Natural Circulation in Boilers

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Abstract

This article is focused towards the author's experience in the design and trouble shooting of Boilers related to the principle of natural circulation. Inadequate circulation causes tube failures. Poor circulation in a boiler may be due to design defect or improper boiler operation. In this paper the factors affecting the circulation are summarized. Further case studies are presented.

Principle of Natural Circulation

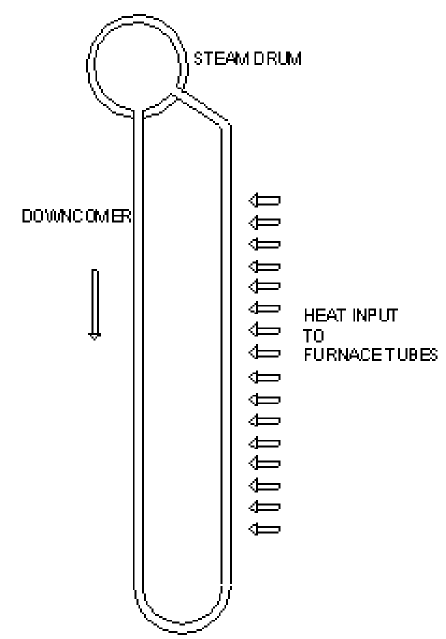

FIG 1. FLOW DUE TO DENSITY DIFFERENCE

Boilers are designed with Economiser, Evaporator and Superheater depending on the Design parameters.

Economisers add sensible heat to water. The Economiser water outlet temperature will be closer to saturation temperature. The water is forced through the Economiser by the boiler feed pumps.

Superheaters add heat to steam. That is the heat is added to steam leaving the Boiler steam drum / Boiler shell. The steam passes through the Superheater tubes by virtue of the boiler operating pressure.

Evaporators may be multi tubular shell, Waterwall tubes, Boiler bank tubes or Bed coils as in FBC boiler. In evaporators the latent heat is added. The addition of heat is done at boiling temperature. The Flow of water through the evaporator is not by the pump but by the fact called thermo siphon. The density of the water, saturated or sub-cooled is higher as compared the water steam mixture in the heated evaporator tubes. The circulation is absent once the boiler firing is stopped.

Boiling mechanism

There are two regimes of boiling mechanisms, namely, the nucleate boiling and the film boiling. Nucleate boiling is formation and release of steam bubbles at the tube surface, with water still wetting the surface immediately. Since the tube surface temperature is closer to saturation temperature the tube is always safe against failure.

Film boiling is the formation of steam film at the tube surface, in which the metal temperature rises sharply. This leads to instantaneous or long term overheating of tubes & failures. Film boiling begins due to high heat flux or low velocity or inclined tubes.

Circulation Ratio / Number

The flow of water through a circuit should be more than the steam generated in order to protect the tube from overheating. The Boiler tubes, its feeding downcomer pipes, relief tubes / pipes are arranged in such a way that a desired flow is obtained to safeguard the tubes. The ratio of the actual mass flow through the circuit to the steam generated is called circulation ratio.

$$\text{CIRCULATIO N RATIO} = \frac{\text{TOTAL FLOW THRO THE CIRCUIT}}{\text{STEAM GENERATED IN THE CIRCUIT}}$$

Depending the Boiler Design parameters, configuration of the boiler this number would be anywhere between 5 & 60. In low pressure boilers, this number is on the higher side as the density difference between water & steam is high.

What if the circulation ratio is less than that required minimum?

Tube deformation / leakage failures / tube to fin weld failures take place. The failure mode varies depending upon the flow, heat input, tube size, boiler configuration, and water quality.

- Wrinkles seen in tubes
- Bulging of tubes
- Wrinkle formation & subsequent circular crack
- Heavy water side scaling inside tubes.
- Corrosion of tubes
- Prolonged overheating & irregular cracks on tubes
- Sagging of tubes if orientation is horizontal / inclined
- Tube to fin weld crack

See figure 2 for the illustrations.

Factors which affect Circulation

- ***No of downcomers, diameter, thickness, layout***

No of downcomers are selected depending upon the heat duty of each section of evaporator tubes. Depending on the length of the distributing header, more downcomers would be necessary to avoid flow unbalance. It is desirable to keep the bends, branches to a minimum so that the pressure drop is less. The selection of downcomers is so done to keep the velocity less than 3 m/s.

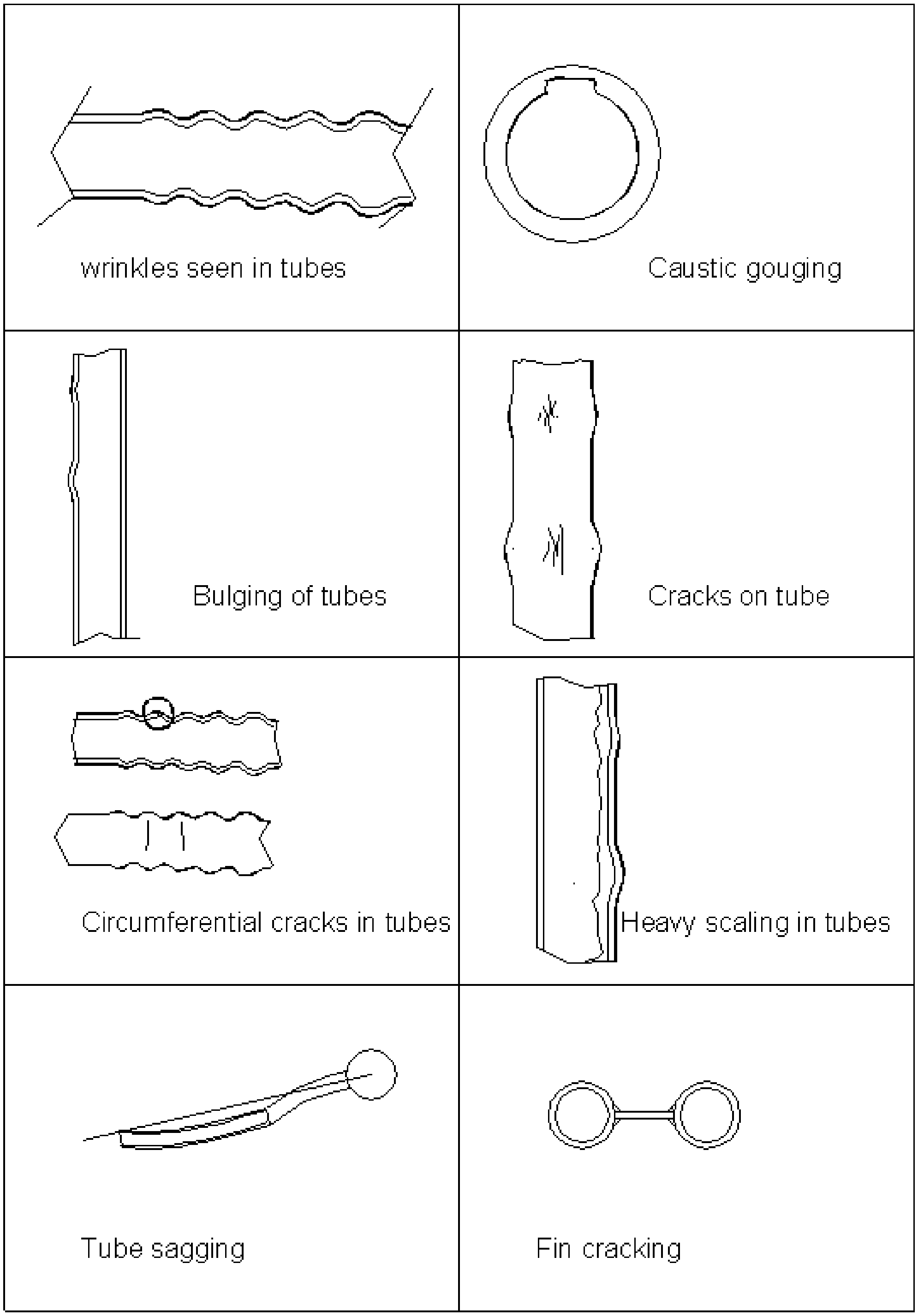

FIGURE 2. ILLUSTRATION SHOWING TUBE FAILURES

- ***Heated down comers***

In some boilers the downcomers are subject to heat transfer, for e.g. rear section of boiler bank in Bi drum boilers. The circulation pattern in these boiler evaporator tubes is a function of heat transfer. In case of heated downcomers, burning of tubes may take place if the design is defective. There could be stagnation of water in some tubes depending on the heat pick up.

- ***Downcomer location & entry arrangement inside the drum***

Depending on the Boiler configuration downcomers may be directly connected to steam drum or else to mud drum. One should ensure that the entry of sub-cooled water is smooth into the downcomer.

A down comer directly connected to steam drum is vulnerable to steam bubble entry into the downcomer. In such a case the circulation is affected. Instead of using big pipes, more no of smaller diameter pipe would avoid this. Vortex breaker would be necessary to avoid steam entry into the downcomer pipe.

In case a set of bank tubes are used for taking water to mud drum, One should ensure that the steam does not enter these tubes during water level fluctuation.

Proper baffle plates would be necessary to avoid mix up of steam water mixture from risers section to downcomer section.

Downcomers taken from mud drum are very safe.

An obstruction in front of downcomer can cause the poor circulation in evaporator tubes.

- ***Arrangement of evaporator tubes***

The circulation in each evaporator tube is dependent on how much it receives heat. If there is non-uniform heating among evaporator tubes, One can expect non-uniform flow. At times even flow reversal can take place. In some situations the water may become stagnated leading to water with high TDS or high pH. Localized corrosion of tubes would occur.

- ***Improper operation of boiler***

Depending upon the boiler capacity there may be number of burners / compartments in a boiler. This is required in order to achieve the boiler turn down in an efficient way.

In FBC boilers no of compartments are provided for turn down. Operating only certain compartments all the time would cause stagnation of water in unheated section of bed coils. The concentration dissolved solids, pH could be far different from the bulk water chemistry. This leads to corrosion of boiler tubes.

Similarly, operating same burner would heat the evaporator tubes in non-uniform way leading to different water chemistry in unheated section of furnace tubes.

- ***Feed pump operation***

In low-pressure boilers, (pressures below 21 kg/cm2 g), the feed pump on /off operation is usually linked to level switches in the steam drum. When the pump is in off mode, it is likely that the steam bubbles would enter the downcomer tubes and cause loss of circulation.

- ***Arrangement of evaporative sections and the interconnection between sections***

In certain configuration of boilers it is possible to obtain better circulation by interconnecting a well-heated evaporator sections to poorly heated evaporator section. It would be necessary to separate the poorly heated section if it lies in parallel to well heated section. The downcomers & risers are to be arranged separately so that the reliable circulation can be ensured. This principle is called sectionalizing for reliable circulation. The inlet headers / outlet headers shall be partitioned for this purpose.

However, it is desirable to arrange the evaporative surface in such a way that heat flux & heat duties in various circuits are more or less same.

If tubes are inclined close to horizontal, the steam separation would take place leading to overheating of tubes.

- ***No of risers , pipe Inside diameter, bends, branches***

No of risers are so selected that the velocity inside the pipes would be 5 – 6 m/s. The no of risers are selected in such a way the flow unbalance is minimum. It is preferable to adopt long radius bends to keep the pressure drop to minimum. The no off bends, branches should be kept as minimum possible as these elements contribute for high-pressure drop.

- ***Arrangement of risers in the drum***

The risers are arranged in such a way that the pressure drop is minimum. The baffles are spaced apart to keep the obstruction to flow is minimum. Instead of terminating the risers below the water level in the drum, it would be better to terminate above water level in the steam drum as it allow free entry.

- ***Feed distributor inside the steam drum***

Feed distributor shall be arranged in such way that the sub-cooled water enters the downcomer section. This will ensure that the good hydrostatic head is available for circulation.

- ***Drum Internals arrangement***

Drum internals such as baffles, cyclone separator also form part of the natural circulation circuit.

The baffles are arranged in such a way the steam would rise easily to the steam space without much resistance. High-pressure drop in the drum internals will retard the flow through evaporator tubes.

- ***Slagging of furnace tubes***

The design of the furnace shall be in such a way that the Slagging of the fuel ash is avoided. Slagging retards the heat transfer to tubes and thus the driving force for circulation will come down. At locations where the tubes are clean, this would lead to overheating of tubes. If unavoidable, soot blowers shall be so arranged that the uniform heat flux to evaporative sections be not hindered.

- ***Critical heat flux, Allowable steam quality, recommended fluid velocity***

In the design of furnace, the heat flux should not be higher that a limit beyond which the tube will burn. Several correlations are available on this.

In a circuit the steam produced divided by the mass flow would be the quality of steam produced in the circuit. The allowable steam quality has been found be dependent on the heat flux, mass velocity and the steam pressure.

Even after ensuring that the heat flux and steam quality are safe, the entry velocity is important to avoid departure from nucleate boiling. For vertical rising circuit the velocity is in the range of 0.3 m/s to 1.5 m/s. for inclined circuit the velocity shall be in the range of 1.54 m/s to 3 m/s.

Analyzing for boiler water circulation

In a circuit, the circulation takes place due to difference in density between the cold water in the downcomer circuit and the density of steam water mixture in the evaporator tube. The flow will increase as the heat input is more and the density of water steam mixture decreases in the evaporative circuit. But pressure loss in a circuit rises as the flow increases. Hence there will be appoint of balancing at which time the pressure loss is equal to the head. In order to improve / retard the flow; the circuit may be rearranged duly considering the above discussed factors.

Using MS EXCEL, practically any circuit can be analyzed for the circulation .

Conclusion

The design of the boiler is not necessarily such a mere calculation of Heat transfer surfaces. It is much beyond that. One such subject of importance is undoubtedly the circulation.

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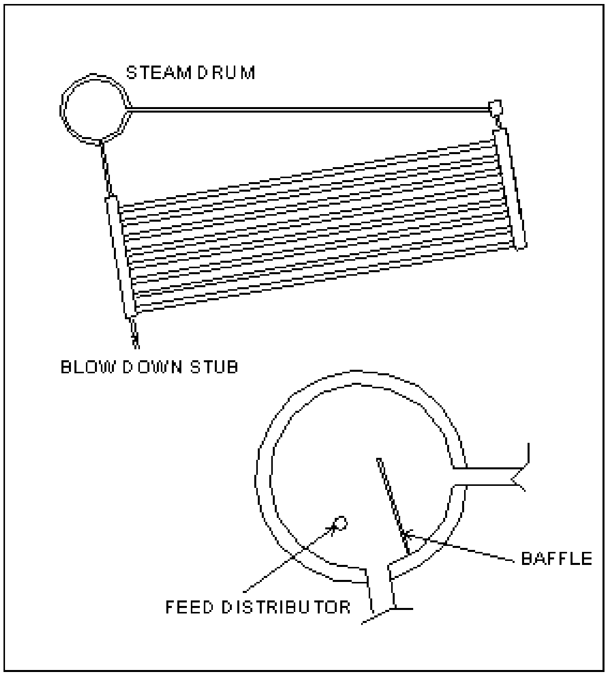
CASE STUDIES

CASE 1

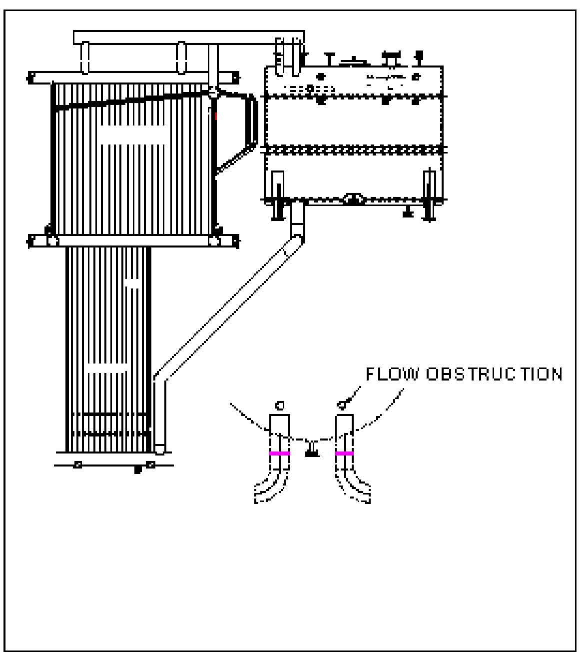


The bottom rows of the bank tubes of this cross tube boiler were sagging.

There were no drum internals. Feed distributor was added to improve the circulation. Further in order to have saturated water into the downcomer baffles were added in the steam drum to promote circulation.

The blow down stub was very close to the bottom row of tubes. Continuous blow down was recommended so that loss of circulation could be averted.

CASE 2



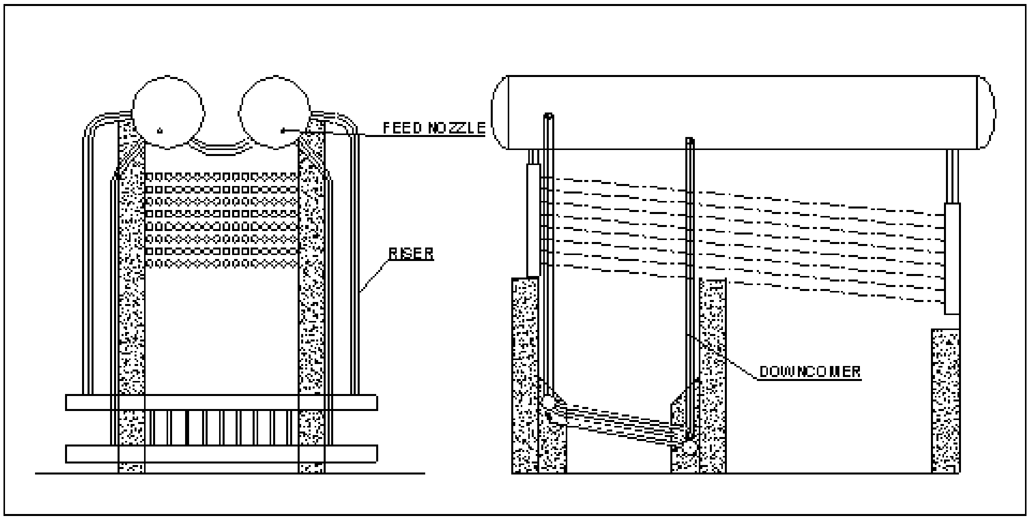
In this case, the water wall & bed coils were failing after bulging & overheating. Thick rough edge cracks were observed wherever the failure took place. There were several locations at which the failures had taken place.

There was severe scaling in the boiler. Hence the water quality was suspected for a long time.

By removing the flue tube immediate to the downcomer, the failure stopped.

Similar failures were noted when there was lot of accumulation inside the headers due to improper post cleaning operation after a chemical cleaning of the boiler.

CASE 3

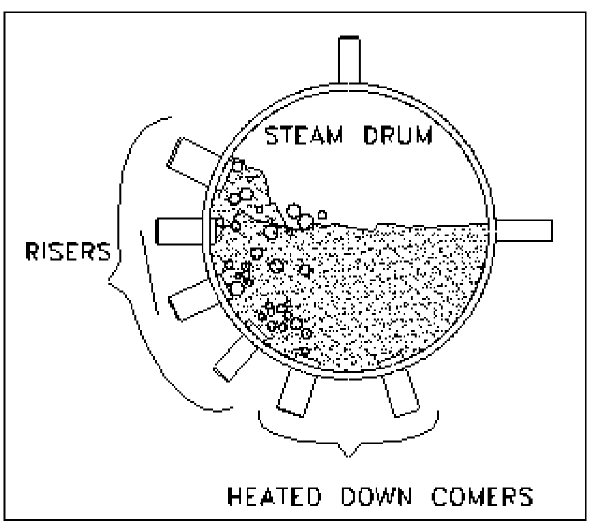


This boiler was converted for fluidized bed firing. There were wrinkle formations in bed coil tubes. It was felt that the Downcomer & risers were inadequate and several modifications were done in order to reduce the pressure drop in the circuit. Still the failures continued. Suspecting boiler expansion problem, the refractory work was reconstructed with adequate provision for expansion. Yet the failures continued.

The two drums were provided with feed nozzles at dished ends with separate non return valves. It was noticed that the feed water was not going into one of the drums, as the NRV was defective. It is possible that flow reversal was taking place in the downcomer in the drum where the NRV was not functioning.

The NRV at each steam drum inlet was removed and a common NRV was provided in the feed line. Also a feed distributor was added in each drum to distribute the water to downcomer area. This way the flow reversal in the downcomer was eliminated and the failures stopped.

CASE 4

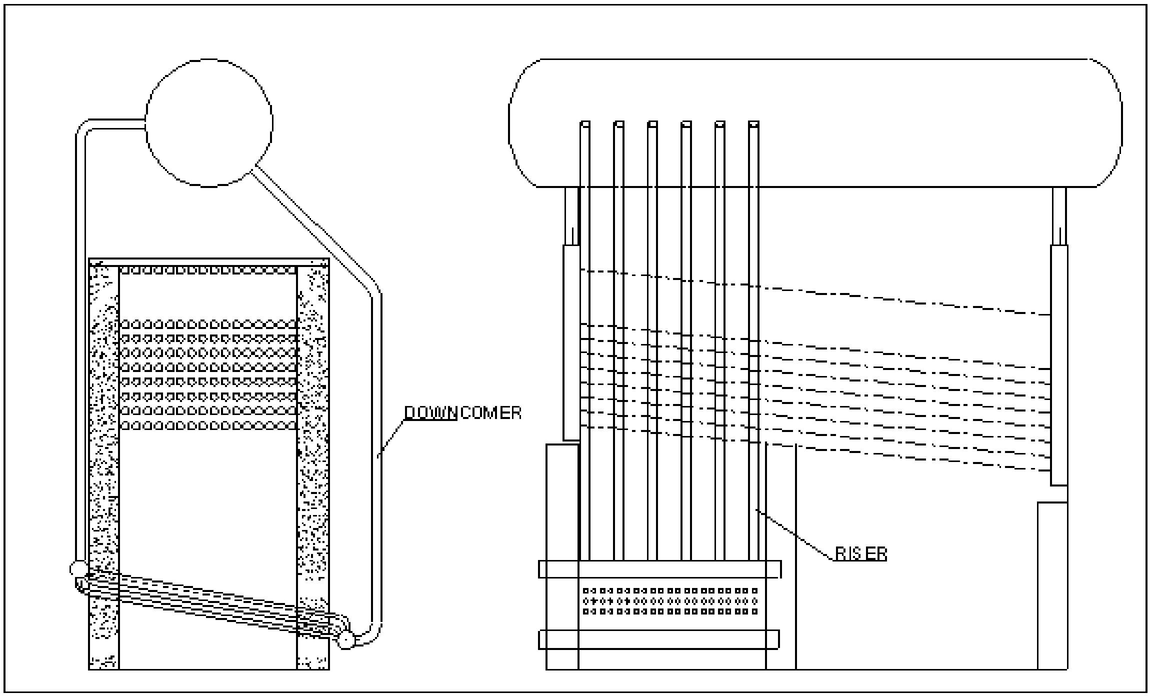


The boiler was provided with heated downcomers. There were no baffles inside the drum to separate the steam water mixture from down comer section. When the load in the boiler increased beyond a point the downcomers started bursting.

This proved the possibility of steam water mixture entering the downcomers.

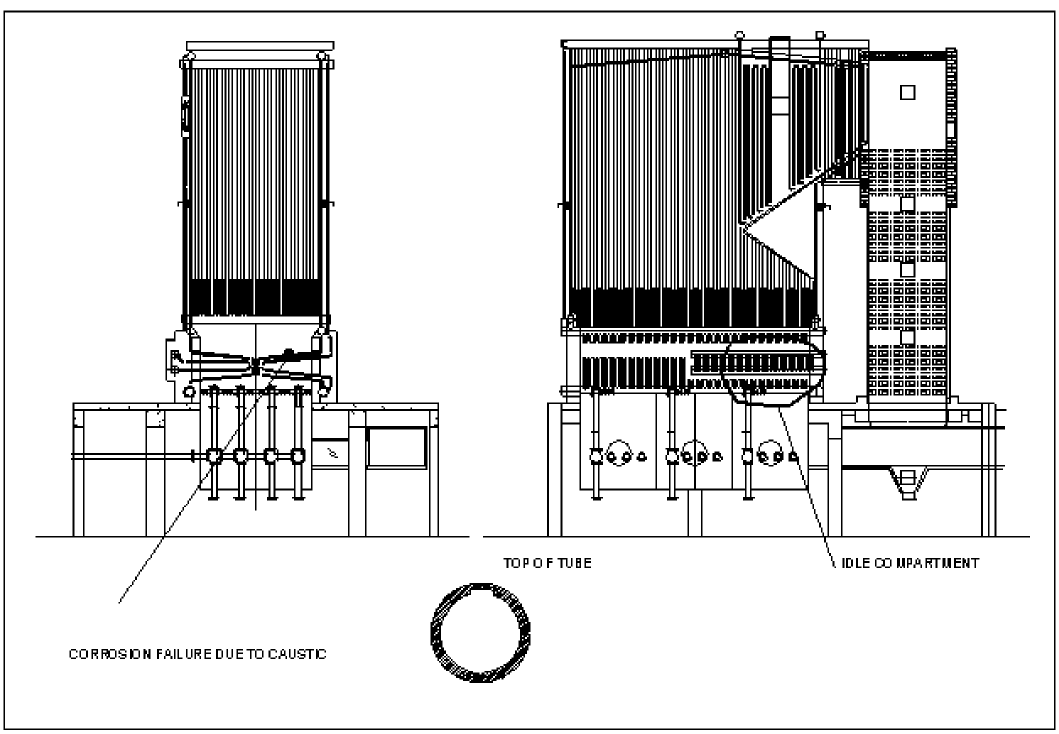
Boiler drum internals with cyclone separators were added.

CASE 5



The illustration shows a boiler converted for FBC firing. In this boiler vibration of riser tubes was experienced. Even after a snubber support was provided, the vibration continued. The circulation calculation showed a velocity of 7 m/s in riser tubes. The vibration problem vanished after one of the risers was removed. The velocity in the riser was then estimated to be less than 6 m/s.

CASE 6



The above is a Fluidized bed combustion boiler with three compartments. A pin hole failure was reported in the 12 o clock position of the bed coil tube. On cutting the tubes, the inside was found have gouging mark for the throughout the inclined portion of the tube. Several adjacent tubes are inspected with D meter. Four adjacent tubes showed less thickness at 12o-clock position. The tubes were cut inspected and these tubes were also found to have the same marks as the leaked tube.

On suspicion the symmetrical tubes about the boiler axis ware also checked with D meter. The tubes were found to have similar gouging attack.

The boiler water log sheets since commissioning were analyzed and found the water chemistry had deviated in the past three months. The boiler was operated on pH of 11, resulting in free hydroxide. The water inside the idle compartment was stagnant, as the compartment was kept idle. Caustic attack had been the cause of failure.

Customer was advised for alternate activation of compartments so that the circulation in all tubes would be good.

The above case is clearly a circulation-related failure due to operational defects.