
- Isolation of the water by manual or, preferable, automatic means after it has been detected.

The same can be said for hot components such as superheaters and reheaters in HRSG's. Water induced into these components will cause damage faster than almost any other failure mechanism known. It is imperative that water from over spraying or equipment malfunction be detected and removed prior to entering these component sections.

For a HRSG this is not always easy. It is nearly impossible to prevent water from impacting hot piping components just downstream of the desuperheater when there are leaks or over spraying. However it is possible to prevent water from entering hot coil components upstream or downstream of desuperheaters fairly easily.

It is recommended that condensate drain pots be placed upstream and downstream of desuperheaters where there is a potential of water to enter hot components, see Figure 8 for a typical example of how this is done. Normally the condensate pot is fitted with conductivity probes that detect water when it enters. After the water level has reached an unsafe height, an automatic valve will open, evacuating the condensate.

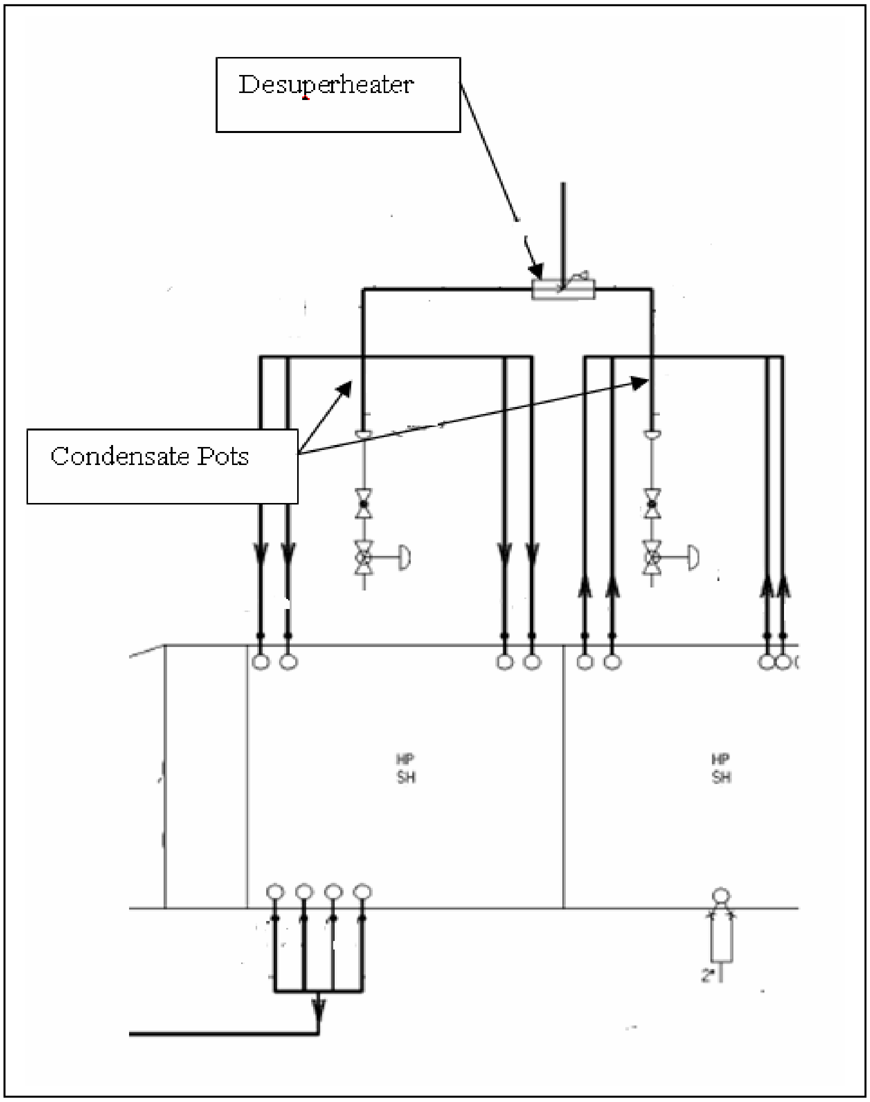

Figure 8
Condensate Pots to protect superheaters

Protection of hot components is considered very important to prevent damage to these parts. Lack of attention to this will eventually lead to damage. See Figure 9 for an example of damage caused by quenching from desuperheaters.

CONDENSATE MANAGEMENT

Condensate management has been recognized for some time now as something that needs attention if a plant is required to cycle. For the steam components such as superheaters and reheaters quenching or uneven tube temperatures caused by not evacuating condensate can create very severe stress conditions.

For plants that are required to cycle it is not unusual to start and stop daily. It is normal to keep the boiler hot and hold pressure before restarting. This minimizes thermal gradients and the pressure stress range. NFPA [6] requires prior to lighting off the GT that the HRSG go through a purge cycle to ensure that all fuel gas has been vented. Since the turbine exhaust gas during the purge cycle will be below the saturation temperature of steam in various sections, large amounts of condensate will form. If not removed the superheaters and reheaters will fill with water.

As the evaporators section begins to produce steam the condensate within the superheaters and reheaters will prevent even steam flow. Some tubes will be blocked with condensate while others clear. This uneven clearing will cause adjacent tubes to heat up at different rates setting up undesirable thermal stresses [7]. See Figure 10 for an example of tube buckling caused by uneven tube clearing.

Figure 9
Damage caused by condensate quenching from desuperheater

Figure 10
Buckled tube as a result of uneven condensate clearing

In addition to the uneven clearing that can occur, if some components are not filled with water the condensate can move around within the boiler causing quenching. This happens when the water is blown into sections that are hot and dry creating a rapid cool down to saturation temperature.

There a several recommendations that should be followed when designing the drain systems for superheaters and reheaters.

1. The size of the drain on each lower header should be large enough to handle the anticipated condensate generated. It is recommended that at least one 2” (50 mm) NPS drain be provided for each header.
2. Drain lines should be sloped under all operating conditions to a sump or blowdown tank.

3. If the drains are routed to a blowdown or flash tank the tank should be located so that the condensate can drain by gravity into the tank. If this is not possible tell tale drains should be provided at low points.
4. Use drain pots to detect condensate as it is created and remove by automatic means. Do not rely on manual valve operation for this function. It is recommended that the drain pots be fitted with conductivity probes instead of thermocouples for this purpose and pneumatic valves for quick operation. Do not use motor operated valves since the time to open is too long.
5. If superheater and reheater drains are routed to a common blowdown tank ensure that the tank, manifolds, and piping are sized properly to prevent back pressuring the lower pressure system. If this not done and the higher and lower pressure systems are operated simultaneously, there is a potential of blowing condensate forward into hot sections causing damage.

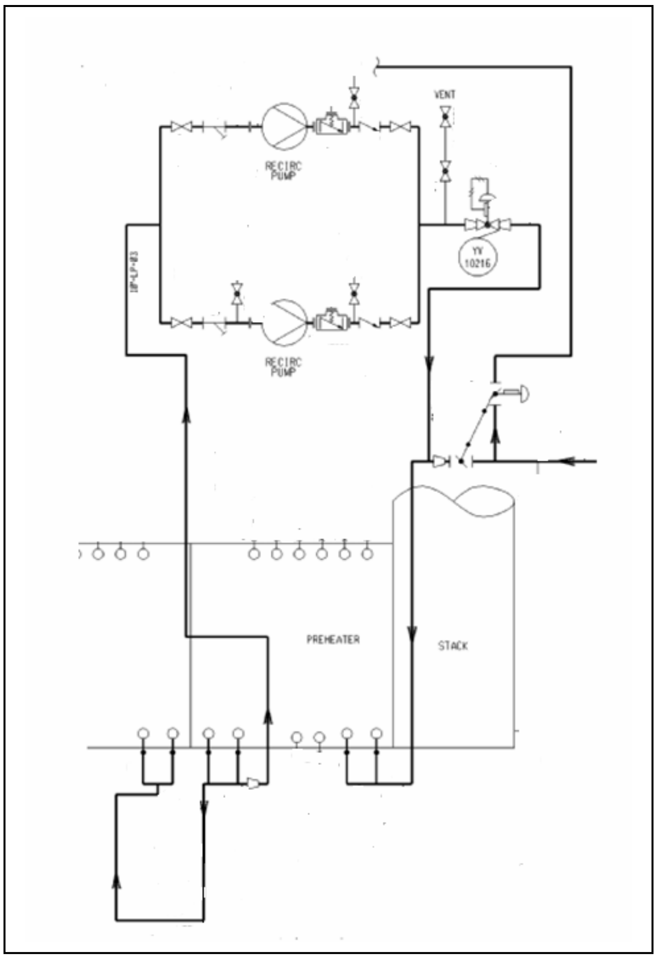

Figure 11
Feedwater Recirculation System

FEEDWATER RECIRCULATION SYSTEMS

After a hot or warm start up it is typical for the preheater to be shocked with cold inlet water. After shut down while the boiler is bottled up the lower pressure sections, such as the preheater, will be elevated in temperature to match the rest of the boiler. Upon start up there is normally no demand for feedwater as the drums are swelling. At these periods the feedwater components can be steaming or at a uniform saturation temperature.

As the feedwater is introduced, the first or second flow passes can be shocked setting up undesirable thermal stresses. One way to prevent or minimize this from occurring is to provide a feedwater recirculation system. An example of one is shown in Figure 11. In this example a feedwater recirculation pump routes water through the feedwater heater prior to start up. As water is required, the colder feedwater can be introduced gradually and mixed with the hotter water already in the feedwater heater. Hence the shocking either does not occur or is minimized.

AUXILIARY EQUIPMENT

For cycling HRSG's it is recommended to hold pressure and temperature between each start and stop [3]. There are several effective ways this can be accomplished.

a) Use of exhaust stack damper
b) Insulating of exhaust stack and outlet breeching
c) Use of steam sparging systems

The stack damper is one the most effective and inexpensive ways to stop the flow of cooler air through the HRSG. In addition, insulating the stack and stack breeching up to the damper helps hold heat much longer allowing the pressure and temperature to be maintained for several days.

The last and probably least affective way to hold heat is to install a steam sparging system. Steam is normally induced into the lower sections of the evaporator coils. The heat from the evaporator will then maintain heat through all boiler components. Although, this method is effective it can be expensive and it can be difficult to generate enough steam to raise the temperature enough to make this approach worthwhile. It is however, very effective in maintaining temperature for freeze protection.

If you only have limited funds to spend on auxiliary equipment spend it on the stack damper and insulation.

CONCLUSIONS

Much has been learned over the past ten years about how to design an HRSG for cyclic service. All of the issues described in this article are important to consider when purchasing new equipment or retrofitting existing equipment for more severe cyclic service. If these areas are not addressed older equipment can experience failures in a very short period of time. For new equipment, some manufacturers do a better job than other in providing equipment suitable for cyclic service, so it is advisable to write specifications that cover these topics. This article has been written to highlight some these important factors.

There are other issues that are relevant when cycling an HRSG. Most of these fall on the operations side of the equation. Things such as start up and shut down rates, the use of GT temperature matching, water chemistry, inspection programs, etc. are all very important but are beyond the scope of this article.

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