Engineering analysis of recovery boiler superheater corrosion

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The focal point of the superheater corrosion analysis is a comprehensive computer-based heat transfer analysis.

The fireside corrosion of superheater tubes in recovery boilers has become increasingly more common and troublesome as recovery boilers are fired above their design levels. This often leads to excessive superheated steam temperatures and elevated superheater metal temperatures. These conditions can accelerate corrosive metal loss if proper modifications are not made to the boiler combustion system or superheater design.

Efforts to reduce saltcake makeup by improving chemical capture and recycle efficiencies have contributed to higher potassium and chloride levels in the as-fired black liquor. The presence of these two elements in elevated amounts can contribute to a higher susceptibility to deposit formation and fireside corrosion in the superheater area.

In addition, the high-performance steam turbines used in some recent cogeneration projects require higher steam temperatures from the recovery boiler than previously considered practical. Operation at higher steam temperatures can also lead to excessive superheater-tube metal temperatures and accelerated corrosion rates.

For these reasons, a better understanding of fireside superheater corrosion has been of recent interest. Along with a better understanding of the mechanisms that promote superheater corrosion, there has been a need for the development of analytical tools to help engineer solutions to corrosion problems. In cases where fireside superheater corrosion is occurring, engineering analysis can offer the following:

- Prediction of tube metal temperatures to identify areas most vulnerable to corrosive attack
- Identification of limits to boiler operating parameters to maintain tube metal temperatures at safe levels
- Allow redesign of superheater tube arrangement and metallurgy to avoid exposure of the tube metal to excessive temperatures and heat fluxes.

This paper describes the "ingredients" of such an engineering analysis tool and provides an example of calculation results.

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Superheater design

The physical arrangement of recovery boiler superheaters plays an important role in their susceptibility to fireside corrosion. Several factors are critical in superheater design, including the location of the superheaters, the tube geometry and arrangement, the number and location of attemperators, the materials of construction, and the direction of steam flow.

In recovery boiler design, the location of the superheater banks often differs greatly relative to the furnace nose, screen, and furnace cavity (**Fig. 1**). Superheater location plays an important role in determining radiant heat flux to the superheaters from flue gases and exposure of the tubes to corrosive compounds from the furnace cavity.

The number of tube passes in a superheater bank (i.e., the number of times that a superheater tube is looped from top to bottom between the feed and discharge headers) affects corrosion rates. With each pass, more surface area is exposed to the flue gases and the higher the final steam temperature becomes. **Figure 2** illustrates how one tube circuit is often routed to reduce its number of passes in comparison to the other tube circuits. The lower flow resistance associated with the shorter tube circuit leads to a higher steam flow rate and reduced steam flow in the other tube circuits.

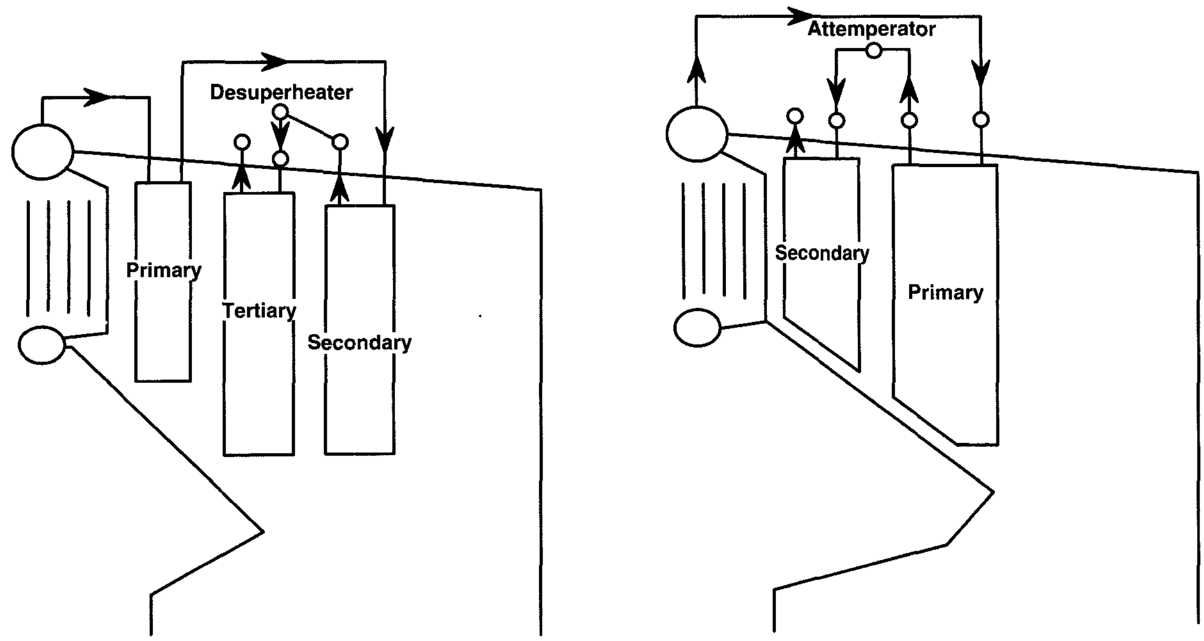
Tight-radius tube bends will result in higher friction losses than large-radius bends. Higher friction losses may also result in an imbalance of flow and steam temperatures in some circuits.

Tight tube bends in the tube circuits not only cause unbalanced pressure loss to the steam flow, but they also generate prestressed areas in the tube material. Corrosion is accelerated in regions of residual stresses (*1*). Also, the lower superheater tube bends are often exposed to a larger radiant heat flux than the vertical tube sections. Consequently, the lower tube bends must be carefully inspected during outages, and special attention should be paid to tube bends when performing engineering analyses.

The distance between tubes, the tube arrangement (inline or staggered tubes), and the tube diameter will have an impact on heat transfer rates. These factors also influence the formation and accumulation of furnace-side deposits.

The header size and feeder tube arrangement partially determine steam flow distribution to the superheater banks. A lack of adequate steam flow through some circuits can lead

1. Typical superheater configurations



Both counter-flow and co-flow; three stage; secondary exposed to furnace radiation; no collection headers between drum and discharge of secondary.

Entirely co-flow; two-stage; primary mostly protected from furnace radiation by nose.

to high steam temperatures in localized regions of the superheater. In addition, the absence of collection headers between superheater sections may result in large variations in steam and tube metal temperatures since there is no opportunity for interstage mixing of steam.

Many different materials of construction have been used for superheaters in recovery boilers. These include carbon steel, SA-213 T-11, SA-213 T-22, Type 347 and 310 stainless steel, and composite tubing (Type 310 stainless steel over T-22). The use of high-grade steels or other metals has helped to alleviate some corrosion problems, but it can be very costly and has not proven to be a general panacea.

A common approach to solving mill corrosion problems is to use a more corrosion-resistant material in troubled areas. This approach is effective in regions where oxidation corrosion is dominant. However, in cases where molten deposits are present at the tube surface, a change in metallurgy is often ineffective. Tran *et al.* (*2*) have investigated corrosion rates for a standard 2-1/4 chromium, 1 molybdenum steel superheater tube material, SA-213 T-22, and a nickel-base alloy, Inconel 800H. Once a critical temperature is reached, in this case between 550°C and 600°C (1020–1110°F), the corrosion rate increases to unacceptably high levels. Although the Inconel performs better than the SA-213 T-22, the metal loss remains excessive when a molten deposit is present.

The number, location, and capacity of attemperators will affect the local steam and tube metal temperatures. Inadequate attemperation capacity can limit steam temperature control in superheater banks. Superheaters with more than two banks often require more than one attemperator to assure adequate steam temperature control in all superheater banks.

The steam flow direction relative to the flue-gas flow will determine the difference between the steam and flue-gas temperature, which affects convective heat transfer. Superheater designs are based on counter-flow, co-flow, or some combination of the two (Fig. 1). Although a counter-flow configuration will result in more efficient use of superheater surface area, its use places the hottest steam in proximity with the hottest flue gases. The high metal temperatures resulting from the counter-flow configuration could lead to high corrosion rates.

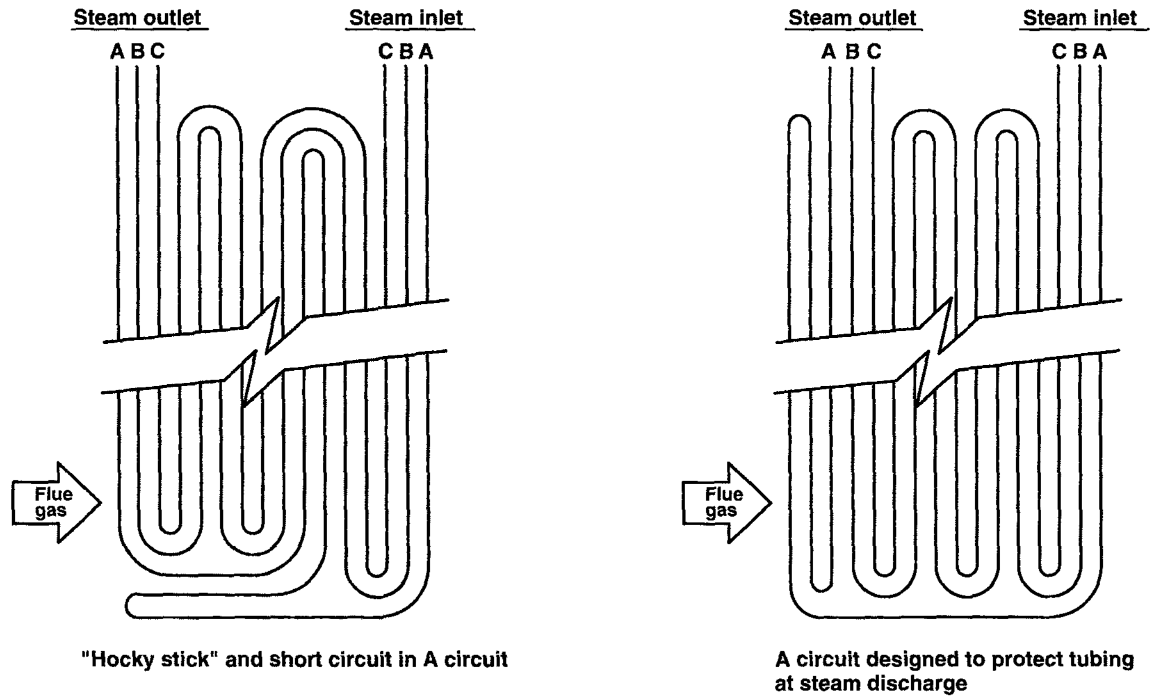
Effect of boiler operation on superheater corrosion

In addition to the design of the superheater, boiler operation will also affect superheater corrosion rates and patterns. In particular, operation of the boiler above the design loading rate will often lead to excessive levels of char particle and smelt carry-over, in conjunction with high flue-gas and superheated-steam temperatures. Corrosion rates of superheater tubes are determined by the physical state and chemical makeup of the deposits. The physical state of the deposit material depends on the tube metal temperature, which is in turn determined by the local flue-gas and steam temperatures. In addition, the composition of the flue gas will affect corrosion rates.

Nature of corrosive deposits

The material that deposits on recovery boiler superheaters can be highly corrosive. The rate of corrosion is accelerated

2. Examples of two superheater tube arrangements. In both cases, A circuit has four passes, B and C circuits have six passes.



when molten deposit material is in contact with the tube metal surface (*2, 3*). This may be due to increased contact at the surface and increased mass transfer rates. Therefore, a key to avoiding severe superheater corrosion is to avoid conditions which lead to a molten deposit at the tube metal surface.

Another factor related to corrosivity of deposits is the presence of significant amounts of unburned carbon material, as will occur when char particle carry-over is high. When a boiler is being operated close to its maximum firing capacity, char particles may be carried over into the upper furnace region and deposited on the superheater tubes. Excess carbon will result in local reducing conditions, leading to the formation of Na_2S. Without the presence of carbon, the Na_2S would be oxidized to Na_2SO_4. The Na_2S can further suppress the melting point of a deposit and can support sulfidation corrosion. Sulfidation corrosion is more severe than oxidation because a passive oxide layer is not formed to reduce the metal wastage rate.

Recent research (*2–4*) has been instrumental in defining the influence of deposit chemistry on the first melting temperature of recovery boiler deposits. In particular, the role of potassium and chloride in forming molten conditions has been defined, and this information can be used in corrosion analysis efforts. Increased potassium in the deposits can cause a strong suppression of the first melting point. The decrease in the melting point makes the tube surface more susceptible to corrosive attack.

In particular, the data generated by Tran *et al.* (*2, 4*) have provided engineers with the ability to approximate the first melting point of the deposits, based on the as-fired black liquor composition. The first melting point serves as a limit to tube metal temperature in analyzing the potential for superheater corrosion in recovery boilers.

Once the metal temperature limit has been established by estimating the first melting temperature of the deposit, a determination of the metal temperature experienced in the superheater is required.

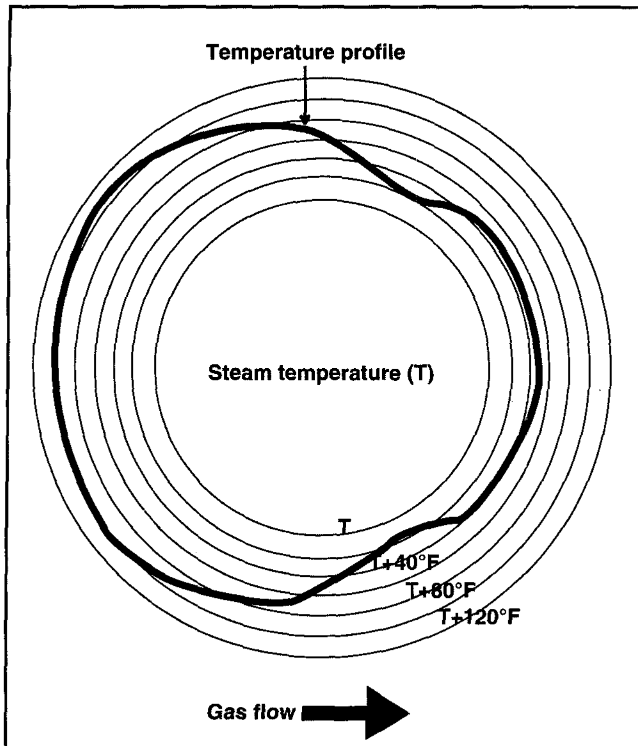
Through conductive, convective, and radiant heat transfer analysis, we can show that the two most important factors that influence metal temperatures are the local steam temperature and the radiation heat flux from the hot flue gases.

Steam temperature

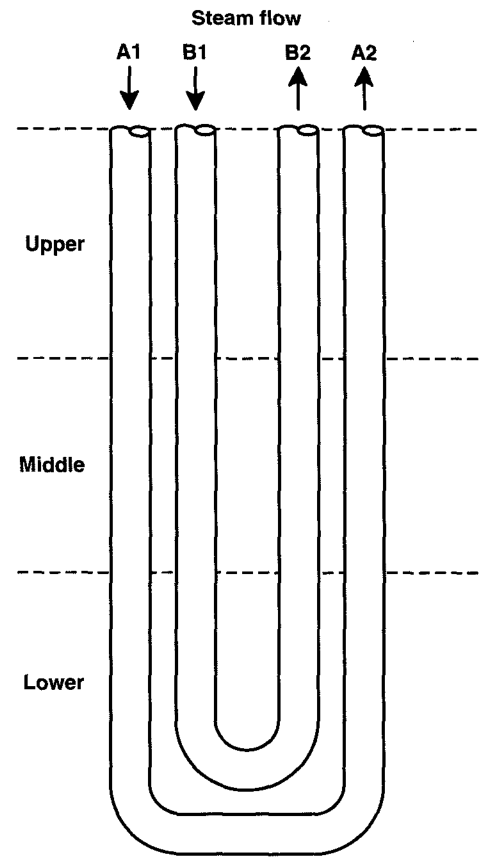
Due to the relatively high heat transfer rates on the steam side versus the fireside, the tube metal temperature is most closely tied to steam temperature. Therefore, accurate tracking of steam temperature throughout a superheater is critical in establishing areas that are susceptible to high corrosion rates.

Steam temperatures in recovery boilers depend on superheater design and recovery boiler operation. In general, as recovery boilers are operated at higher loads, the steam temperature increases. The current trend is to design and operate recovery boilers at higher pressures. This raises the saturated steam temperature entering the superheater and increases the temperature of the steam throughout the superheater. Increases in the solids loading to the recovery boiler also generally increase the flue-gas temperatures in the upper furnace, if the proper countermeasures are not taken.

3. Typical superheater tube circumferential metal temperatures in a recovery boiler



4. Simplified superheater tube arrangements to illustrate heat transfer calculation scheme



Improved combustion in the lower furnace can allow higher liquor solids loading without increases in flue-gas temperature at the superheater due to higher radiative heat fluxes in the lower furnace (*5*).

Flue-gas temperature

Flue-gas temperatures dominate the rate of radiant heat transfer in the furnace cavity since radiation is a function of the gas temperature raised to the fourth power. High radiant heat flux from the furnace cavity can produce locally higher tube metal temperatures. **Figure 3** presents a typical circumferential temperature profile of a recovery boiler superheater tube. In a utility boiler under a large radiant load, the tube metal that faces the furnace cavity (windward) is over 70°F higher in temperature compared to the back side of the tube (leeward) (*6*). A similar effect is present in recovery boilers, although cavity radiation levels are typically not as high as in utility boilers.

Radiant heat flux can be particularly high in recovery boilers that are being pushed beyond the capabilities of their combustion system. In these cases, an extended combustion zone will result in higher temperatures, char particles, and combustible gases in the screen and superheater region.

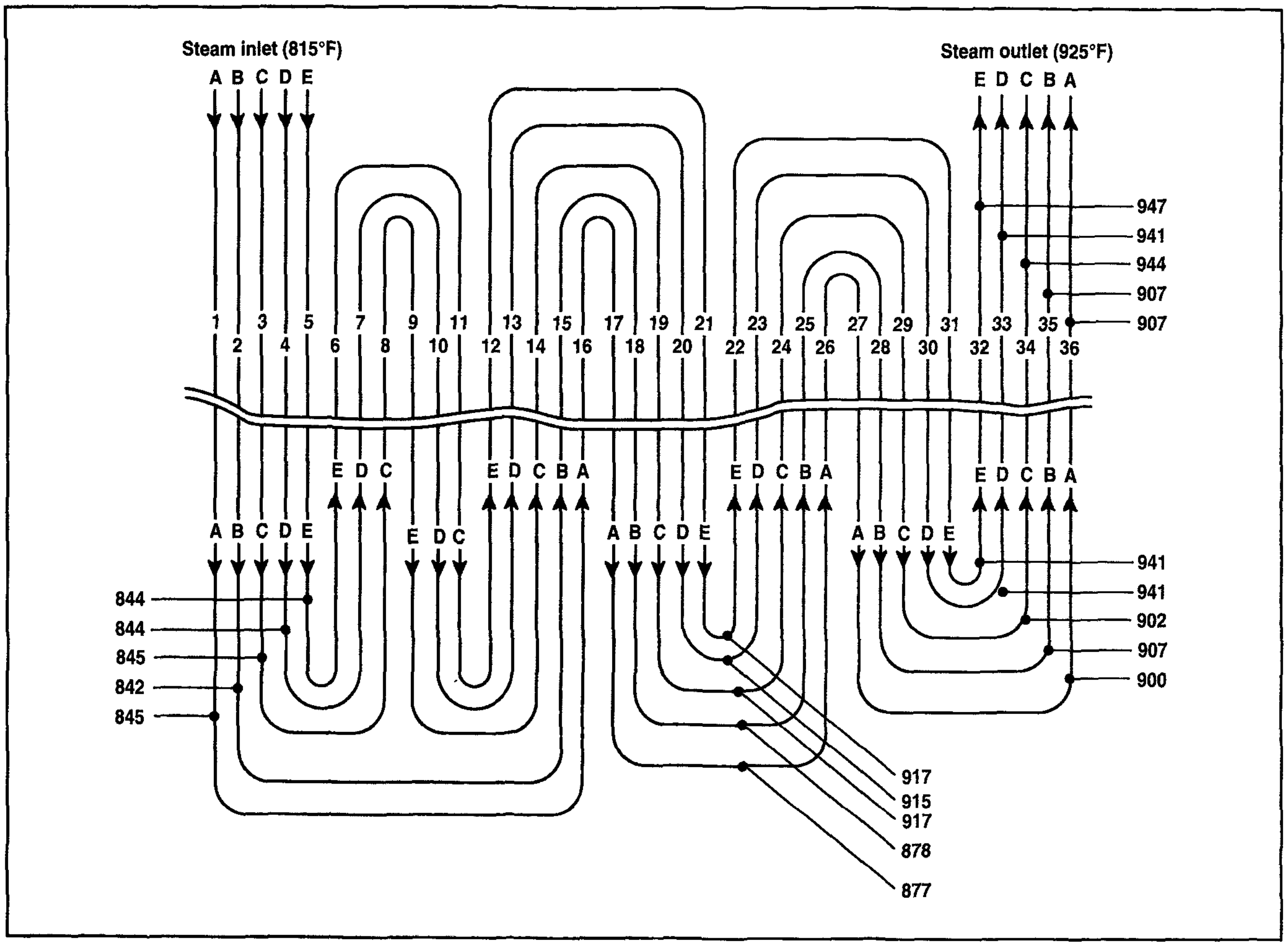
Engineering analysis

The previous sections have highlighted the important features of superheater design and the operating parameters that have the largest impact on corrosion in recovery boiler superheaters. Engineering analysis provides the means to apply research data and fundamental heat transfer calculations to develop viable solutions to corrosion problems. The elements involved in the engineering analysis process include review of superheater design, collection of field data, chemical analysis of black liquor and superheater deposits, and a heat transfer analysis of superheater tubes.

Design review

The first step in the engineering analysis process is to obtain design drawings that accurately reflect the current design of the boiler and superheater in question. In particular, tube diameter, tube wall thickness, tube metallurgy, tube spacing, tube weld locations, header design, attemperator capacity and location, pendant location, and furnace design operating conditions all have an impact on the heat transfer analysis and engineering approach.

5. Calculated average tube metal temperatures for a five-circuit superheater bank. Flue-gas flow is from left to right.



Collection of field data

A critical element in the engineering analysis process is to collect the operational information required to conduct the study. A superheater corrosion analysis is typically one part of a comprehensive boiler performance evaluation (7). Included in the evaluation are flue-gas temperature measurements, determination of inlet and outlet steam temperatures and flows, and calculation of flue-gas flow rates through overall mass and energy balances.

This data is used as a cross-check of the overall energy and mass balances around the superheater, developed as part of the heat transfer analysis. Consequently, the uncertainties in the heat transfer analysis can be reduced.

Chemical analysis of process streams

As part of the boiler performance evaluation, samples of black liquor, smelt, and fly ash are collected for chemical analysis. As mentioned earlier, the potassium and chloride levels in the superheater deposits have a large influence on the first melting point temperature and liquid fraction characteristics of the deposits.

Tran *et al.* have shown from a survey of 49 recovery boilers that relatively little enrichment of potassium and chloride occurs in the superheater deposits as compared to the as-fired black liquor (8). This allows the use of the as-fired black liquor chemical analysis to calculate an approximate first melting temperature for the superheater deposits without actually retrieving a representative sample from the superheater area. If a more accurate determination of the first melting temperature is required, *in-situ* probing can be performed to actually measure the temperature where corrosion is accelerated.

With an estimate of the first melting temperature in hand, the engineer next needs to predict tube metal temperatures to determine where the potential for "hot spots" may lie.

Heat transfer analysis

The heart of the engineering evaluations of superheater corrosion is a computer-based heat transfer analysis program. The heat transfer analysis has been developed for use in a spreadsheet format to allow flexibility in the analysis of varying superheater designs. Conductive, convective, and radiative heat transfer rates are calculated for each tube row to provide tracking of steam, metal, and flue-gas temperatures throughout the superheater.

Since the designs of superheaters can be so different, the format of the calculation steps must be "customized" for each analysis. The spreadsheet format of the program allows for relatively rapid and straight-forward reconstruction of the program to match the physical arrangement of the superheater being analyzed.

Figure 4 presents a simplified two-tube circuit, two-pass superheater to illustrate the calculation methodology. The superheater bank can be broken into any number of vertical zones. (In this example, three are shown.) Flue-gas conditions, preferably based on field measurements, are input to the program for each zone, which gives a variation in temperature, flue-gas flow rate, and radiation heat flux in the vertical plane of the superheater.

Inputs. The required inputs to the program include flue-gas conditions and properties, tube metallurgy and geometric parameters, furnace geometry, and steam conditions and properties.

Calculation methodology. Heat transfer calculations are performed on each tube row of each vertical zone in a progressive, step-wise fashion so that the result of one block of calculations can feed into the adjacent block. An open-loop iteration is required for some configurations since there is not always full closure of the underlying equations.

The heat transfer equations used in the program were based on similar equations contained in the literature for recovery boilers (*9*). For example, arrangement factors and intertube radiation conductance factors are used in accordance with previously described methods.

Fouling factors are not utilized. Instead, a more fundamental equation is used, allowing for variation in deposit layer thickness throughout the superheater. The deposit layer may be determined through comparison of the deposit radical deformation temperature to the calculated external temperature or by prescription in areas that have an average thickness based on soot blower effectiveness. The thermal conductivity of the deposit layer is based on a value contained in the literature (*3*).

Outputs. The outputs from the program include flue-gas, steam, and tube metal temperatures; heat absorption profiles; mass and energy balances; and average deposit thicknesses. A typical example of calculation results for tube metal temperature in a five-circuit superheater bank is presented in **Fig. 5.**

In a complicated analysis of this type, some simplifying assumptions must be made. These include:

- No side-to-side variations in flue gas and steam conditions
- Deposition on the tubes is symmetrical and circumferential
- Flue gas over the tube banks is in pure cross-flow
- No mixing between vertical zones
- Furnace cavity radiation is empirically distributed.

Considering the variability in recovery boiler operations and the general level of uncertainty in the heat transfer equations, these simplifications are not considered detrimental to the practical utility of the heat transfer program.

Results of the engineering analysis

To date, the engineering analysis procedure has been applied to units supplied by Ahlstrom, Babcock & Wilcox, Combustion Engineering, and Gotaverken.

Results and recommendations have led to the following actions: installation of additional attemperators and sweet water condensers, establishment of new steam exit temperature limits, improved steam temperature monitoring, evaluation and installation of new superheater designs, and combustion system modifications. Examples of three case histories can be found in the original TAPPI Engineering Conference publication (*10*).

Conclusions

The methods described in this paper have been successfully used for analysis of the superheaters of seven recovery boilers with the following general conclusions:

- Energy balances on the steam- and flue-gas side close within 5%.
- Areas most likely to suffer from severe corrosive attack can be identified.
- Steam attemperation schemes can be redesigned and easily evaluated.
- Superheater metallurgy and tube arrangement designs can be evaluated prior to operation to determine critical areas and the potential for fireside corrosion. □

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