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A VIEW FROM THE PENTHOUSE: USEFUL INFORMATION FOR THE WORLD OF BOILERS

SOME DESIGN THOUGHTS

The design of a boiler begins with the steam pressure, temperture and quantity. These three factors determine the amount of heat energy required. Fuel type and heat content will dictate furnace size and shape. Drum pressure sets the saturation steam temperature which in turn fixes the correct operating temperature of the waterwalls. Superheater-outlet steam temperature determines the amount of superheat and hence the size of the superheater required. Combustion energy heats the steel boiler tube surfaces and steam or water cools the steel to maintain proper metal temperature. In the process steam is generated in the furnace and heated in the superheater. Thus the overall design becomes a dynamic balance between heat transfer and fluid flow. When this equilibrium is upset, then corrosion, oxidation, and creep failures occur sooner than expected.

Combustion of fuel provides the necessary heat energy. The furnace size must be large enough to efficiently and completely burn the necessary quantity of fuel. For example, methane (natural gas) and carbon monoxide (a by-product from iron-ore reduction to pig iron in a blast furnace) are both gaseous fuels. However, methane has a heat content of nearly 24,000 BTU/LB while carbon monoxide has only about 10,000 BUT/LB. It takes almost $2\frac{1}{2}$ times the weight of carbon monoxide to give off the same heat as natural gas. It follows that the furnace volume of a carbon monoxide-fired boiler needs to be much larger than a natural-gas fueled boiler.

The second important factor in the determination of furnace size is the local heat flux, Q/A, BTU/HR-FT^2. In a natural-circulation boiler, the water-steam emulsion in the furnace tubes is at a fixed temperature, the saturation temperature. There is a temperature increase on the waterside along the tube's inside surface, through the laminar boundary layer. In essence, this means the metal temperature on the ID is slightly higher than the fluid temperature. This gradient, ΔT_i °F, from tube wall to bulk fluid temperature is related to the waterside heat-transfer coefficient, h_i, BTU/HR-FT^2.

$$\Delta T_i = \frac{Q}{A}\left[\frac{r_o}{r_i h_i}\right] \qquad \text{EQ 1}$$

where r_o and r_i are outside and inside radii of the tube. There is also a temperature gradient, ΔT_m °F, through the steel tube wall related to the thermal conductivity, k_m, BTU/HR-FT-°F, of steel, given by:

$$\Delta T_m = \frac{Q}{A}\left[\frac{r_o \ln r_o/r_i}{k_m}\right] \qquad \text{EQ 2}$$

Both gradients are proportional to the heat flux; the two gradients are additive and determine the tube-metal operating temperature.

The furnace size must be large enough to keep the maximum heat flux less than about 125,000 BTU/HR-FT^2. At this value, 125,000, $\Delta T_i + \Delta T_m$ is about 150°F. If saturation temperature is 650°F the fireside metal temperature is 800°F. The usual temperature limit of carbon steel is 850°F. Thus any higher heat flux than 125,000 BTU/HR-FT^2 will lead to excessive metal temperatures for carbon steel. These peak heat fluxes occur in the burner zone. Above and below, the heat absorption drops off so that the furnace wall average is considerably less.

A third factor comes into play in coal-fired boilers: the ash fusion temperature, the point at which the ash becomes sticky. The amount of heat absorbed in the furnace should be sufficient to reduce the furnace exit gas temperature (FEGT) below the ash fusion temperature. The FEGT depends on the ratio of heat released during combustion to the size of the furnace-wall cooling surfaces. Furnace exit gas temperature is determined by the ash fusion temperature of the fly ash entering the convection pass. This temperature should be low enough that the ash deposits, when they form, are friable and easily removed by soot blowers. Too high a gas temperature and the fly ash will be molten, tightly adhering, and impossible to remove.

In the design of all boilers the primary objective is to maintain sufficient fluid flow through the heated tubes for adequate control of tube-metal temperatures. The expected heat-transfer regime on the fluid side is nucleate boiling for all operating conditions. To maintain nucleate boiling the heat flux must be balanced by appropriate fluid flow. Steam bubbles form at discrete locations on the inside surface of the heated risers. When they reach a critical size, each is swept away by the moving liquid. So long as single bubbles of steam form and are removed, nucleate boiling is said to occur. When the volume of steam becomes too great, at a very high heat flux for example, individual bubbles cease to exist but form a continuous film. This is the point of departure from nucleate boiling (DNB) and rapid tube failures follow.

Similarly, the superheaters and reheaters also have a balance between heat transfer and fluid flow. In equilibrium the metal temperatures are within the design limits and the stress levels are within the ASME Boiler & Pressure Vessel Code requirements and below the oxidation and corrosion limits of the alloy selected.

There are factors that can upset the balance between heat transfer and fluid flow and raise tube-metal temperatures to the failure point: 1) Too high a heat flux, e.g., from flame impingement or laning. 2) Excessive steam-side scale. Scale has a thermal conductivity less than that of the steel. The net effect is to raise tube-metal temperatures, refer to VOL. I, No. 1 of this newsletter.) 3) Too small "h_i", which in EQ 1 is a function of mass flow of the steam or water. The fluid flow is resisted by the frictional forces between the fluid and the walls of the conduit. At every bend or turn there is a change in momentum and thus an energy loss. To keep the fluid moving takes energy to overcome these flow resistances. The longer the tubes, the larger are these frictional resistances. The trick in design is to make sure that the internal resistance along each parallel flow path is the same. The easiest way to do this of course, is to make the length of the individual tubes between inlet and outlet headers the same. If the length of an individual tube through a SH pendant, for example, differs from its neighbor, then the flow resistance is greater and there is less mass flow of steam through that particular circuit. The smaller the steam-mass flow, the smaller will be "h_i" and thus the tube-metal temperature is increased. A tube-metal temperature increase of 50°F over the design temperature will reduce the expected life by about 85%. Thus small increases in tube-metal temperature can have disastrous effects on the expected life.

We can begin to see reasons for some of the tube failures that occur throughout a boiler. Something has upset the dynamic balance between heat transfer and fluid flow. The increases in internal scale reduce the heat flow and thus raise tube-metal temperatures. Changes in heat flux and variations in steam flow will also raise tube-metal temperatures. Design mistakes occur. Flow is a function of the length through a superheater or reheater circuit. Every tube should have the same effective tube length for comparable steam flow, and thus comparable heat transfer and cooling. This, unfortunately, is not always the case.

The gas-side, heat-transfer coefficient also can be variable from tube to tube; e.g., wrapper tubes designed to align the pendant bundle can stick out into the gas path where heat transfer is greater than within a tube protected by the rest of the bundle. Since wrapper tubes contain a substantial number of bends that constrict steam flow, steam-side heat transfer and steam-side flow are restricted. Wrapper tubes, as a consequence, overheat and have creep failures before the rest of the bundle.

At the time a SH or RH is replaced, be sure to correct previous design flaws that have prevented optimum performance or life. A SH or RH is nothing more than a large heat exchanger. Failure to perform properly for the expected 25-30 year life results from metal deterioration. In reality the failure is usually one related to design. From a metallurgist's viewpoint, it is essential that tube-metal temperatures be kept as low as possible relative to the metal's strength and corrosion and oxidation resistance.

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