2. LITERATURE REVIEW

Theory of Boiler Tube Failure

Boiler tube failures continue to be the leading cause of forced outages in fossil-fired boilers. To get the boiler back on line and reduce or eliminate future forced outages due to tube failure, it is extremely important to determine and correct the root cause. Experience shows that a comprehensive assessment is the most effective method of determining the root cause of a failure.

A tube failure is usually a symptom of other problems. In addition to evaluating the failure itself, all aspects of boiler operation and causes leading to the failure must be fully understood. It is important to gather all the pertinent information. In many cases, the field investigation can isolate the root cause that led to the tube failure. The increasing demand, fluctuating load, socio-economic impact, political influence etc force the power stations to continue function though routine shutdown is required. Privatization of power sector and increased competition, forced many power generation utilities to adopt business strategies centered on increasing availability and extending the life of their plants. Various programs have been implemented to increase availability, but boiler tube failures continue to be the number one cause of forced outages in the fossil plants today, responsible for nearly 6% to 10% loss of availability. Each forced outage can cost the owners millions of Rupees in replacement power.

Boilers are used to heat water for industrial purposes, and to produce steam in power generating plants. Steels, cast irons, stainless steels and high temperature alloys are used to construct various boiler components. Design defects, fabrication defects, improper operation and improper maintenance are some common causes for boiler failures. Elevated temperature and corrosion failures are common failure modes for boilers. Additionally, mechanical failures such as fatigue or wear occur as well. Some of the most common failures modes for boilers used for steam generating include overheating, fatigue or corrosion fatigue, corrosion, stress corrosion cracking, and defective or improper materials. Boilers and steam power plant components experience various failure modes. Some of the common failures associated with boilers are listed below:

Boiler tube failures (BTFs) are the first and foremost cause for loss of availability for fossil fuel power plants. Poor design, fabrication and installation practices, operation, maintenance, and water chemistry initiate failures. Much of these damages sustained by boiler tubing in service can be avoided or controlled. It is important to know the boiler tube damage mechanism and its root cause and implementing long-term, corrective actions to prevent BTF recurrences. It is required to detect the damage prior to the BTFs for the non-repeated failure events and take preventative actions. Materials can fail due to creep, fatigue, corrosion, and erosion. These factors can act independently or jointly to cause material to fail. Particular components fail in unique ways. Boiler tubes are under high-temperature and high-pressure conditions, are subjected to variety of mechanical and thermal stresses and by environmental attack on both the fluid and firesides. In accordance with the ASME Boiler and Pressure Vessel Design Code, the water-touched (WT) boiler tubes (for example, water-walls and economizers) are generally not subject to the high temperatures that produce creep damage. The tube metal should have an infinite life. However, in the past, the water-wall has contributed to the highest BTF rates. This indicates that there are many other harmful factors that contribute to the water-wall problems. The high-temperature components, such as in the super-heater (SH) and reheater (RH) tubes, have limited lifetime due to creep phenomena.

2.1.1 Boiler Tube Failure Mechanisms

The boiler tube can fail due to creep, fatigue, corrosion, or erosion. Stress rupture is a result of these four factors and is not treated as a separate BTF mechanism. These factors can act by themselves or, more commonly, act together to cause boiler tube degradation or failure. If the failure mechanism is a compound of the four basic mechanisms, then root cause analysis can be very complex. Thirty-six specific BTF mechanisms are listed by EPRI. It is must to study the significance of BTFs and options to tackle the boiler failure:

EPRI suggested action steps to tackle Boiler Tube Failure:

- Identify the mechanism of failure
- Determine (confirm) the mechanism
- Determine root cause(s)
To develop a Predictive Tool for Boiler Tube Failure

• Determine the extent of damage or affected areas
• Implement repairs, immediate solutions, and actions
• Implement long-term actions to prevent repeat failures
• Determine possible ramifications/ancillary problems

The boiler tube failure mechanisms identified in the EPRI program are summarized in the following list. The mechanisms are subdivided into four categories reflecting the service conditions under which the failure mechanisms are active.

(a) BTF Mechanisms in Water-Touched Tubes of Conventionally-Fueled Power Plants [5]


(b) BTF Mechanisms in Steam-Touched Tubes


(c) Mechanisms Affecting Both Water-Touched and Steam-Touched Tubes

i) Maintenance damage, ii) Material flaws, iii) Welding flaws

(d) BTF in Non-Conventionally Fired Units

i) Bubbling fluidized bed combustion units, ii) Circulating fluidized bed combustion units, iii) Water-touched tubes of MSW/RDF units

These 36 specific BTF mechanisms are summarized in the following general categories:

(a) Creep/Stress Rupture

i) Short-term overheating (WT), ii) Low-temperature creep (WT), iii) Long-term overheating (ST), iv) Dissimilar metal welds (ST), v) Short-term overheating (ST), vi) Stress corrosion cracking (ST), vii) Graphitization (ST)
(b) **Fatigue**

i) Corrosion fatigue (WT), ii) Thermal fatigue in supercritical water-walls, Thermal fatigue of economizer inlet headers, iii) Fatigue in water-cooled circuits (WT), iv) Dissimilar metal welds (ST), v) Fatigue in steam-touched tubes

(c) **Erosion**

i) Fly ash erosion (WT), ii) Erosion corrosion (economizer inlet headers) (WT), iii) Soot-blower erosion (WT), iv) Coal particle erosion (WT), v) Falling slag damage (WT) vi) SH/RH soot-blower erosion (ST), vii) Rubbing tubes/fretting

(d) **Corrosion**

i) Corrosion fatigue, ii) Hydrogen damage (WT), iii) Acid phosphate corrosion (WT), iv) Caustic gouging (WT), v) Fireside corrosion (WT), vi) Thermal fatigue in supercritical water-walls, vii) Erosion corrosion (economizer inlet headers) (WT), viii) Chemical cleaning damage (WT), ix) Pitting in water-cooled tubes (WT), x) Acid dew-point corrosion (WT), xi) Fireside corrosion in coal-fired units (ST), xii) Fireside corrosion in oil-fired units (ST), xiii) Stress corrosion cracking (ST), xiv) Pitting (RH loops) (ST), v) SH/RH chemical cleaning (ST)

(e) **Others**


\(WT – \) Tubes with Water, \(ST – \) Tubes with Steam

**Boiler Tube Failures:**

The Nalco Guide to Boiler Failure Analysis [6] discuss in detail different boiler tube failure mechanisms and types of failures. Abstract of that report discuss different boiler tube failure in the context of location, general description, vital factors, recognition and detection methods, and removal methods. This exhaustive report helps to understand mechanism of failure, operational triggering factors that cause failure, laboratory methods (metallurgical investigations) to identify the type of failures and corrective actions that can be taken. But no method talks about prediction of failure. It is decided to restrict the scope of research to failure by erosion hence erosion failure mechanism is discussed in detail in the succeeding sections and the
effect of triggering factors on erosion wear and development of wear rate equation is discussed in Chapter 5.

Table 2.1 shows the typical relationship of key boiler pressure components and damage mechanisms. These relationships are highly unit specific, and depend on the design, operation, and maintenance practices. For example, if the water chemistry is poor, then the corrosion effect will be high for most of the components. If the ash percentage in the flue gas is more, then erosion contribution will be much higher.

Table 2.1 Key Boiler Pressure Components and Damage Mechanisms [6]

<table>
<thead>
<tr>
<th>Component</th>
<th>Fatigue</th>
<th>Creep</th>
<th>Erosion</th>
<th>Corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-wall tubing</td>
<td>High</td>
<td>xx</td>
<td>High</td>
<td>xx</td>
</tr>
<tr>
<td>Water-wall Headers</td>
<td>xx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Economizer</td>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Economizer inlet Header</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Super Heater/Re-heater</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Super Heater Header</td>
<td>High</td>
<td>High</td>
<td></td>
<td>xx</td>
</tr>
<tr>
<td>Re-heater Header</td>
<td>xx</td>
<td>High</td>
<td></td>
<td>xx</td>
</tr>
<tr>
<td>Hot Reheat Piping</td>
<td>xx</td>
<td>High</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold Reheat Piping</td>
<td>xx</td>
<td></td>
<td>xx</td>
<td>xx</td>
</tr>
<tr>
<td>Main Steam Piping</td>
<td>xx</td>
<td>High</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drums</td>
<td>xx</td>
<td></td>
<td></td>
<td>xx</td>
</tr>
<tr>
<td>Down-comers</td>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attemperator</td>
<td>High</td>
<td>xx</td>
<td></td>
<td>xx</td>
</tr>
</tbody>
</table>

Tables 2.2, 2.3, and 2.4 indicate the general relationship between the failure mechanisms and the design, operation, and maintenance activities. The actual relationship can be unit specific.

Table 2.2 Potential Contributors to the Failure Mechanisms in Tubes with Water

<table>
<thead>
<tr>
<th>No</th>
<th>Failure Mechanism</th>
<th>Design*</th>
<th>Operation**</th>
<th>Maintenance***</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Corrosion Fatigue</td>
<td>xx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Fly Ash Erosion</td>
<td>xx</td>
<td>xx</td>
<td>xx</td>
</tr>
<tr>
<td>3</td>
<td>Hydrogen Damage</td>
<td>xx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Acid Phosphate</td>
<td>xx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Caustic Gouging</td>
<td>xx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Fire side corrosion in coal-fired units</td>
<td>xx</td>
<td>xx</td>
<td>xx</td>
</tr>
<tr>
<td>7</td>
<td>Thermal fatigue in supercritical WW</td>
<td>xx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Thermal fatigue of ECO inlet headers</td>
<td>xx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Erosion corrosion (ECO inlet headers)</td>
<td>xx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Soot-blower erosion</td>
<td>xx</td>
<td></td>
<td>xx</td>
</tr>
</tbody>
</table>
To develop a Predictive Tool for Boiler Tube Failure

<table>
<thead>
<tr>
<th>No.</th>
<th>Failure Mechanism</th>
<th>Design</th>
<th>Operation</th>
<th>Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Short Term Overheating</td>
<td>xx</td>
<td>xx</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Low-temperature creep</td>
<td>xx</td>
<td>xx</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Chemical cleaning damage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Fatigue in water-cooled circuits</td>
<td>xx</td>
<td>xx</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Pitting in water-cooled tubes</td>
<td>xx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Coal particle erosion</td>
<td>xx</td>
<td>xx</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Falling slag damage</td>
<td>xx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Acid dew-point</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.3 Potential Contributors to the Failure Mechanisms in Tubes with Steam

<table>
<thead>
<tr>
<th>No.</th>
<th>Failure Mechanism</th>
<th>Design</th>
<th>Operation</th>
<th>Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Long-term overheating/creep</td>
<td>xx</td>
<td>xx</td>
<td>xx</td>
</tr>
<tr>
<td>2</td>
<td>Fireside corrosion in coal-fired units</td>
<td>xx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Fireside corrosion in oil-fired units</td>
<td>xx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Dissimilar metal welds</td>
<td>xx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Short-term overheating</td>
<td>xx</td>
<td>xx</td>
<td>xx</td>
</tr>
<tr>
<td>6</td>
<td>Stress corrosion cracking</td>
<td>xx</td>
<td>xx</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>SH/RH soot-blower erosion</td>
<td>xx</td>
<td>xx</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Fatigue in tubes with steam</td>
<td>xx</td>
<td>xxx</td>
<td>xx</td>
</tr>
<tr>
<td>9</td>
<td>Rubbing tubes/fretting</td>
<td></td>
<td>xx</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Pitting (RH loops)</td>
<td>xx</td>
<td>xx</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Graphitization</td>
<td></td>
<td>xx</td>
<td>xx</td>
</tr>
</tbody>
</table>

Table 2.4 Potential Contributors to the Failure Mechanisms Affecting Both Tubes with Water and Tubes with Steam

<table>
<thead>
<tr>
<th>No.</th>
<th>Failure Mechanism</th>
<th>Design</th>
<th>Operation</th>
<th>Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Maintenance damage</td>
<td></td>
<td></td>
<td>xx</td>
</tr>
<tr>
<td>2</td>
<td>Material flaws</td>
<td>xx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Welding flaws</td>
<td>xx</td>
<td>xx</td>
<td></td>
</tr>
</tbody>
</table>

*Design includes defects in original design, material, fabrication, and installation

**Operation includes problems from water chemistry, operator errors, and coal quality

***Maintenance includes improper practice in maintenance and chemical cleaning
2.2 Boiler Tube Failure Mechanisms of Interest

Boiler tube failure data and Nalco Tube Failure guide emphasizes the Creep and erosion failure and hence it is necessary to study it in detail.

2.2.1 Creep/Stress Rupture [7]

Boiler water tubes, steam super heater elements are internally pressurized tubes and critical components in heat-exchange applications. Tubes in such applications are susceptible to temperature variations: as a consequence the material enters the creep regime, and creep deformation (bulging) and even fracture (longitudinal rupture) consequently occurs, with serious after effects on the boiler and its function. It is estimated that 10% of all power plant breakdowns are caused by creep fractures of boiler tubes. In general, 30% of all tube failures in boilers and reformer tubes are caused by creep.

All water tubes are intended to operate under conditions of the highest possible heat transfer. High temperature flue gases are cooled by the heat transfer between the tube surface and inside flowing water result of which water gets heated. Thus anything that is against the heat transfer process will lead to increase in tube surface temperature and thus overheating. Scale formation, of corrosion product and steam blanketing at the tube wall provide ruinously effective thermal barriers. In many water-tube boilers, the conditions for circulation some times are insignificant. Risers and down-comers may become mixed up and there can be regions water starvation in the boiler. Water-tube boilers are also prone to “steam blanketing”, where a stable layer of steam forms between the water and the inner surface of the tube. This helps to insulate the tube from the circulating water and thus the heat transfer between the flowing water and hot flue gases is reduced. This increases the tube surface temperature. The situation can become unstable: as the tube surface temperature increases the steam blanket tends to grow and the whole tube may boil dry. Once this happens, the tube surface temperature may reach to the surrounding flue gases. If this continues, a large number of tubes boil dry, and the situation worsens. The furnace gases fails to be cooled by the risers and the temperature of the gas around the dried-out tubes can in principle be as high as the inlet temperature of the flue gases, which an alarming situation.

There are three basic mechanisms of creep failure. (i) Inter-granular creep fracture, most likely mechanism at low stresses. (ii) Trans-granular creep fracture,
failure mechanism at high stresses and (iii) Dynamic recrystallization, a mechanism at high temperature and stresses. Thus creep properties are structure sensitive. The circumference of the tube increases during creep, the wall thickness decreases so as to conserve volume. There is no change in the length of the tube, which is necessary otherwise the creeping tubes could distort the whole boiler.

2.2.2 Erosion Failure

Erosion is a process by which material is removed from the layers of a surface impacted by a stream of abrasive particles. The magnitude of the wear is quantified by the volume or mass of the material that is removed by the action of the impacting materials. In coal fired boilers, ash particles collide with surface of the boiler steel components viz. air preheater, economizer, and superheater tubes, resulting in considerable erosion of metallic materials. [8]

a) Fly ash erosion

Fly ash erosion takes place when fly ash particles in flue gas impact boiler tube surfaces at high velocity. The process increases the fireside wastage rate, eventually leading to stress-rupture. Depending on the wastage rate, the tube can fail in one of two modes: a fast wastage rate leads to rapid wall loss and thin-wall failure, while a slower rate of wall loss leads to thick-wall failures due to creep damage from the combined effect of increased temperature and a thinner tube wall. Tube wastage due to fly ash erosion occurs via two mechanisms: fly ash directly impacting the metal surface and removing metal by abrasive wear, or removing the fireside scale during impact, which exposes the base metal and accelerates the oxidation rate. The contribution from these mechanisms changes as the metal temperature increases, with the scale removal mechanism becoming dominant at temperatures above about 800°F (430°C). Fireside erosion is common in units that burn high-ash-content coals and those that contain a high percentage of abrasive ash material, such as quartz (SiO2). Particle velocity is the most important parameter as the rate of erosive loss is proportional to the velocity raised to an exponent that ranges between two and four. Particle velocity is driven by the local flow velocity at any particular boiler location. The optimum long term solutions are based on identifying and reducing the highest velocity locations. The risk of erosion is largest in baffles, bends and other areas where increased turbulence may take place. It is important to be noted that local velocities, not bulk velocities across a section of the boiler are those of interest. [9]
The metal loss on convection pass tubes due to fly ash erosion is proportional to the total ash quantity passing through the boiler and is an exponential function of flue gas velocity. While with a given fuel there is no control of the ash quantity, erosion problems can be eased by reducing flue gas velocities. Velocity limits are determined based on the ash quantity basis and the relative proportion of abrasive constituents in the ash. Typical limits range from 19.8 m/s for relatively non-abrasive low ash coals to 13.7 m/s or less for coals with high ash quantities and/or abrasive ash. [10]

Erosive metal loss increases as particle hardness, flow velocity, and ash concentration increase. Of these factors, flow velocity and ash concentration are most important. Erosive loss increases as the angle of impingement between gas flow and the metal surface increases. The direct incidence of fly ash is more damaging than glancing blows. As temperature increases, erosive metal loss decreases because particles become softer. Size, hardness, and composition of particulate matter also influence attack. Particles larger than about 0.0025 cm and those containing high concentrations of aluminum and silicon compounds are more erosive because of high particle hardness and large particle kinetic energy.

b) Erosion Corrosion

In erosion-corrosion, the protective oxide layer or the created corrosion product is removed from the tube surface by erosion. Tube material loss may be accelerated by erosion caused by steam flow. In erosion-corrosion, the protective scale on the surface of steel is removed by a local turbulence, and corrosion can attack a non-protected area. Erosion-corrosion can be avoided by proper design and proper material selection.
The term erosion-corrosion is used for describing cases in which the metal is weakened by corrosion, and the corrosion products are removed by erosion. According to Meuronen (1997), erosion of heat transfer surfaces is dependent on process conditions, particle flow density, mass flow and velocity, angle of collision, and material properties of both the colliding particle and the heat transfer surface. When combined with parameters affecting corrosion rate and mechanism, combined erosion-corrosion may unexpectedly result in a very complex and rapid metal degradation (Reponen et al. 1999). This type of corrosion is very difficult to detect reliably, because there are very few detectable corrosion products left on the sample. Several tests for erosion-corrosion have been reported (Wright, Nagarajan and Mertz 1984, Rautala et al 1988), but generally, the results of these tests apply only on the process conditions used during the tests. General rules for estimation of the rate and reduction of erosion-corrosion are not available. Different tube coatings for protection have been tested with varying results, see Dutheillet and Prunier (1998) or Nanba, Mizo and Kajigaya (1998). Currently, the best means of protecting heat transfer surfaces from erosion-corrosion is proper boiler design. [11]

2.3 Literature Review

Bitter (1963) [12] in the paper discussed various types of erosion. He showed that erosion is due to two mechanisms: the mechanism of erosion due to cutting, and mechanism of erosion due to deformation. He did not consider the effect of temperature. He showed that the total erosion is the summation of erosion due to deformation and erosion due to cutting. Wellinger determined the erosion as a function of the impact angle for low carbon steel, which is soft and ductile and hardened high carbon steel, which is brittle. The hard and brittle steel appeared to be more erosion resistant at low impact angles than the soft steel; while at high impact angles the reverse was true.

A. Magee [13] in 1995 developed a mathematical model derived from that of Finnie and Bitter. It considered the nature and microstructure of the material, together with the angle of impact of the particles, their hardness and their sharpness. Microstructural examinations showed the damage phenomena due to deformation and cutting effects. The author didn’t consider the effect of temperature of either the target material or eroding material. The author’s analysis on effect of sharpness of particle
and effect of hardness of eroded and eroding surface is used develop the final erosion rate equation.

B.A. Lindsley, A.R. Marder, [14] in this paper, authors have studied the effect of velocity on the solid particle erosion rate of alloys. Velocity is a critical test variable in erosion, and can easily overshadow changes in other variables, such as target material, impact angle, etc. The effect of velocity on erosion rate was studied and it was found, as previously shown, that erosion rate is dependent on velocity by a power law, given by \( ER = kV^n \). The author didn’t heat the specimen eroding in the experiment performed by him. He assumed that air and particle will reach to same temperature once they are mixed. He assumed that the particle velocity becomes same as air velocity in accelerating tube.

Authors Y.I. Oka, H. Olmogi, T. Hosokawa, M. Matsumura [15], studied the impact angle dependence of erosion damage caused by solid particle impact. The dependence of erosion on impact angle was studied on various kinds of materials. It has been found that dependence of erosion on impact angle of particle is independent of velocity within range of 50 to 130 m/s. So the effect of sharpness of particles and effect of hardness on erosion is neglected in the analysis.

R. Tilley [16], ‘Impact of Operating Factors on Boiler Availability’, EPRI report, 2000 emphasize the significant impact of changing operating conditions of boilers on boiler performance and component reliability. It is highlighted that many operating changes are made without full consideration of possible negative impacts. To take advantage of a lower cost on the basis for energy per unit weight the coal supply may be changed, however, the characteristics of the new coal may be such that it increases damage rates to critical boiler tubing sections and increases both the risks and actual occurrences of forced outages to the unit.

In most of the cases the extended surfaces are used to increase the heat transfer, but the use of an extended surface without due consideration to effectiveness is less desirable. The heat transfer characteristics are highly dependent upon cleanliness. Economizers have the most sensitive and obvious effect on the unit capability. The extended surface economiser may lead to plugging and fouling due to deposition of ash and thus the potential for limiting load due to fouling and plugging is raised. There are cases where this is the only means by which lowering the gas temperature entering the air heaters to an acceptable level can be achieved and in such
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cases, vigilant monitoring and cleaning are required. The un-finned economizers are preferred to minimize plugging and fouling.

E. Raask [17], “Tube erosion by ash impaction”, Central Electricity Research Laboratories, Leatherhead, Surrey, Gt. Britain. The author found that Tube failures occurring in the primary superheater and re heater and in the economizers of coal-fired boilers are the results of erosion wear caused by impaction of ash particles. The authors constructed a laboratory assembly to study the erosion wear of mild steel, and the following parameters were considered; the abrasiveness of ash, the velocity of impacting particles, the angle of impaction and the metal temperature. The velocity was shown to be the most important parameter for tube erosion in coal-fired boilers. For a given concentration of particulate ash in the flue gas the rate of metal loss is proportional to the impact velocity to power 3.5. The wear rates should be negligible when the velocity of flue gas is in the range of 15–20 m/sec, whereas with the values of 30–40 m/sec tube failures are to be expected after 10,000-50,000 h in service. Some remedies to reduce the erosion wear are discussed. The author studied the erosion pattern on mild steel. Hence there is a scope to study the erosion pattern on actual metal that is used for tube and real size parameters.

Ray AK, et.al. [18] “Remnant Life assessment of service –exposed pendant super heater tubes” Engineering failure Analysis. The Author discussed the causes of failure of super heater tube. They found that yield strength and UTS lower down at higher temperature similarly the hardness of tube was observed lowest at higher operating temp. Thus the higher temp has impact on reliability and remnant life. The excessive rise in temp may be due to non uniform flow of steam and also to some extent the physical location tube.

• High operating temp.

• Non uniform flow of steam.

• Thus it is important to find the cause of rise in temp and simultaneously the cause of non-uniform flow of steam through the tube.

Byeong-Eun Lee et. al, [19] “Computational study of solid particle erosion for a single tube in cross flow”, Wear. The authors have computationally predicted the boiler tube erosion for economizer using single tube flow and compared with experimental data. The authors have also used all previously described variables for prediction. They also emphasized the effect of impinging particle shape and size on
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erosion rate. The erosion is described as power law of impact velocity. The authors also found that erosion rate increases with temperature. This study shows concern in reduction in flue gas velocity in the pass, reduction in particulate concentration of flue gas. Fly ash particles are angular and spherical. It is important to find which operating conditions will create more irregularly shaped un-vitrified quartz particles? Erosion rate thus has considerable impact of High working temperature, Non uniform flow of steam, impinging particle size, shape, velocity and angle.

Hence it is decided to computationally analyze the flow through the tubes and over the tubes in that specific zone where frequency of failure is more. These zones are Re-heater and Economizer. The literature survey reveals that Erosion rate has considerable impact of, high working temperature, non uniform flow of steam and impinging particle size, shape, velocity and angle. It is difficult to study the impact of these parameters on failure tendency on a test set up. Hence it decided to computationally analyze the flow through the tubes and over the tubes in that specific zone where frequency of failure is more. These zones are re-heater and economizer.

Luis I. Diez, Cristobal Cortes, Antonio Campo, [20] ‘Modelling of pulverized coal boilers: review and validation of on-line simulation techniques’ Applied Thermal Engineering 25 (2005) 1516–1533. The authors in 2005 had shown the use of computational fluid dynamics in the modelling of pulverized coal boiler. The authors used CFD tool for analysis of pressure parts. CFD analysis can provide an insight into the function of heat exchanging equipments and can help to identify areas for improvement. The analysis showed that the non-uniform heating lead to hot spots, leading to failure. The analysis suggested that there are areas where hot spot are generated but they didn’t discuss about the reasons for the hot spots at that locations. Thus CFD tool can be used for boiler to estimate the velocity and temperature in different zones. This analysis will help to identify the areas that are more susceptible to failure.

Masoud Rahimi, et.al. [21] “CFD modelling of a boilers’ tubes rupture, Applied thermal Engineering (26) (2006)2192-2200. The authors in 2006 studied, CFD modelling of a boiler’s tubes rupture. A three-dimensional modelling was performed using an in-house computational fluid dynamics (CFD) code in order to explore the reason. The whole boiler including; walls, burners, air channels, three types of tubes, etc., was modelled in the real scale. The boiler was meshed into almost 2,000,000
tetrahedral control volumes and the standard k–ε turbulence model and the Rosseland radiation model were used in the model. The theoretical results showed that the inlet 18.9 MPa saturated steam becomes superheated inside the tubes and exit at a pressure of 17.8 MPa. The predicted results showed that the temperature of the steam and tube’s wall in the long tubes is higher than the short and medium size tubes. In addition, the predicted steam mass flow rate in the long tube was lower than other ones. Therefore, it was concluded that the main reason for the rupture in the long tubes elbow is changing of the tube’s metal microstructure due to working in a temperature higher than the design temperature.

It is also decided to model the boiler in the purview of this study. It is observed that the tubes in the super heater region failed on account of high surface temperature and the economiser tube due to erosion. There is possibility of reduction in mass flow rate of feed water due to scaling. This will lead to rise in surface temperature. The CFD analysis of boiler zone will help to identify the zone of higher temperature. The flow analysis inside the tube will help to predict the possibility of rise in surface temperature.

C. Bhaskar,[22] “Flow predictions in power station equipment components through state of art CFD software tools, ASME Turbo Expo Land Sea Air, IJPGC-2001, New-Orleans,USA. The authors in this paper presented flow analysis in the three dimensional geometries of boiler equipments. Several findings obtained from the results gave a good insight for improvements. The author extensively studied and visualised in terms of materials loss (erosive wear) based on practical trajectory. The author also studied the practical impacts when interacting with turbulence on circular tubes. Comprehensive analysis has been made to predict several practical trajectories along with turbulent flow characteristics around the tube.

Boshu He, et.al,[23] “Computational fluid dynamics based retrofits to reheater panel overheating of No. 3 boiler of Dagang Power Plant”. In this research the commercial CFD package, FLUENT had been employed successfully to the overheating diagnosis for the metal surface of the reheater and superheater pendants of the No. 3 boiler in Dagang Power Station, Tianjing, China. The numerical simulations include one base case and eight retrofitting cases for this boiler with the designated coal. Some factors that may affect the velocity and temperature distributions at the section of the final reheater inlet (final superheater outlet) had
been taken into account when the designated coal was burned, such as the quantity and fashion of counter-flow in the operation, the pressure difference in the air box, and the downward inclination of the secondary air injection. The basic conclusion is that some corresponding measures must be taken to rebuild the flow field constructions in order to effectively avoid the boiler re-heater and super heater pendant metal overheating. To obtain detailed background, eight reformation cases were arranged on the main field influencing reasons to retrofit this boiler numerically. Compared to the base case A, all the reformation cases had some emendatory effects to the flow and temperature distributions. One of the cases was observed to efficiently modify the velocity and temperature deviations in the overheating place of case A to ensure the furnace will operate within stable and safe conditions. Much better flow field is built by the case and it is recommended for the final operation when the BCD grinder combination is in service. Undoubtedly, these conclusions are of value to the other units of this power plant.

K. S. Bhambare, Sushanta K. Mitra, U. N. Gaitonde, [24] “Modeling of a Coal-Fired Natural Circulation Boiler”. The authors presented modelling of a natural circulation boiler for a coal-fired thermal power station is presented in this paper. The boiler system is divided into seven subcomponents, and for each section, models based on conservation of mass, momentum, and energy is formulated. The pressure drop at various sections and the heat transfer coefficients are computed using empirical correlations. Solutions are obtained by using SIMULINK. The model is validated by comparing its steady state and dynamic responses with the actual plant data. Open loop responses of the model to the step changes in the operating parameters, such as pressure, temperature, steam flow, feed water flow, are also analyzed. The authors have claimed the use of this model for the development and design of effective boiler control systems.

Electric Power Research Institute, Report [25] “Demonstration of the Cold Air Velocity Technique to Control Fly Ash Erosion at a National Thermal Power Corporation (NTPC) Plant”, Final Report, September 2004. Boiler tube failures (BTF) are the leading cause of availability loss and forced outage in fossil plants worldwide. Fly ash erosion is generally one of the top three failure mechanisms. This report demonstrates the cold air velocity technique (CAVT) to address fly ash erosion in a Singrauli plant boiler of the National Thermal Power Corporation (NTPC) in India.
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The CAVT was applied to unit 7 at Singrauli in three stages as a full demonstration of the technique:

• The velocities were measured across five planes in the boiler.
• A series of distribution and diffusion screens were installed near to, and in association with, the measured planes.
• A second series of velocity measurements were made at the same planes. Key results were that the peak velocities responsible for fly ash erosion were reduced and that no new serious peaks were discovered. This study’s objective was to demonstrate that FAE could be seriously reduced by measuring the peak velocities and addressing them through the CAVT.

In this paper the authors suggested to install the SS screen, in the passage of flue gases to reduce velocity. But its effect on other location is not studied. It is observed that screens reduce velocity at some section but increase at other. Hence in-depth study is necessary.

S K DAS, et.al.[26] “Analytical model for erosion behaviour of impacted fly-ash particles on coal-fired boiler components”, Sadhana Vol. 31, Part 5, October 2006, Fly ash particles entrained in the flue gas from boiler furnaces in coal-fired power stations can cause serious erosive wear on steel surfaces along the flow path. Such erosion can significantly reduce the operational life of the boiler components. A mathematical model embodying the mechanisms of erosion on behaviour has been developed to predict erosion rates of coal-fired boiler components at different temperatures. Various grades of steels used in fabrication of boiler components and published data pertaining to boiler fly ash have been used for the modelling. The model incorporates high temperature tensile properties of the target metal surface at room and elevated temperatures and has been implemented in a user-interactive in-house computer code (EROSIM–1), to predict the erosion rates of various grades of steel. Predictions have been found to be in good agreement with the published data. The model is calibrated with plant and experimental data generated from a high temperature air-jet erosion-testing facility.

Authors developed a model to predict the erosion rate for fly ash particle impingement on boiler component surfaces and investigated the variation of erosion rate with various parameters. They found that the erosion rates on steel surfaces subjected to a stream of fly ash particles vary with the particle impingement angle.
For low values of impingement angle, erosion rate increases with increase in impingement angle, with the maximum erosion rate occurring at an impingement angle of about 30°. Thereafter, erosion rate decreases with further increase in impingement angle. It is also noted that erosion rates at low impingement angles increase significantly with increasing temperature, but at high impingement angles the effect of temperature is insignificant. They found increase in erosion rates with temperature. Variation of erosion rate shows monotonic rise with ash particle impact velocity. Ash particle impact angle, which is one of the important parameters influencing erosion rate, requires further study. The influence of the shape and rotation angle of ash particles on erosion rates also needs further investigation using appropriate mathematical models.

S. K. Das, et.al,[27] “Erosion-Oxidation Response of Boiler Grade Steels: A Mathematical Investigation”, Hindawi Publishing Corporation Research Letters in Materials Science Volume 2008, Article ID 542161, A mathematical model has been developed by authors to predict the erosion rate for fly ash particles impingement on typical boiler grade steels. Stochastic approach is employed to model erosion-oxidation interaction phenomena. The following conclusions are drawn: (i) erosion rate increases monotonically with an increase in impact velocity for a given impingement angle and temperature of the substrate; (ii) erosion rate is maximum for impact angles in the range of 20°–40° for a given velocity and temperature; (iii) the erosion rate is significantly enhanced with an increase in silica content of the ash; (vi) erosion rate of nickel oxide is faster with regard to iron and chromium oxides, which is attributed to the relatively faster growth of nickel oxide with respect to other oxides.

Chris Harley and Mike Palmer,[28] “Advanced Erosion Protection Technology For Steam Boiler Superheat, Reheat And Evaporator Tubes’, The report highlights that one of the major causes for premature tube failure is excessive fireside boiler tube erosion caused by the impact, cutting action, and abrasive wear of fly ash entrained flue gases undercutting the area they strike. An estimated seventeen causes of tube leaks have been sited. However, one of the most problematic, hardest to predict and seemingly increasing is erosion caused failures. The authors tested various specimens in the controlled conditions and found that there is a wide variety of wear resistant materials (e.g. Cr3C2 - NiCr coating, Nickel alloy 625, 312 Stainless steel,
SA387 steel etc.) for the protection of high erosion prone fireside boiler tubes but their laboratory performance needs to be verified in actual field trials.

M.A. Habib, et.al, [30] “Erosion rate correlations of a pipe protruded in an abrupt pipe contraction” These authors studied the numerical investigation of the erosion of a pipe protruded in a sudden contraction, which are exposed to most of the serious erosion rates. The turbulent, steady, 2-D axi-symmetric flow inside an axi-symmetric abrupt contraction pipe with a pipe protrusion embedded in it was solved by steady-state time averaged conservation equations of mass and momentum along with two equation model for turbulence. Particles are tracked using Lagrangian particle tracking. An erosion model was employed to investigate the erosion phenomena for the given geometry. The influence of the different parameters such as the inlet flow velocity (3–10 m/s), the particle diameter (10–400 µm), the protruded pipe geometry (thickness T = 1–5mm and depth H = 2–5 mm) and the pipe contraction ratio (Cr = 0.25–0.5) on the erosion of pipe protrusion was investigated. Correlations for the influence of inlet flow velocity; depth and thickness of the protruded pipe on the erosion rate were studied. The authors found that Erosion rate of the protruded pipe is very prominently influenced by the variation of inlet flow velocity, V (m/s). Particle diameter, dp (mm) imposes a significant impact on the erosion phenomena of the protruded pipe. With increasing particle diameter, the erosion rate is gradually increased for the same inlet flow velocity. One of the prime findings in this study is that, the fluid flow is remarkably influenced by the presence and configuration of the protruded pipe. It will be worth to conduct study for prediction of erosion rate for a fluid flow outside the target surface. The results of such study will help to predict the life of the target surface.

A. Husaina, K. Habibb, [30] “Investigation of tubing failure of super-heater boiler from Kuwait Desalination Electrical Power Plant” A report, Department of Building and Energy Technologies, Kuwait Institute for Scientific Research, Kuwait. This paper presents the results of an investigation into the failure of steel tubes in a super heater boiler used at one of Kuwait Electrical and Power plant. The authors concluded that the material of the tubes has suffered localized overheating, the materials of the tube has suffered localized overheating, as a result of a local heat flux impingement phenomenon, particularly by gas or oil burners, which gave rise to the rapid steam formation causing steam blanketing. This phenomenon most likely
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prevented the accessibility of the water to the tube materials and consequently local, prolong overheating took place, in which the temperature rose up to 700°C for quite long time in a frequent manner, due to the magnetite scale formation at the inner surface of the tube surface of the tube. Consequently, the properties of the materials of the tube have changed from its original design values with respect to the operational design values due to the effect of the localized prolong overheating. Therefore, the original design values are no longer valid and the materials of the tube failed in a premature manner, at less than 250,000 hours. At such high temperature, the steel microstructure underwent phase transformation and absence of pearlite and in its place a spheroidized structure emerges indicating lengthy exposure to temperatures of 700°C. It was established then, that the defective tubes had been overheated which gave rise to rapid steam formation causing steam blanketing. These results emphasises the need of maintaining and monitoring water chemistry and flow through the tubes. At the same time it also highlights the need to monitor the tube surface temperature and means to regulate the tube surface temperature.

D.R.H. Jones, [31] “Creep failures of overheated boiler, superheater and reformer tubes”, A report, Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK. Internally pressurized tubes are critical components in heat-exchanger applications, such as boiler water tubes, steam superheater elements and chemical plant reformer tubes. Tubes in such applications are vulnerable to temperature excursions. And hence as a consequence the authors observed that the material enters the creep regime, and creep deformation (bulging) and even fracture (longitudinal rupture) subsequently occur, with serious consequences. This paper gives details of four case studies in which internally pressurized tubes failed by creep bulging and rupture (two boilers, one superheater and one reformer). In general, creep caused 30% of all tube failures in boilers. The conditions of temperature and time under which the failures occurred were deduced from the morphology of fracture and the changes in microstructure, and are correlated with the deformation-mechanism and fracture-mechanism maps for the tube materials. During test the authors also observed that there was a sudden overshoot in flue gas temperature that also has effect in rise in surface temperature. Hence it is necessary to find what which operating parameters e.g., Firing rates, Flue gas velocity, safety-
valve discharges, boiler blow-downs etc. were instrumental in overshooting the flue gas temperature.

Masoud Rahimi, et.al, [32] “CFD modelling of a boiler’s tubes rupture”, Chemical Engineering Department, Faculty of Engineering, Razi University, Kermanshah, Iran. This paper reports the results of a study on the reason for tubes damage in the superheater. In the present work, in order to find the reason for the tube damage in the Platen long superheater tubes the predicted operating condition in the long and short tubes were analyzed. The authors concluded that The CFD modelling is a useful method to explore the real phenomena, which happens in places that the experimental investigations are impossible or expensive. The CFD can predict combustion; heat, mass and fluid transfer in a large-scale boiler’s tubes damage. The CFD prediction shows that working at a temperature higher than design temperature is the main reason of the long tube failure. CFD analysis can be used to optimize the operating conditions so as not to allow the working temperature higher than the design temperature.

J.G. Mbabazi, T.J. Sheer, R. Shandu,[33] “A model to predict erosion on mild steel surfaces impacted by boiler fly ash particles”, Wear 257. Fly ash particles entrained in the flue gas from boiler furnaces in coal-fired power stations can cause serious erosive wear on steel surfaces along the flow path. Such erosion can, as a particular example, reduce significantly the operational life of the mild steel heat transfer plates that are used in rotary regenerative heat exchangers (‘air heaters’) that extract heat from the flue gas and transfer it to the incoming boiler combustion air. This paper describes research into fly ash impingement erosion on such surfaces.

The effect of the ash particle impact velocity and impact angle on the erosive wear of mild steel surfaces, using three different power station ash types, was determined through experimental investigations. The experimental data were used to calibrate a fundamentally-derived model for the prediction of erosion rates. The model incorporates the properties of the ash particles and the target metal surface, as well as the characteristics of the ash particle motion in the form of the impingement velocity and the impingement angle. When tested using the three different types of ash, the experimentally-calibrated general model yielded results that generally differed by less than 15% from the values that had been measured experimentally.
The experimental investigations confirm that the erosion rate on a mild steel surface subjected to a stream of fly ash particles varies with the particle impingement angle. For low values of the impingement angle, the erosion rate increases with an increase in impingement angle, with the maximum erosion rate occurring at an impingement angle of about $30^\circ$. Thereafter the erosion rate decreases with a further increase in impingement angle. The variation of the erosion rate for mild steel follows a power law with the ash particle impact velocity. The value of the velocity exponent appears to be affected by the size and shape of the ash particles. The silica content of the ash particles has a large influence on the erosion rate for mild steel.

Jianren Fan, et.al. [34] “A numerical study of a protection technique against tube erosion”, Wear 1999. Erosion of tubes by coal particles or coal ash impingement has caused serious problems for many pulverized coal energy conversion systems. It is important to study erosion protection methods for heat exchanger tubes undergoing erosion. In this paper, the finned tube erosion-protection technique is proposed. Fins located on both sides of tubes alleviate tube erosion in the way they change gas flow field, then consequently change particle trajectories, particle-tube collision frequency, and erosion damage of tubes. A numerical study has been conducted for the flow of a dilute particle-laden gas moving past a finned tube undergoing erosion. Eulerian equations are used to describe gas-phase motion, with the turbulence viscosity evaluated from the turbulent kinetic energy $k$ and its dissipation $\varepsilon$ model of turbulence. The prediction of particle velocities and trajectories takes into account the effect of the turbulence with a stochastic particle dispersion model. The particle impaction/rebound model and the erosion model of ductile alloys are used to predict the particle-rebound phenomena and the erosion damage to the tubes. The paper discusses the effect of relative length of fins, free stream velocity and particle size on particle-tube collision frequency and erosion damage of the tubes. The results show that the finned tube is a simple and efficient erosion protection method in most industrial two-phase systems where erosion occurs. The dynamics of the suspended coal ash particles, which are entrained by air through finned tubes, were numerically investigated. The findings in this investigation on particle-tube collision and tube erosion damage have provided both quantitative descriptions of the erosion processes of the finned tubes, particularly concerning the influences of relative fin length, free stream velocity and particle size. The results show that the method of fixed fins on
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tubes is a simple and efficient erosion protection method. If the erosion protection efficiency only is considered, the longer the fins, the more the finned tube erosion damage decreased in comparison with that of the non-finned tube. In this paper the calculation and analysis are only considered from the point of view of the protection ability of the finned tube erosion and the problems of the economical optimization and performance (w.r.t heat transfer) of the finned tubes are not mentioned.

Clayton A. Erickson, [35] “Coal Pipe Erosion Predictions Using Two Phase Flow CFD”. Multi-burner, pulverized coal-fired boilers have an extensive network of coal pipes which supply the pulverized coal to each individual burner. The balancing of air and coal flows in this network is essential to improve boiler efficiency and reduce boiler emissions. The analysis of coal piping systems is complex due to the two phase nature of the air/pulverized coal mixture and the physical arrangement of the piping system. Due to these complexities, the balancing of coal piping systems using static orifice plates is often difficult. In a few installations, the variable orifice plate has caused excessive coal pipe erosion resulting in operational problems. In this paper author modelled the variable orifice plate design has using FLUENT with coal particles accounted for as a discrete second phase. The coal particle trajectories from FLUENT have been post-processed using erosion prediction models to determine relative erosion rates on the pipe surface resulting from the variable orifice plate. The model results indicate that by redesigning the variable orifice blade shape and/or limiting the blade attack angle, the erosion rates can be reduced by an order of magnitude, as compared to the original design.

The dimensionless relative erosion is calculated using the following functional form:

\[ E = K M f(\theta) V^n \]

Where: \( E \) is the dimensionless erosion rate; \( K \) is the particle/target material erosion proportionality constant; \( V \) is the impacting particle velocity; \( M \) is the impacting particle weight; \( f(\theta) \) is the impact efficiency of the impacting particles; \( n \) is the velocity power coefficient. The impact efficiency of the particles is only a function of the impact angle of the particle. Maximum impact efficiency was obtained at impact angle 25° to 30°.

Steam: Its Generation and Use; Babcock and Wilcox; 41st Edition. Chapter 21, Fuel Ash Effects on Boiler Design and Operation states that the metal loss on
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convection pass tubes due to fly-ash erosion is proportional to the total ash quantity passing through the boiler and is an exponential function of flue gas velocity. While with a given fuel there is no control of the ash quantity, erosion problems can be eased by reducing flue gas velocities. Velocity limits are determined based on the ash quantity on pounds per million Btu (kg/MW) basis and the relative proportion of abrasive constituents in the ash.

Typical limits range from 19.8 m/s for relatively non-abrasive low ash coals to 13.7 m/s or less for coals with high ash quantities and/or abrasive ash.

L. Zhang, et.al, [36] “Analysis of boiler-tube erosion by the technique of acoustic emission- Part I. Mechanical erosion”. This paper investigates the mechanical erosion of the metal tubes in bagasse-fired boilers with the aid of the acoustic emission technique. By studying the material removal under various collision conditions, the paper analyzes the dependence of the erosion wear upon the impact angle, velocity, size and concentration of the particles. It was found that the material removal mechanisms were mainly dependent on the particle collision angle and fell into four regimes characterized by rubbing and scratching, cutting and cracking, forging and extrusion as well as sputtering and adhesion. The highest wear rate took place with the cutting and cracking mechanism when the particle collision angle was in the range of 20–30°. Author studied effect of collision angle and found that The wear is small when the angle is small, reaches its maximum when it varies between 20 and 30° and decreases steadily until the angle becomes 80°. The larger the particle size, the greater the erosion wear is. The material removal by mechanical erosion is directly through the mechanism of cutting, adhesion, forging–extrusion, etc. or due to their combinations. It was also noted that when the average particle diameter is <350 μm, the amount of wear increases approximately linearly with the particle size. However, beyond 350 μm, the effect of particle size becomes stronger, leading to an increase of material removal and suggesting that a change of the material removal mechanism may have occurred due to the change of the particle impact energy. The particle concentration c is defined as the mass of the particles per unit volume in the pressurized air-stream. Effect of particle concentration highlighted that at a given velocity, high c means more particle impacts onto the tube surface in a given time span. The increase of particle concentration promotes erosion wear in general. This is straightforward because erosion with more particles within a given period of time will
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certainly remove more materials. However, the effect of particle concentration is much related to the dominant mechanism of wear when the particle collision angle changes. If rubbing, scratching, forging or extrusion governs the material removal, the dependence of erosion wear upon the increase of c is rather moderate, But in the regime where cutting and cracking dominate, the increment of particle concentration promotes the tube wear,

Author studied the effect of particle velocity, V, on the material loss with a fixed value of particle concentration. They observed that a particle with a higher speed carries greater energy and in turn deforms the tube material more upon impingement. The extent of the velocity effect depends on the material removal mechanism involved, which is similar to the effect of particle concentration.

Author tried to study a relationship wear with erosion variable and found that the particle velocity V, particle diameter d, collision angle α, particle concentration c, erosion time τ and the property parameters of both the particle and tube materials, such as the hardness and density affect the erosion. However, because the relative properties of the tube and particle materials remain constant during the mechanical erosion in the erosion system, the ratios of the corresponding material parameters, such as the ratio of the tube hardness to that of the particle, do not need to be regarded as the variables in the dimensional analysis. In addition, the environmental humidity and temperature in the present erosion system are also constant, and thus, their effects can be ignored. But only the particle density ρ and tube hardness H are taken as the material variables because the former is related to the impact energy of a particle and the latter represents the plastic deformation property of the tube material.

Author suggested using the π-theorem of dimensional analysis to form the relationship between all the independent non-dimensional products. Ratio of tube hardness and to that of particle and effect of temperature can be neglected. Pi-theorem is used to develop the functional relationship.

R. P. Roy, M. Ratisher, V. K. Gokhale, [37] “A Computational Model of a Power Plant Steam Condenser with porous medium”, A computational model of a power plant steam condenser which incorporates the effects of air in-leakage and removal on the performance of the condenser is analyzed. The condenser interior space is modelled as a porous medium. A quasi-three-dimensional approach is taken in which the steady-state steady-flow conservation equations for the steam-air mixture
mass, momentum, thermal energy, and air mass fraction are solved for a series of two-dimensional grids perpendicular to the circulating water flow direction. The air removal system is explicitly modelled. Some of the calculated variables are compared with measurements obtained in the condenser. A computational model of a power plant steam condenser is developed. The model is capable of analyzing the effects of air in-leakage and removal rates on the performance of the condenser. The steady-state steady-flow balance equations for the wet steam-air mixture mass, momentum, thermal energy, and air mass fraction are solved on a series of two-dimensional grids. The condenser interior space is modelled as a porous medium. The wet steam is represented as saturated steam at its local partial pressure mixed homogeneously with the appropriate amount of water at saturation temperature depending upon the local quality. A simple model for wet steam condensation is introduced.

Barry Dooley & Peter S. Chang, [9] “The Current State of Boiler Tube Failures in Fossil Plants” Power Plant Chemistry (2000) by throws light on boiler tube failure demographics. It specifies that in terms of boiler locations, most comprehensive boiler tube failure data compilations worldwide indicate that the order of decreasing failures is water-walls, superheater, reheater and economizer. The paper clarifies that fly ash erosion is the most serious or second cause of availability loss for fossil plants. Historically the approach has been to arbitrarily position solid shields and baffles or apply a variety of coatings in ‘areas’ where fly ash erosion was occurring. The paper recognizes through an earlier study that the use of these palliative repair techniques was the main cause of repeat failures due to fly ash erosion because they simply redirected the high velocity flow onto an adjacent tube area.

Dr V T Sathyanathan, ‘Fly Ash Erosion in Boilers Firing High Ash Coals’[37], talks about the specific measures to reduce the fly ash erosion. This includes use of reduced the gas velocity in second pass, use inline arrangement of tubes for all second pass heat transfer surface, provide shield & baffles etc.

Vesa Meuronen, [38] “Ash particle erosion on steam boiler convective section”, Lappeenranta University of Technology Research Papers. (1997), discusses the erosion testing results that was conducted using an in-line tube bank, and a staggered tube bank each with six tube rows. Three flow velocities and two particle concentrations were used in the tests, which were carried out at room temperature. The results show that erosion wear in the staggered tube bank had a maximum value
in a tube row 2 and a local maximum in row 5. In rows 3, 4 and 6, the erosion rate was low. On the other hand, in the in-line tube bank, the minimum erosion rate occurred in tube row 2 and in further rows the erosion had an increasing value, so that in a six row tube bank, the maximum value occurred in row 6.

**Findings from Literature Survey**

Literature survey revealed the general trend on boiler tube failure. Mechanisms of tube failures, design operational factors, coal and other factors that cause major failure were understood. A general idea about zones where the triggering factor gets aggressive is obtained. Thus the areas which are more prone to failure were marked. This helped to focus on those areas e.g. Economiser, LTSH, and Re-heater. Knowing about Cold Air Velocity Test opened up opportunity for validation of the model. The literature survey recommended the use of CFD for flue gas and temperature estimation. While developing the real scale model of flue gas path with all the tube bundles, the complexity of the model was increased and the computational resources available were not sufficient to analyze the real geometry. Literature survey prompted the concept of porous medium which is discussed in detail in subsequent chapters.