This chapter includes a review of the previous literature on solid particle erosion. The erosion mechanism and factors effecting solid particle has been discussed. The boiler study was done at National Fertilizers Limited Naya Nangal Punjab (India). Various boiler tube failures were analyzed and responsible reasons causing boiler tube failures were identified.

2.1 EROSION

Erosion is defined as the material removal process. It is caused due to impact of particle called erodent. The erosion wear mechanism involves the removal of materials from a given surface due to impact of solid particles. Erosion is a generalized wear mechanism and mass loss occurs through impact of discrete particles entrained in a fluid stream. This mechanism applies to a range of situations; the use of the term in this work is in regard to mass loss by small, hard particles contained in an air stream. The extent of erosion in this manner has been defined as:

\[
\text{Erosion Rate} = \frac{\text{Mass flow rate of impinging particles}}{\text{Mass of material removed from substrate}}
\]

The material loss caused by the impingement of tiny, solid particles, which have a high velocity and impact on the material surface at defined angles, is called erosive wear. Erosive wear is caused in the solid bodies by the action of sliding or impact of solid, liquid or gases or a combination of these [35]. ASTM standard G76-07 (2007), defines erosion as the progressive loss of original material from a solid surface due to mechanical interaction between that surface and a fluid, a multi-component fluid, or impinging liquid or solid particles. Erosion is a serious problem
in many engineering systems, including steam and jet turbines, pipelines and valves used in slurry transportation of matter, and fluidized bed combustion system [36] and solid particle erosion is a phenomenon in which a series of particles strikes and rebounds from the sliding of abrasive particles across a surface under the action of an externally applied force. He further reported that solid particle erosion is expected whenever hard particles are entrained in a gas or liquid medium impinging on a solid at any significant velocity, greater than 1m/s. In both the cases, particles are accelerated or decelerated, and their directions of motion can be changed by the fluid, this is more significant in liquid media, and slurry erosion. Schematic view of erosion wear is shown in Figure 2.1.

![Figure 2.1 Schematic view of solid particle erosion of material](image)

An extensive amount of research has been published in regard to the mechanisms and relative rates of erosion of materials in order to develop measures to mitigate the effect of damage. Most erosion work has focused on bulk materials, with testing primarily conducted at ambient temperature under relatively low particle impact velocities. As a result, the erosion mechanisms and effect of the variation in process variables and material properties on the erosion response have been well characterized under such conditions. The erosion response of materials under the industrially significant conditions of high temperature and/or high impact velocity is less understood.
Material loss of the combustor wall and the in bed tubes is one of the most serious problems associated with fluidized bed combustors (FBC) technology. The term ‘wastage’ is commonly used for this phenomenon, which is generally accepted to be a result of erosion or abrasive wear that may be accelerated by oxidation or high-temperature corrosion [37]. Huge levels of surface degradation of metal containment walls and heat exchanger tubing by a combined erosion-corrosion (E-C) mechanism have been experienced in some boilers, particularly fluidized bed combustors. According to [36] erosion-corrosion refers to the simultaneous, synergistic interaction between the solid particle erosion and corrosion. Erosion-corrosion is of great technical importance in several types of applications, including coal gasification or liquidification, steam turbines, jet turbines, and in the in-bed evaporator tubes, water walls, and convection pass surfaces of fluidized bed combustion systems. Material damage due to combined effect of erosion and corrosion is a problem in many industrial applications like hydraulic turbines, slurry pumps, valves, pipelines conveying solid particles [3].

2.1.1 Erosion Fundamentals

In erosion, the detailed process that causes material removal is still poorly understood [38] and continuous efforts are being made in this regard. Analysis of the cutting action of a single particle launched against a ductile target and was the first model of solid particle erosion capable of predicting material removal rate. The mechanisms by which erosion mass loss occurs are broadly defined into two categories, ductile and brittle mechanisms [39]. Such classifications were initially based on the response of classical “ductile” and “brittle” materials, which, by virtue of their erosion mechanisms, showed mass loss as a function of impact angle responses similar to those in Figure 2.2.
Subsequent work has shown that the material response as a function of impact angle depends on an extensive number of variables, well beyond those related to the material properties. For different materials under varying test conditions, different response may be generated. Variation in test conditions may generate responses characteristic of each mechanism for a single material. Such classifications are still widely used, however, in describing the material response and serve to differentiate between the two primary mechanisms of erosive mass loss.

2.1.1.1 Ductile erosion mechanism

As previously discussed, of the cutting action of a single particle launched against a ductile target was the first model of solid particle erosion capable of predicting material removal rate. In his scheme, the particles were assumed to be non-deforming and impacting a target, which was assumed to reach a constant flow pressure, (i.e. the target is assumed perfectly plastic) immediately upon impact. By
assuming that no rotation of the particles occurs during the impact process, he could solve for the trajectory of the particle in closed form as it cuts the surface, and thus predict material removal rates [40]. This theory formed the foundation for later rigid-plastic models, which removed the restriction of particle rotation during impact. To predict erosion rates an analytical model was developed that was based on the assumption that the mechanism of erosion was that of micromachining [39]. According to him the impacting particle penetrates the target by a small amount, translates along the surface removing material ahead of it in a machining mode and finally leaves the surface. A refined model has been developed for this mechanism by [41] utilizing the equation of motion of the particle tip to define an amount of target material that would be removed. The classical “ductile” erosion response, exhibits the greatest magnitudes of mass loss at low impact angles ranging from 15-30º. At higher angles the erosion rate drops away, though the rate does not tend to 0 at 90º. The severity of low angle impact damage has been related to the efficiency of the generalized “machining” mechanism postulated to account for erosive mass loss in ductile materials over these angles. This generalized mechanism has been subdivided into 3 modes of response shown in Figure 2.3.

Figure 2.3 Schematic diagram of various metal removal mechanisms during metal erosion[3]

The angle impact of erosive particles i.e. the glancing angle impact of rounded erodent results in furrow indentations, with material physically displaced outwards
and to the sides and terminal end of the crater. While mass loss typically does not occur by direct impact in this manner, the plastically deformed “lips” or “platelets” of highly strained material are prone to fracture or fatigue during subsequent impacts [42] [43]. While Angular particles impart more of a “cutting” action during impact, the resulting damage dependent on one of two possible mechanisms. Type I cutting [44], involves impact by an angular particle in a similar manner to the “ploughing” mechanism of rounded particles. The erodent particles penetrates the surface and carves out an angular furrow of material, plastically deforming material to the side of the crater and typically generating a chip or lip of material at the terminal end of the crater. As with the “ploughing” mechanism no direct material loss occurs in this process, with degradation occurring through fracture of the displaced material upon subsequent impact. Type II cutting [44] occurs in a similar manner to the Type I mechanism, however, rotation of the erodent particle during impact results in a machining-type action that directly “cuts” chips of material from the surface as shown in Figure 2.4

![Figure 2.4 Characteristic mechanisms of ductile erosion based on the variation in erosion conditions](image)

At higher impact angles i.e. greater than 30°, the “machining” mechanisms of mass loss become increasingly inefficient, and the mechanism of erosive mass loss is less clear. Several mechanisms have been proposed, including work hardening of the surface leading to a brittle response, delamination wear, temperature effects and
extrusion [45]. The most widely referenced process, however, is the “platelet” mechanism [43, 45, 46]. At high impact angles the erodent particle indents the surface resulting in displacement or extrusion of material upwards and outwards [43], generating mounds and circumferential lips of highly strained material similar to that generated by ploughing, shown in Figure 2.5. Repeated impacts on the displaced material leads to fracture or fatigue based loss of material. The volume of material displaced in this way is a lot lower than that generated at low angles i.e. less than 30º. Figure 2.6 shows lip fracture in as ductile mode in metallic erosion. In addition, many more particles are required to generate loss of the smaller deformed platelets, this lack of efficiency in material removal accounts for the lower rates of mass loss at high impact angles.
2.1.1.2 Brittle erosion mechanism

For brittle materials, the first known study for solid particle erosion damage has been investigated [47], who studied the erosive regime, usually referred to as hertzian fracture, where the contact between the particle and the body is exclusively elastic. In their analysis they considered dynamic forces between the surface and the particle and this resulted in a prediction of the volume removed for a material with specific properties. They also concluded that the fracture at the surface is a function of the volume of material constrained in the primary erosion zone in relation to the surface and volume flows. Unlike the classical ductile erosion response, the classical “brittle” erosion response shows the greatest rate of mass loss at high impact angles, with the rate continually decreasing to negligible degrees of mass loss at low impact angles. This response reflects the mechanism of fracture induced mass loss, whereby the extent of substrate damage is dictated by the magnitude of the vertical component of the impact load applied by the erodent particle. For a given particle impact velocity, the component of the load applied perpendicularly to the surface continually decreases with decreasing impact angle, resulting in reduced erosion damage [48]. The erodent particle impact generates brittle fracture in ceramic materials [49]. Mass loss occurs by chipping, whereby segments of material formed by the intersection of crack networks are ejected from the surface. The cracks radiating downward from the point of impact. Initially an initiation period of negligible mass loss is typically observed, whereby particle impacts generate the extensive crack network required for
steady state erosive mass loss to proceed. Generation of crack occurs by two mechanisms; broadly differentiated by whether indentation occurs by a blunt or sharp indenter. The blunt indentor under light loads generates a ring crack, termed as Hertzian crack, studied by [44, 46, 48], around the impact site that propagates down into the substrate at an angle to form a cone, as shown in Figure 2.7. No plastic deformation occurs in this process as it is an elastic process [48], with the extent of crack propagation dependent upon pre-existing substrate flaws, the particle diameter and substrate fracture resistance.

![Figure 2.7 Cross-sectional schematic of impact by a blunt indenter on to a brittle substrate, resulting in the formation of a conical Hertzian crack](image)

Under more aggressive conditions, particularly with sharp indenters i.e. erosive particles with sharp edges, cracking becomes more extensive [50]. They have characterized the mechanism as shown in Figure 2.8. Indentation generates a zone of plastically deformed material around the indenter, the surrounding material being elastically loaded [43]. According to this mechanism under the effect of loading, radial cracks propagate out from the indent perpendicular to the surface, while “medium vent” cracks propagate down into the material below the indenter. Upon unloading, lateral cracks form below the plastically deformed zone and propagate outwards and upwards towards the surface [44]. As a result, large chips of material may be formed in this process by the intersection of the various crack networks propagating from the indent [44][45][48][51] as well as by fracture of indented
material generated by the combined action of the “wedging action” of the erodent with the cracks formed during impact.

![Figure 2.8 Schematic sequences of crack formation and development as a function of indentation loading and unloading on a brittle substrate [49]](image)

At low impact angles the mechanism of erosive wear of materials exhibiting brittle erosion is less clear. [45], has suggested that the vertical component of the erodent impact geometry determines the extent of brittle erosion. But the results cited in the review of [48] at low angles the response of alumina tended towards that seen in ductile metals. In their work [48] demonstrated that no cracking occurred, while
the furrows generated by glancing impact showed significant plastic deformation indicative of a "shear deformation mechanism".

2.1.1.3 Erosion mechanisms at high temperature

The most important and the least studied is the Erosion mechanism at high temperature. Many studies concerning the interaction between erosion and a surface oxide film have been conducted by [52 - 58]. Mechanisms of material removal have been proposed which include oxide fracture and chipping, oxide spallation at the metal-oxide interface and plastic deformation of metal substrate resulting in both oxide and metal loss.

These interactions between surface oxide and erosion have been summarized by [52] using schematic diagrams typical of Figure 2.9 which shows that for low energy particles, scale fracture does not occur and therefore metal recession rates will be determined by the oxidation process only. As the impact energy is increased and damage to the oxide scale occurs, an interaction between erosion and oxidation will result in accelerated metal loss. At still higher impact energies, deformation of the substrate produces metallic erosion. It is suggested that for materials to operate successfully at high temperatures a key requirement is the formation and maintenance of a protective oxide scale.

Figure 2.9 Schematic diagram showing the types of degradation that can occur under conditions of combined oxidation-erosion [52]
Figure 2.10 Classification of erosion-corrosion \(^{[59]}\)

Figure 2.11 Erosion mechanism at high impact angle \(^{[59]}\)
In another study by [59] it has been suggested that the exact behavior and the resulting morphology of the metal surface depend on the severity of erosion and the oxidation rate as shown in figure 2.10. Pure erosion of the oxide dominates at high temperatures where the oxidation rate is high, while pure erosion of metal occurs at low temperature. In the erosion-enhanced oxidation regime a steady-state oxide thickness develops, with the rate of oxide formation equal to the rate of scale removal by erosion. When the erosion rate is high as compared with the scaling rate, the oxidation-affected erosion regime is entered and under these conditions a continuous oxide scale is unable to form and the metal surface comprises a composite layer of oxide, embedded erodent fragments and extruded metal. Figure 2.11 shows erosion mechanism at high impact angle. [60] Has modified the above model by subdividing the ‘erosion-enhanced oxidation regime’ into three categories: Type I, Type II and Type III, as illustrated in Fig. 2.12. The intermediate category, Type I, is the regime in which the thickness loss due to erosion is balanced by the thickness gain due to oxidation. This sub-division was proposed based on the basis of microscopy of the eroded surfaces in the various corrosion environments. Figure 2.13 shows oxide removal from the exposed surface at high temperature.

Figure 2.12 Schematic of the different erosion-oxidation regimes [60]
Has assumed in the first instance that oxide scales respond in a brittle manner and therefore their fracture behavior must be quantified whereas erosion of the metallic substrate is controlled by localized plastic deformation and therefore high temperature strength must be considered [61]. They proposed that the fracture stress of oxides can be determined using acoustic emission or resonant frequency techniques and have demonstrated the importance of both temperature and scale thickness. They estimated the localized deformation behavior of the metallic substrate from hot hardness testing. They concluded that structural, high temperature alloys such as the nickel base superalloys maintain their strength up to temperatures of 700°C however, at higher temperatures result in a sharp reduction in strength [56]. The less heat transfer increases the temperature [71].

Four regimes of erosion have been proposed by [62, 63], Figure 2.14. According to them when the impact conditions are such that no damage results, Figure 2.14 (a), metal loss will be predicted from the standard oxidation kinetics. Further if the erosion damage is highly localized at the surface such that only loss of oxide occurs, for example by localized fracture and chipping, Figure 2.14 (b), but the scale remains protective, then metal loss can be expected to increase due to enhanced oxidation. In this oxide dominated regime the boundary conditions for the on-set of damage require that the fracture stress of the oxide is exceeded and that the oxide behaves as though it were of infinite thickness.
They estimated this latter requirement from the modelling work of [64] and depends on the ratio of the particle-target contact radius “a” and oxide thickness “x.” The analysis showed that the substrate has no influence on the scale surface properties when x/a > 0.23.

Further they proposed that the oxide modified regime Figure 2.14 (c) occurs when the fracture strength of the oxide is exceeded and x/a is below 0.23, i.e. for relatively thin oxide scales. They reported that damage morphologies vary from through thickness scale fracture to oxide spallation, although damage to the substrate is not observed. They suggested that in this regime metal loss rates are likely to be high since the surface oxide is non-protective and linear kinetics prevails.

According to them as the relative thickness of oxide is reduced, the maximum normal force at the oxide-metal interface will increase and if the particle velocity is sufficiently high, plastic deformation of the substrate will occur. They have proposed that in this substrate dominated regime, Figure 2.14 (d) material removal is primarily
from the substrate with a contribution from the surface oxide. They concluded that from knowledge of the particle, oxide and substrate properties and the impact dynamics, the boundary conditions between each regime can be quantified by considering the contact conditions at the oxide surface and how these change with oxide thickness. They also reported that the conditions for scale fracture can be determined by calculating the maximum radial tensile stress at the oxide scale surface for a given impact event and comparing this with the fracture stress values. They estimated the contact radius assuming Hertzian behavior with the ‘effective’ elastic properties of the surface which are determined using the [64] analysis, which could be used to evaluate both the oxide dominated and oxide modified regimes.

There are two important factors which differentiate the high temperature erosion of metals from their low temperature behavior [62]

(i) The surface properties of the metal may change significantly with time due to the growth of a surface oxide. The rate of growth of the oxide is a function of the temperature.

(ii) The mechanical properties of oxide and metal may change with temperature and time.

### 2.2.1 Factors effecting solid particle erosion

After studying the literature it was observed that solid particle erosion is depend upon many factors out of which some are directly concerned and some are indirectly related. The erosion is caused by many factors like:-

- Flow and environmental conditions
  - Impingement angle
  - Particle velocity
  - Temperature
  - Impingement particles per unit time
  - Presence of corrosive agents
- Impingement particles properties
  - Size
Various researchers gave their research findings about factors effecting erosion. Erosion rates are affected by various factors [43, 65, 66, 67] Some of these important factors are impact velocity, impact angle, particle concentration, particle shape, particle size, particle density, particle friability, temperature, particle hardness, material hardness, toughness, microstructure and chemical composition etc.

Erosion performance and the response of variations in the main erosion test variables; particle size, hardness, velocity and impact angle, has been investigated by various researchers broadly match those observed in bulk materials [68, 69, 70, 72, 73, 74, 75, 76, 77, 78]. As such these coatings were classed as exhibiting “brittle” type behavior. Variation in this response occurred as a function of other test variables, primarily erodent velocity. At very low velocities the kinetic energy of each particle is insufficient to generate the minimum threshold load for indentation fracture. Erosive wear occurs by localized plastic deformation and the observed maximum in erosion rate shifts to lower impact angles. At higher impact velocities the erosion rate as a function of impact angle has been observed to flatten out, becoming almost independent of this variable. Under such high impact conditions the erodent particles are able to generate high stress in the coating, resulting in brittle erosion characteristics, even at low impact angles. As with bulk samples, higher particle velocities generate greater rates of erosion.

Erodent particle characteristics have received significant attention in regard to cermet coatings based on attempts at simulating fluidised bed and turbine erosion. The erodents with higher hardness ratios to the substrate generate greater erosion wastage [43]. SiC, Al₂O₃, SiO₂ are noted as aggressive erodents. In many research papers for erosion and abrasion testing Al₂O₃ has been used as erodent due to its
influential characteristics [54]. Where mixtures of phases occur in the erodent stream, such as fluidized beds, it is the concentration of the hard phases, typically Al₂O₃ and SiO₂ that dictates the erosion rate [75, 83]. Such behavior is complicated by the shape of the particles, irregular particles being more aggressive than rounded erodents, as they are able to concentrate the impact energy on sharp protrusions [43] [80]. For particle sizes below 100μm the erosion rate is noted to increase with increasing particle size. Above this, the so called “size effect” occurs, whereby the erosion rate plateaus out or begins to decrease with increasing erodent size [81].

In ductile erosion the greatest mass loss occurs at impact angles of 15-30°. Mass loss occurs by repeated impact on platelets of material displaced by erodent impact to the point where they fracture from the surface, or as chips of material formed by direct impact. At high impact angles, these mass loss mechanisms become less efficient leading to lower rates of material wastage.

Brittle erosive mass loss occurs most significantly at high impact angles. Erodent particles impact the surface with sufficient energy to generate fracture and cracking within the material. Mass loss occurs by chipping, whereby segments of material formed by the intersection of crack networks are ejected from the surface [73], [80], [82].

2.2.2 Erosion rate

Erosion testing consists of impinging a coated sample with a known abrasive particle utilizing compressed air as a propellant. The amount of erosion is measured either by the loss of weight or the loss of coating thickness. As per ASTM standard erosion value is the volume loss of specimen material divided by the total mass of abrasive particles that impacted the specimen (mm³/g) [ASTM Standard G76-07]. Normalized Erosion Rate is calculated by dividing the erosion value of the specimen by erosion value of reference material [84]. According to [85] the erosion rate is defined as the ratio between the change in the sample mass and the mass of the impacting particles. [84] Compared the erosion rates of alloys, ceramics, and cermets. He proposed that the order of material rankings would change with any change of variables such as velocity, particle type or size, and angle of impingement. He
performed the erosion tests using 27 µm Al₂O₃ particles at normal incidence and 170 m/s at 20°C and 700°C in nitrogen. Hansen also conducted the tests with a gas-jet erosion apparatus in which particles are fed from a hopper into a nozzle, where they mix with and are accelerated by a flowing gas stream (ASTM G76). He normalized the erosion rates by defining the relative erosion factor as specimen volume loss divided by that of a standard material. As explained above, erosion resistance is normally measured using weight loss technique by measuring the weights before and after the test but at high temperatures, this leads to erroneous results due to oxidation of samples. So in order to overcome the above limitation of weight loss measurement technique erosion resistance can also be measured in terms of thickness loss [86]. Also volume loss measurement technique has been used by Miyoshi et al, 2003 for erosion rate determination. The method has been used to evaluate surface characteristics, such as erosion volume loss and depth, surface topography, and surface roughness. The volume loss occurred after erosion testing was measured by using non contact optical profilometry.

2.3.1 Erosion in energy generation and coal gasification systems

In industrial applications and power generation such as coal burning boilers, fluidized beds and gas turbines, solid particles are produced during combustion which leads to solid particle erosion. Figure 2.15 shows schematic diagram of a typical coal fired boiler. Continued operation under particulate flow conditions adversely affects the performance of energy generation and coal gasification systems [85]. The burning of coal in thermoelectric power plants generates a huge amount of fly ash which causes intense and localized erosive wear of power plant equipment. Many power plant engineers, as well as researchers of industrial wear problems are of the opinion that ash impacting erosion wear is the principal cause of boiler tube failure in economizer, primary superheater and reheater groups of boiler tubes [87]. According to them wear of boiler tubes in pulverized fuel power stations by erosion is a serious problem that often leads to unscheduled and costly outages.

It has been reported by [88] that the development of coal-fired combined cycle power generation systems is receiving considerable worldwide
interest. These systems, utilizing both steam and gas turbines, have many advantages over conventional coal-fired power generation systems, which include increased efficiency of the electricity production and lower environmental emissions (specifically CO$_2$, SO$_x$ and NO$_x$). According to them the influence of materials on the development of these systems can be considerable as it is necessary that components have adequate lifetimes in their operational environments. They further added that successful development and commercialization of these new systems require that all the component parts are manufactured from appropriate materials and that these materials give predictable in-service performance.

In coal-fired power stations, about 20% of the ash produced in the boilers is deposited on the boiler walls and superheater tubes [89]. This deposited ash is subsequently discharged as slag and clinker during the soot blowing process and the rest of the ash is entrained in the stream of flue gas leaving the boiler. They reported that the ash-laden flue gas passes through the narrow passages between the corrugated steel plates that constitute the air heater elements. Then the ash particles collide with the surfaces of the steel air heater elements and material is eroded from the surfaces. Further in advanced stages of erosion, the plates become perforated. The air heater elements fail once they cannot maintain their structural integrity. According to them such erosion, together with the processes of blocking, fouling and corrosion, shortens the service life of the air heater elements. Once this happens, the power station unit has to be shut down in order to replace the damaged air heater elements. The resulting penalty is not only the cost of replacing the elements but also the cost of stoppage of power production. They proposed that it is desirable to predict the rate of erosion of the air heater elements in order to plan systematically for the maintenance or replacement of the air heater elements to avoid forced outages.
They further opined that in large coal-fired power stations, pulverized coal is burnt in the burners of the boilers. To improve upon the overall thermal efficiency of the boiler plant, heat exchangers are used to extract residual heat energy from the flue gas before it is released to the atmosphere and to transfer it to the combustion air supplied to the boiler burners. According to them part of the air supplied, the ‘primary air’, is fed to the coal mills and is used to dry the pulverized coal and to transport the coal to the burners in the furnace. Whereas the greater part of the air supplied, the ‘secondary air’, is used in burning the coal. Further the heat exchangers used for preheating the combustion air are of the rotary regenerative type, commonly referred to as "air heaters". While these air heaters are prone to erosion, corrosion, blocking and fouling, particularly if the coal is of relatively poor quality, as is often the case in large South African power stations (ash content typically above 25%).

[90] Reported that the coal used in Indian power stations has large amounts of ash (about 50%) which contains abrasive mineral species such as hard quartz (up to 15%), which increase the erosion propensity of coal. They also reported that a
performance review of thermal power stations indicated that erosion problems contribute significantly towards partial unavailability of power in India. They added that in coal-fired boilers, the pulverized fuel is transported to the boiler using a network of PF pipes. Components such as PF bends and elbows, multiple-port outlets, the orifice and the burner assembly are prone to high erosion wear, especially in certain locations oriented favorably for impacting wear particles.

Heat exchanger tubes immersed within a bubbling fluidized bed combustor often experience unacceptably high levels of thinning on their outer diameter and this loss in wall thickness is typically concentrated on the lower half of tubes and is frequently termed metal wastage [92]. They reported that this is consistent with aggregate impacts or any process associated with an upward particle flow. According to them, the wastage is primarily due to mechanical wear by bed particles in contact with the tubes, though an oxidation or corrosion component cannot be ruled out. They proposed that there are several macroscopic bed conditions that lead to particles with sufficient energy to cause wear. They opined that some of these are related to characteristics of the bed design or individual component failures, and others are related to intrinsic or unintentionally induced long-range flow patterns within the bed. Further they suggested that there is a general consensus however, that some of the worst wear is associated with energetic events intrinsic to bubbling bed combustors and that these events are associated in some way with bubbles themselves. They further reported that bubbles rising through tube banks are known to throw highly energetic dense aggregates of defluidized particles against tube bottoms. Also, voids, which can form beneath tubes as the entire bed undulates, will collapse against the underside of tubes with a similar effect. They concluded that the bottom of a tube is intermittently hammered by particle aggregates that strike and slide across the surface before dropping away. The study of the mechanisms of erosive wear is therefore extremely important in order to develop suitable solutions to minimize or even eliminate maintenance procedures of such equipments.

The failure of industrial boiler has been a prominent feature in fossil fuel power plants which appeared in the form of bending, bulging, wearing, rupture, decarburization, carburization causing leakage of the tubes studied by [1].
Erosion-corrosion of boiler tubes remains an operational and economical constraint in power generation plants. The industries are struggling to overcome this problem for the possible solutions like modifying process conditions, redesigning equipments and selection of new materials [2]. The superheater and reheater tubes in boilers are exposed solid particle erosion at high temperature.

In order to investigate the factors responsible for failure of materials before the designed limits, various researchers suggested that the experimental conditions should be similar to working or operational conditions of boilers. The erosion testing rigs are of two types’ one isothermal type and second non-isothermal type. The isothermal type test rigs are capable to create actual working conditions to get actual results [3].

In solid particle erosion, the contact time between the erodent and target material is only momentary, which makes it different from other related processes like, sliding wear, abrasive wear, grinding, and machining, in which the contact between the tool/abrasive and target/work piece is continuous [3].

### 2.4.1 Effect of temperature

The wear of metallic materials significantly depends on temperature [79]. The temperature dependence of the erosion rate can be classified into three groups. In the first group, the erosion rate decreases with the increase in temperature, reaches a minimum and starts increasing with increasing temperature. Materials such as 5.0 Cr-0.5 Mo, 17-4 PHSS, 410 SS, Alloy 800, Ti-6Al-4V and tungsten belong to this group. The second group comprises metals such as Ta and lead (for oblique impact) and alloy such as 310 SS (for oblique impact), 1018 steel and 1100 aluminum (for normal impact) which exhibits a temperature independent erosion rate up to critical temperature followed by an increase of the erosion rate with increasing temperature. Finally group materials show a monotonically increasing erosion rate with increasing temperature. Inco 600, carbon steel, 12 Cr-1MoV steel, and 2.25 Cr-1.0Mo steel, lead and 20245 Al, belons to this group [3]. Almost all metallic materials exhibit ductile erosion response at room temperature, whereas at elevated temperature both brittle and ductile erosion responses are noted by [93, 95]. The wear of steel was increased with the increase in temperature at 800°C [91]. Figure 2.16 shows solid particle
erosion rate of Inconel at different temperature at 90° impingement angle at 40 m/s and 70 m /s velocities [169]. Figure 2.17 shows solid particle erosion rate at room temperature and 850°C at different impingement angles at 40 m/s velocity [169]. The effect of increase in temperature has clearly reflected in figures. This showed that with the increase in temperature erosion rate has been increased.

![Figure 2.16 Erosion rate at different temperature at 90° impingement angle velocity 40 m/s (●) and 70 m /s (○) [169]](image-url)

![Figure 2.17 Erosion rate at impingement angle at 40 m/s (●) and 70 m /s (○) [169]](image-url)
2.4.2 Effect of impact velocity

In solid particle erosion the velocity dependant of erosion rate (E) is characterized by the velocity exponent, \( p \), given by

\[
E = K_1 V^p
\]

Where \( K_1 \) is a constant and \( V \) is the impact velocity. The velocity exponent (\( p \)) was investigated by various investigators. The velocity exponent decreases with an increase in erosion temperature for 304 SS to value as low as 0.9 at low impact velocities. At relatively higher impact velocities \( p \) lies in the range 2-3. The velocity exponents for metallic materials are 2.5 during ambient temperature erosion. At elevated temperature the velocity exponent of metals and alloys varies over a wide range from 0.9 to even more than 3.0 studied by [93, 96, 97]. Figure 2.18 shows the effect of impact velocity on the erosion loss on ductile material [168]. Figure 2.19 shows the effect of impact velocity on the erosion loss on brittle material [168].
Figure 2.18 The influence of impact velocity on the erosion loss (ductile) [168]

Figure 2.19 The influence of impact velocity on the erosion loss (ceramic) [168]

Figure 2.20 shows effect of erodent particle velocity on erosion rate for the Fe–0.6%C alloy in the WQ and WQ&T conditions at 90° impact angle, 25°C temperature, Al₂O₃ erodent of 355 µm average particle size at 90 gm/min erodent feed rate [10].

Figure 2.20 Erosion rate vs. particle velocity for the Fe–0.6%C alloy in the WQ and WQ&T conditions. Erosion conditions: impact angle: 90°; temperature: 25°C; erodent: 355 µm Al₂O₃; feed rate: 90 gm/min [10]
2.4.3 Effect of impact angle

Most of the metallic materials, irrespective of the temperature of erosion, exhibit a ductile behavior that is a maximum erosion rate at oblique impact angles (10° to 30°). As studied by [93, 95-99] obtained a higher erosion rate at normal impact angles than oblique impact angles for 9Cr-1Mo steel at 1123 K using rounded Al₂O₃ (130µm) erodent for a range of impact velocities (30-70 m/s). But at a low impact velocity of 20 m/s, maximum erosion rate occurred at oblique impact angle. The maximum erosion rate occurred at 60° for Co at a test temperature of 1053 K when impacted with alumina power of 20 µm angular size at impact velocities of 70-140 m/s observed by [97]. However, erosion rate peaks at 30° impact angle, when erosion test was carried out at 873 K at impact velocity of 140 m/s observed by [100]. So there are it becomes necessary to evaluate the erosion behavior of particular material at different impact angles to get actual results. Figure 2.21 shows the erosion scar produced on the eroded surface at 90° and 30° impact angles. Mark “A” represents a localized region of material removal and Mark “B” represents the peripheral region of the elastically loaded material. Figure 2.22 shows material fracture at oblique impact angle and normal impact angle. Figure 2.23 illustrates material deformation and lip formation during normal impact of erodent in solid particle erosion.

Figure 2.21 Erosion scar produced in general on the eroded surface at an impact angle of 90° and 30°; Mark “A” represents a localized region of material removal and Mark “B” represents the peripheral region of the elastically loaded material [44]
Figure 2.22 Material fracture representations at (a) Oblique impact angle (b) Normal impact angle \cite{44}

Figure 2.23 Material deformation and lip formation during normal impact of erodent \cite{46}

Figure 2.24 shows relation between the impact angle and the erosion loss in case of ductile material. Figure 2.25 shows relation between the impact angle and the erosion loss in case of brittle material.
Figure 2.24 Graphical representation between the impact angle and the erosion loss in ductile material [168].

![Graphical representation between the impact angle and the erosion loss in ductile material](image)

Figure 2.25 Graphical representation between the impact angle and the erosion loss in brittle material [168].

![Graphical representation between the impact angle and the erosion loss in brittle material](image)

Figure 2.26 shows the surface morphology of ductile material with the impact of 30 erodent particles at (a) 30° impact angle (b) 90° impact angle. Figure 2.27 shows the
surface morphology of brittle material with the impact of 30 erodent particles at (a) $30^\circ$ impact angle and (b) $90^\circ$ impact angle.

Figure 2.26 The surface morphology of ductile material with the impact of 30 erodent particles at (a) $30^\circ$ impact angle and (b) $90^\circ$ impact angle [168]

Figure 2.27 The surface morphology of brittle material with the impact of 30 erodent particles at (a) $30^\circ$ impact angle and (b) $90^\circ$ impact angle [168]
2.4.4 Effect of particle size

[98] Performed erosion test on Inco 600 alloy using quartz particles having sizes between 70 and 800 µm, the study reflected that erosion rate marginally increased with the increase in particle size. [99] Investigated the effect of particle size of SiC on the erosion rate of 304 SS at 923 K, impacted at 30° with impact velocity of 65 m/s, the results indicated that erosion rate increases with the increase in particle size up to 50 µm and there after it becomes independent of particle size. [95,101,102,103] noted only the increase of erosion rate with the increase of particle size for 9Cr-1Mo steel eroded at temperature of 923 K and that for 1018 steel eroded at 723 K. It was also established that the erosion rate at room temperature increases with the increase of the particle size up to 50µm and beyond such magnitude the particle size has no effect on the erosion rate reported by [98].

2.4.5 Effect of particle shape

The erodent shape plays important role in solid particle erosion. The erodent shape is classified into spherical and angular shaped particles. The angular shape particles are assumed to give more erosion effect as compared to spherical shaped particles [94]. From the literature study, [95, 101,102,103] investigated the erosion rate of a number of Cr steels at 1123 K with angular SiC and spherical Al2O3 as erodent particles. The results reflected that erosion rate is quite high with angular shaped erodent as compared to spherical shaped erodent. At ambient temperature, changing the particle shape from angular to spherical results in altering the erosion response from brittle to ductile studied by [104,105]. At elevated temperature, brittle to ductile response is noted irrespective of the particle shape by [95,101,102]. Figure 2.28 shows effect of erodent shape on the erosion loss of ductile material under the impact of one sand particle. The triangular shaped erodent particle has removed maximum material in comparison to square and circular shape erodent particle.
2.4.6 Effect of particle feed rate

The erodent feed rate of was studied, [106] have investigated the influence of the particle feed rate on the erosion rate of 304 and 430 SS over a large temperature range. The results suggested erosion rate is independent of increase of feed rate by 16 points up to 773 K, a lower feed rate results in higher erosion rate. In other study [107] also noted a decrease of erosion rate with the increase of particle feed rate, especially at low impact velocity. Particle feed rate has a negligible effect on room temperature erosion rate studied by [108, 109]. A remarkable effect of the particle feed rate has been noticed at elevated temperature by [110].

2.4.7 Effect of eroded material characteristics

The eroded material characteristics include my factor like mechanical properties of materials, physical properties, chemical compositions of alloying elements and metallurgical considerations. Different materials exhibits different mechanical properties, the hard materials offer more resistance to solid particle erosion as compared to soft materials. The surface hardness is further governed by
many factors; microstructure grain structure, crystallographic packing, percentage of alloying elements. The solid particle erosion is significantly affected by oxidation behavior of material at elevated temperature. So the behavior of the oxide scale under erosion conditions needs to be considered in additions to the behavior of the metallic materials. The oxidation characteristics of the eroded material play a more important role than the mechanical properties of the eroded materials at elevated temperature. The experimental data of [111] related to 1.25 Cr-1Mo-V, 2.25Cr-Mo, 12Cr-1Mo-V and plain carbon steel (up to 923K), that of [112] pertaining to 304, 316,410 stainless steel (up to 773K) and that of [113] and [114], pertaining to 2.25Cr–1.0Mo steel, 5Cr–0.5Mo steel, 1018 steel, 304 SS, 310 SS, 410 SS and 17-4PHSS can be considered elevated temperature erosion of metals with minimum or negligible oxidation. Under such conditions the dependence of the strength of the material on temperature is a reasonable indicator of the temperature dependence of erosion resistance of the materials. Erosion data further indicate that austenitic stainless steels have superior resistance to elevated temperature erosion than ferritic steels. The 410 stainless steel having a tempered martensitic matrix exhibits an erosion resistance comparable to that of austenitic stainless steels. The oxidation effect is reported to be important for elevated temperature erosion tests conducted at low impact velocities and using rounded Al₂O₃ as an erodent. The influence of Cr content on the erosion rate of steel indicated that the erosion rate decreases to a very low value when Cr content in the steel exceeds 10–12% [99]. In the case of steel having Cr less than 10%, thick Fe₂O₃ scale was formed during erosion leading to high erosion rates [110]. The experimental results given by [100], reflected that the nature of the scale that forms during erosion at elevated temperature also affects the erosion rate. It is also noted that materials with high scaling rate such as nickel and cobalt exhibit the highest erosion rates. The superiority of the Al₂O₃ forming alloy stems from the fact that the Al₂O₃ forming scale forms much more slowly than the Cr₂O₃ scale. Extensive work by Levy and co-workers [106, 108, 113, 116, 117] implies that the morphology of the oxide scale that forms during erosion is important. Segmented scales have a better erosion resistance than thick, continuous and dense scale since the spalled area is confined to oxide crystalline only in the case of erosion of the segmented scale. A striking illustration of the above fact is obtained when Si is added to steels. Addition of Si to low chromium steel results in the formation of a segmented scale even at high impact velocity and thereby reduces the erosion rate substantially as compared with the same steel without
Si [117]. The above discussion clearly brings out certain features of elevated temperature erosion of metallic materials.

### 2.5.1 Propagation of erosion mechanism

In solid particle erosion when erodent strikes the metal surface, the interaction involved with various modes of material removal mechanism, which are discussed below. On the basis of the extensive literature [118-122] four different types of E–O mechanisms can be envisaged:

In the first case, at low temperature, high impact velocities and feed rates, there is no oxide scale. Under these conditions, erosion take place from the metallic surface and this mechanism of erosion is called metal erosion. The erosion behaviour in this regime is similar to the ambient temperature erosion behavior of metallic materials. The erosion response in the metal erosion regime is ductile, the velocity exponent of the erosion behavior is between 2 and 3 and the erosion rate is independent of the particle feed rate. The metal erosion mechanism is schematically shown. In the metal erosion regime, there are two modes by which materials can be removed. These modes are ploughing and cutting. In general, when a particle is in contact with a target at positive rake angle, the cutting mode operates. On the other hand, the ploughing mechanism operates at negative rake angle. Cutting mechanisms result in generation of new surfaces while the ploughing mechanism involves the displacement and extrusion of the material with no new surface generation.

The solid particle erosion occurs in two ways one in ductile erosion, the metal is indented by the particles impacting the surface and material is extruded around the indentation. At high angles the energy of the particle is dissipated through ductile deformation and is more resistant to erosive wear than at low angles were the metal indentation proceeds by a plowing or micromachining action. At high angles the material removal mechanism is thought to proceed by work hardening of the extruded material by repeated impacts, leading to local fatigue or fracture based loss of material. With brittle materials the particle impact generates brittle fracture within the near surface zone of the material, with cracks radiating outward and downward from the point of impact.
In addition, the cutting mode is more efficient than the ploughing mode when considered in terms of energy consumed per unit volume removal of the target material. The work carried out by a large number of investigators [123,124,125,126] has revealed that almost all metals and alloys lose material by the formation of a lip and its subsequent fracture. In metals and alloys, during erosion, once the lip is formed, it is fractured by several modes. In the case of ductile metals like copper, brass [127], aluminum [128] and iron [129] the lip fracture occurs by necking, and the resulting fracture is ductile, as exemplified by the dimpled fracture surface. In the case of a high strength alloy such as Cu–Be in age hardened condition [127], 301 SS and TD nickel [129] the lip removal is greatly aided by the formation of adiabatic shear bands at the base of the lip and subsequent easy separation/fracture across this band. In this case also the fracture is ductile, as indicated by the presence of shear dimples on the fracture surface. These two modes of material removal considered above involve the fracture of pre-existing lips. On the other hand, a new mode termed ‘adiabatic shear induced spalling’ involves the formation of intersecting adiabatic shear bands at the base of the crater and subsequent removal of chunks of material. This mode of weight loss, which is highly efficient in terms of energy expended per unit volume of target material removed, is important only at normal impact where maximum resistance is offered to curtail spreading of deformation. The erosion response under such circumstances will be similar to that observed for ceramic materials. But the underlying mechanism is entirely different. In the case of ceramic materials, material removal occurs with the formation of intersecting cone or radial cracks, which nucleate from pre-existing flaws once a critical tensile stress is exceeded. Further, these cracks are essentially brittle in nature. On the other hand, formation of an adiabatic shear band requires critical strain [130]. In addition, the fracture surface resulting from adiabatic shear induced spalling exhibits shear dimples, implying an essentially ductile fracture.

In the second case, at very high temperatures and low velocities and particle feed rates, erosion takes place from the oxide scale. Under these conditions, a thick oxide scale is formed on the target material during erosion and the deformed zone formed due to impact is confined within the oxide scale. The erosion behavior from the oxide scale is characterized by a brittle erosion response, strong velocity dependence and particle feed rate independent of the erosion rate. This erosion
mechanism is termed oxide erosion. In oxide erosion, material removal occurs with the formation of intersecting cones and radial cracks, which nucleate from pre-existing flaws once a critical tensile stress is exceeded.

At an intermediate temperature, impact velocity and particle feed rate, an oxide scale of intermediate thickness is formed. However, the depth of the deformed zone extends to the metallic substrate beyond the oxide scale. Consequently, the oxide scale beneath the eroding particle tends to crack, gets pushed down into much softer base material and in the process the softer base material gets squeezed out onto the top surface through the cracks in the oxide scale. Over a period of time, the repetition of such a process during each impact causes the formation of a composite layer comprising the bulk metal and broken pieces of oxide scale. Erosion takes place from composite layer is termed oxidation affected erosion. The interesting aspect of oxidation affected erosion is that the volume fraction of the oxide in the composite layer is a function of erosion conditions such as temperature, impact velocity and particle feed rate. As a result, the erosion behavior in the oxidation affected erosion regime can vary from a ductile to a brittle response depending on the amount of oxide scale present in the composite layer. Further, unlike in the case of metal erosion or oxide erosion, the oxidation affected erosion rate depends strongly on the test temperature and particle feed rate.

The final erosion mechanism is oxidation controlled erosion. At relatively higher temperatures and lower particle feed rates and impact velocity, the oxide scale that forms during erosion is brittle and non-adherent. In such cases, the oxide scale gets removed after it attains a critical thickness. The erosion behavior in this regime exhibits a brittle erosion response, weak velocity dependence and particle feed rate dependent erosion rate. Figure 2.29 shows oxidation affected erosion mechanism and deformed zone formed due to erodent impact.
Figure 2.29 Diagram showing probable mechanism of oxidation affected erosion showing deformed zone formed due to erodent impact [3]
2.2 CASE STUDY

The research study done by [5] reported that the super heated tube wall thickness was reduced by 10% of its original thickness during its operational due to solid particle erosion. In another investigation [131] reported 20% wall thickness reduction due to solid particle erosion. Carbon steel is the standard tube material for high pressure boilers up to 625 psig steam and normal design temperature limit of about 440°C. Due to exposure to high temperature in service, microstructure changes occurred including carbide spheroidization, graphitization and other transformations [132].

The present research was focused on investigation of solid particle erosion behavior of boiler tube materials and characterization of various erosion mechanisms responsible for the degradation of materials and premature failure of boiler parts. The research work was started with the study of boilers which are Bharat Heavy Electrical Limited make, in operation from 32 years having height of 36 meters at National Fertilizers Limited Naya Nangal (Punjab) India. The speed of fly ash is 10 to 15 m/s, having operating temperature range between 400°C - 800°C. The steam generation plant has three boilers and they face frequent boiler tube failures results in unplanned shut down of plant and production loss. The job history cards were studied and parts facing repeated failures were identified and the reason responsible for failure were investigated.

Table 2.1 Steam generation plant NFL Naya Nangal (Boiler-I) boiler part failure and reason of failure

<table>
<thead>
<tr>
<th>S. No</th>
<th>Date</th>
<th>Part of Failure</th>
<th>Reason of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22/07/2008</td>
<td>Bank tube leakage</td>
<td>Pin hole due to fly ash erosion</td>
</tr>
<tr>
<td>2</td>
<td>10/03/2007</td>
<td>Economizer coils leakage</td>
<td>Replacement of Economizer coils due to Reduction of tube thickness due to fly ash erosion</td>
</tr>
<tr>
<td>3</td>
<td>02/11/2007</td>
<td>Water wall tube leakage</td>
<td>Due to vibration welding crack formation occurred</td>
</tr>
<tr>
<td>4</td>
<td>03/01/2007</td>
<td>Economizer coils leakage</td>
<td>Due to Overheating</td>
</tr>
<tr>
<td>5</td>
<td>13/11/2005</td>
<td>Economizer coils leakage</td>
<td>Pin hole due to fly ash erosion</td>
</tr>
<tr>
<td>6</td>
<td>18/09/2005</td>
<td>Import steam super heater tube leakage</td>
<td>Due to fly ash erosion at high temperature</td>
</tr>
<tr>
<td>7</td>
<td>19/01/2004</td>
<td>Water wall tube leakage</td>
<td>Due to fly ash erosion</td>
</tr>
</tbody>
</table>
Table 2.2 Steam generation plant NFL Naya Nangal (Boiler-II) boiler part failure and reason of failure

<table>
<thead>
<tr>
<th>S. No</th>
<th>Date</th>
<th>Part of Failure</th>
<th>Reason of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17/07/2011</td>
<td>Bank tube leakage</td>
<td>Crack due to welding failure</td>
</tr>
<tr>
<td>2</td>
<td>13/12/2005</td>
<td>Economizer coils leakage</td>
<td>Due to fly ash erosion tube thickness was reduced to 2.00 mm</td>
</tr>
<tr>
<td>3</td>
<td>26/12/2005</td>
<td>Economizer tube leakage</td>
<td>Due to fly ash erosion</td>
</tr>
<tr>
<td>4</td>
<td>13/10/2005</td>
<td>Bank tube leakage</td>
<td>Due to fly ash erosion</td>
</tr>
<tr>
<td>5</td>
<td>05/09/2005</td>
<td>Import steam super heater leakage</td>
<td>Due to fly ash erosion</td>
</tr>
</tbody>
</table>

Table 2.3 Steam generation plant NFL Naya Nangal (Boiler-III) boiler part failure and reason of failure

<table>
<thead>
<tr>
<th>S. No</th>
<th>Date</th>
<th>Part of Failure</th>
<th>Reason of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>07/07/2011</td>
<td>Water Wall Tube Leakage</td>
<td>Fish Mouth Failure was observed due to overheating and thickness was reduced from 5.6 mm to 2.00 mm.</td>
</tr>
<tr>
<td>2</td>
<td>24/12/2005</td>
<td>Economizer Tube Leakage</td>
<td>Longitudinal crack of ten inches size on the bottom side of economizer tube was observed which was due to thinning of tube due to erosion of fly ash.</td>
</tr>
<tr>
<td>3</td>
<td>22/11/2005</td>
<td>Economizer Tube Leakage</td>
<td>Hole of 3.00 mm size was observed and thickness of tube was reduced to 2.5 mm over three meter length due to erosion of fly ash.</td>
</tr>
<tr>
<td>4</td>
<td>24/03/2005</td>
<td>Water Wall Tube Leakage</td>
<td>The water wall tube was detached from mud drum due to overheating.</td>
</tr>
<tr>
<td>5</td>
<td>06/05/2002</td>
<td>Water Wall Tube Leakage</td>
<td>Due to fly ash erosion the water wall tube was facing frequent leakages</td>
</tr>
</tbody>
</table>

During investigation it was observed that bank tubes and economizer tubes faced repeated failure [133-134]. The bank tubes are made of SA 192 steel and...
Economizer tubes are made of SA 210 Gr A1 steel. The detail study of the boiler tube materials composition, dimensions and mechanical properties was done the results are tabulated in Table 2.4.

Table 2.4 Name of boiler part, dimensions, material composition and mechanical properties

<table>
<thead>
<tr>
<th>Sr No.</th>
<th>Name of Part</th>
<th>Material</th>
<th>Dimensions (Out Side Diameter X Wall Thickness) in mm</th>
<th>Composition</th>
<th>Mechanical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bank Tubes</td>
<td>SA 192</td>
<td>50.0×4.5 mm</td>
<td>C-0.10%, Si-0.17%, Mn-0.43%, P-0.016%, S-0.012%, N-0.0050%</td>
<td>Yield Stress 38,120 Psi, Tensile Strength 56,470 Psi, % elongations 65% BHN-108</td>
</tr>
<tr>
<td>2</td>
<td>Economizer Tubes</td>
<td>SA 210 GR-A1</td>
<td>31.8×4.5 mm</td>
<td>C-0.20%, Si-0.17%, Mn-0.63%, P-0.014%, S-0.022,</td>
<td>Yield Stress 26.0 Kg/mm², Tensile Strength 42.2 Kg/mm², % elongations 30% BHN-143</td>
</tr>
</tbody>
</table>

The failure analysis of economizer tubes was carried out, it was observed that the tube failed due to reduction of wall thickness cause by erosion due to fly ash in combustible flame. The images of failed boiler tubes are shown in Figure 2.30. A hole in the tube was observed which has three mm diameter and the tube was eroded over the length of three inches. The tube thickness was reduced over the length of four inches near the point of tube failure.
Figure 2.30 Failed boiler-I tubes at SGP NFL Naya Nangal (a) pin hole in tube (b) fractured tube (c) wall thickness reduction (d) Scale deposition causes overheating [133]

The failure analysis of bank tubes was carried out it was observed that the bank tube has a hole near the steam drum as shown in Figure 2.31. The thickness of the tube was measured at the point of failure and reduction of wall thickness was observed. The main reason of the tube failure was due to erosion caused by fly ash in the combustible flame.
Figure 2.31 Failed boiler-II tubes at SGP NFL Naya Nangal (a) fractured tube (b) tube wall thickness reduction (c) fish mouth failure (d) fractured tube \[133\]
Platen super heater coil of BLR-III (6th coil from west side)

14/11/2011

PSH TUBE NO. 11 FROM EAST OF BOILER NO. 3

28/05/2011
Figure 2.32 Failed boiler-III tubes at SGP NFL Naya Nangal (a) fish mouth failure of boiler tube (b) crack propagation on tube surface (c) fractured tube at bend (d) fish mouth failure at the centre tube \[133\]

Solid particle erosion is governed by many factors like size and shape of particle, velocity of fluid stream containing erodent, angle of impingement and concentration of erodent. So to investigate the main reason of erosion the coal sample were collected from National Fertilizers Limited Naya Nangal and tested in the laboratory. The results are given below in Table 2.5. The result reflects that it contains high ash content of 47.95 % which is the main cause of boiler tube failure due to erosion. The high ash content in Indian coal was also validated by [20, 21]. The coal sample images were captured for the identification of stone particle mixed in coal mines. The figure 2.33 shows the intensity of stones in coal sample.

Table 2.5 Coal sample test results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IM% w/w</td>
<td>1.04</td>
</tr>
<tr>
<td>Volatile Matter %w/w</td>
<td>16.02</td>
</tr>
<tr>
<td>Ash %w/w</td>
<td>47.95</td>
</tr>
<tr>
<td>Fixed Carbon %w/w</td>
<td>34.99</td>
</tr>
<tr>
<td>Gross Calorific Value cals/gm</td>
<td>3844</td>
</tr>
<tr>
<td>Net Calorific Value cals/gm</td>
<td>3699</td>
</tr>
</tbody>
</table>
Figure 2.33 Identification of stones in coal samples at SGP NFL Naya Nangal (a) separation of stones in coal (b) coal containing stones (c) coal unloading from railway bogies (d) heap of stones separated from coal
Figure 2.34 shows the scanning electron microscope (SEM) images of fly ash were captured to see the particle size and shape. The images reflected that the size of ash particle varies from 20 to 50 micron and it is a mixture of round and sharp corner particles. This fly ash in combustible flame is highly responsible for the erosion of boiler tubes which results in premature failure of boiler parts.

Figure 2.34 Scanning electron microscope images of fly ash of boilers at SGP NFL Naya Nangal

Figure 2.35 Percentage of boiler components failure as per Steag O&M Company 2007
Figure 2.35 shows percentage of boiler components failure as per Steag O&M 2007, this also indicated that water wall tubes and economizer tubes face considerable failure. The identification of causes responsible for frequent water wall tube and economizer tube may be the scope of research work. To investigate the material loss, erosion behavior of these materials and erosion mechanism involved in solid particle erosion, we have to conduct actual experimentation under same boiler operating conditions.