DESIGN AND FABRICATION OF EROSION PROTECTION SHIELD FOR BOILER TUBES AND ITS ANALYSIS

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ABSTRACT
A major portion of the total electricity generated in our country is through thermal power plants using direct combustion of pulverized coal. The coal used in Indian power stations has large amounts of ash (about 50%) which contain abrasive mineral species such as hard quartz (up to 15%) which increase the erosion propensity of coal. The majority of forced outages of these thermal power stations are due to premature failure of vital components such as boiler tubes. Boiler tube failures (BTFs) represent the largest portion of availability loss in the fossil boiler industry at about 4%. Approximately 25% of all tube failures are due to fly ash erosion (FAE).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. An understanding of these problems and thus to develop suitable protective system is essential for maximizing the utilization of such components. These problems can be prevented by either changing the material or altering the environment or by separating the component surface from the environment. Corrosion prevention by the use of coatings for separating material from the environment is gaining importance in surface engineering. In this paper, the use of tube shields for the boiler tube protection is studied and an analysis of different alloy materials for tube shielding is done by comparing its thermal property and a suitable material is selected.

INTRODUCTION

Coal is one of the main fuels for power production. Coal quality deterioration over the years has created challenges for boiler designers the world over to compact and minimize erosion in pressure parts. Fly ash erosion is a major factor for pressure parts damage in high ash coal fired boilers. In high ash coal fired boilers, fly ash erosion is a major concern and the tube failures due to fly ash erosion are almost 25% of the total tube failures. The amount of ash in coal and its velocity are major factors in the rate of pressure part erosion. Fly ash erosion is experienced in the economizer, primary SH, and inlet section of steam reheater tubes. When non-uniform flue gas flow distribution occur in these areas, the rate of erosion increases multifold [1].

In coal-fired power stations, about 20% of the ash produced in the boilers is deposited on the boiler walls, economizers, air-heaters and super-heater tubes. This deposited ash is subsequently discharged as slag and clinker during the soot-blowing process. The rest of the ash is entrained in the stream of flue gas leaving the boiler. These ash particles collide with the boiler steel components and cause extensive surface erosion. In advanced stages of erosion, the components get perforated, and may fail once they lose their structural integrity. Such erosion, together with the processes of blocking, fouling and corrosion, shortens the service-life of boiler components

The resulting penalty is not only the cost of replacing the components but also the cost of stoppage of power production [2]. Solid particle erosion (SPE) is a serious problem for the electric power industry, costing an estimated US$150 million a year in lost efficiency, forced outages, and repair costs [3]. Erosive, high temperature wear of heat exchanger tubes and other structural materials in coal-fired boilers are recognized as being the main cause of downtime at power-generating plants, which could account for 50-75% of their total arrest time[7]. Maintenance costs for replacing broken tubes in the same installations are also very high, and can be estimated at up to 54% of the total production costs [4]. Coal is a complex and relatively dirty fuel that contains varying amount of sulfur and a substantial fraction of non-combustible mineral constituents, commonly called ash [5]. The coal used in Indian power stations has large amounts of ash (about 50%), which contain abrasive mineral species such as hard quartz (up to 15%), which increase the erosion propensity of coal [6]. High temperature oxidation and erosion by the impact of fly ashes and unburned carbon particles are the main problems to be solved in these applications. Therefore, the development of wear and high temperature oxidation protection systems in industrial boilers is a very important topic from both engineering and an economic perspective [7].

INDIAN COAL CONTENT AND ITS COMBUSTION

Coal gasification systems operate at temperature of up to 2000 F (1093^{0}C) and at a pressure of up to 100 atm depending on the specific process and the product, coal gas generates the greatest problems. In addition to hydrogen and carbon-containing gaseous species, there are many undesirable species including sulphides, sulphites, sulphates, ammonia, cyanides, volatilized oils, phenols and aggressive trace elements such as potassium, sodium, vanadium and lead [8].

The coal used in Indian power stations has large amounts of ash (about 50%), which contain abrasive mineral species such as hard quartz (up to 15%), which increase the erosion propensity of coal [9]. The Indian coal proved to be exceptional in that they had significant amounts of alkali feldspars, (K, Na)AlSi3O8, and a garnet, minerals usually thought of as trace components of a coal. The garnets found in the Indian coals were found to follow the general formula (Mg, Fe^{2+})$_3$Al$_2$Si$_3$O$_{12}$. J.J. Wells et al [10] have studied the Ash content, major minerals and trace materials in 10 coals and found the maximum ash content in Indian coal. Table: 1 indicate the Indian coal with dry ash content and mineral matter [10].

PROBLEM BACKGROUND

The corrosive nature of the gaseous environments, which contain oxygen, sulfur, and carbon, may cause rapid material degradation and result in the premature failure of components [11]. Combustion of coal generates very corrosive media particularly near the super heater tubes of the boilers. In the boiler tubes suffering severe fireside corrosion, sulphate salts concentrate at the deposit/scale interface and become partially fused since these salts contain alkali metals of sodium and potassium [12]. In the combustion systems, much of the sodium and potassium is volatized from the mineral matters in the flame to form Na$_2$O and K$_2$O vapours. The sulphur released from the coal, forms SO$_2$ with a minor amount of SO$_3$ and reacts with the volatilized alkalis to form Na$_2$SO$_4$ vapours, which then condense together with fly ash on the pendant superheater and reheater tubes in the boiler.

The vast technical literature available is evidence that corrosion and deposits on the fireside of boiler surfaces or in gas turbines represent important problems [13]. When a comparison is made between the amount of ash collected in a boiler or a gas turbine, in the form of deposits, and the total amount of ash released during combustion, the conclusion is clear that most of the ash passes through the unit. For particles to collect on boiler surfaces or blade surfaces, they must first be brought close to the surface itself and be of the proper size. This can be ascribed to physical phenomenon involving the reaction of particles to the forces to which they are subjected within the stream of gases passing near the surfaces [13]. A particle may hit and then rebound from the surface. If it hits or rubs the surface with sufficient force, erosion will result. On the other hand, if the particle is captured physically or chemically by the surface, a deposit is initiated whose growth appears aerodynamically inevitable. Because of high temperatures, reactions can then take place between the various particles deposited, and also with the gases passing nearby, particularly SO$_3$ and SO$_2$. The resulting compounds may then react, by diffusion, with the metal structure on which they are attached and cause accelerated corrosion [13].

EROSION

Erosion is caused by the impact, cutting action or abrasive wear of small solid particles freely immersed in the direction of fluid flow that frequently undercut portions of the material they strike. Erosion is the progressive loss of original material from a solid surface due to mechanical interaction between that surface and the impinging fluid or solid particles. If high erosion-resistant particles such as Tungsten carbide exist in low erosion resistant or soft matrix, the impacting

Particles can undercut and remove portions of the material. However, if the high erosion resistant particles are densely packed in a matrix material that causes the impacting particles to impinge on a greater percent of the hard particle, the erosion resistance increases dramatically [14]. Solid particle erosion (SPE) is the progressive loss of original material from a solid surface due to mechanical interaction between that surface and solid particles.

In many engineering systems, including steam and jet turbines, pipelines and valves used in slurry transportation of matter, and fluidized bed combustion systems [15]. High temperature oxidation and erosion by the impact of fly ashes and unburned carbon particles are the main problems to be solved in these applications, especially in those regions where component surface temperature is above 600°C. Therefore, the development of wear and high temperature oxidation protection systems in industrial boilers is a very important topic from both engineering and an economic perspective [7]. Erosion-corrosion at high temperature is a field within high temperature corrosion that is growing in importance [16]. Degradation of materials is a function of many parameters. These are normally classified in terms of properties of the particle (size, shape, velocity, impact angle, hardness), target (hardness, ductility, corrosion resistance) and the environment (temperature, partial pressure of the gaseous environments) [11].

FACTORS AFFECTING EROSION

Understanding the erosion degradation failure modes of the boiler heating surfaces is the key to the effective management of their life. It encompasses knowledge of boiler heating surface materials and material properties, operating conditions, possible deterioration mechanisms and their deleterious effects and data needed for assessment and management of these effects [10].The number of factors affecting the erosion processes is relatively large but can be classified into three basic groups:

1.Flow processes around the surface exposed to erosion
2.Erodent characteristics
3.Erosion resistance characteristics of materials

The first two groups of parameters depend on the operating conditions of a plant exposed to erosion, the boiler and furnace designs and technological processes involved. The second group is defined by the characteristics, means of preparation and combustion of fuel. The third group represents the material's initial state and is apparently time independent. However, since the processes occurring in the furnace affect the state of material and erosion mechanisms resulting from the boiler operating conditions, material erosion resistance can also be considered as time-dependent [13].

The flow processes around the surface exposed to erosion include the following

1. The velocity of flue gas
2. The temperature of flue gas
3. The mineral content in coal
4. The change in direction of flue gas
5. The arrangement of pressure parts and
6. The operation above the maximum conditions design rating or with excess airflow above design rate.

Of these factors, the velocity of flue gas, the temperature of flue gas (ash), and mineral matter in coal are the main influencing factors [1].

For low ash coals, the weight loss in pressure parts due to erosion is proportional to flue gas velocity to the power of 1.99. However for high ash Gondwana coals the erosion rate is velocity to the power of 3 to 5. The power depends upon the percentage of ash in coal, the percentage of silica in coal ash, the percentage of quartz in this silica, the percentage of alpha quartz in this quartz, and the structure of alpha quartz [1]. Higher temperature softens the minerals in the ash as well as reduces the strength properties of the material of pressure parts; due to this ash erosion is not predominant in high temperature zones like furnaces, final super heaters, exit reheater, etc. The ash erosion mainly starts in the conventional two-pass boilers from the area where gas temperature is around 700 – 750 deg C. The low temperature superheater (LTSH) and economizer are the areas where ash erosion is severe in a conventional two-pass boiler. The temperature of flue gas entry to LTSH can be around 650 to 700 degree C and leaving, the economizer can be around 350 – 300 degree C. The minerals, which mainly constitute the ash in flue gas at these temperatures, become hard and attain its full abrasiveness. The proportion and composition of the mineral matter in coal will determine the extent of fly ash erosion that can take place. All the mineral matter undergoes phase transformation during the process of combustion of coal in furnace. The phase transformation of the mineral matter is dependent on various factors like the presence of oxygen (oxidizing or reducing atmosphere) in the localized area of furnace, the temperature of the flame / furnace, the retention time, the composition of the minerals in question, etc [1].

CRITICAL AREAS AFFECTED BY EROSIONS

The following are the areas in boiler where coal ash erosion is normally experienced.

(i) Economizer bends and tubes
(ii) LTSH bends and tubes
(iii) Screen tubes
(iv) Goose neck portion at furnace top
(v) Soot blower openings in the water walls
(vi) Wind box opening in the furnace
(vii) Bottom hopper tubes

In the case of (i), (ii) and (iii) the erosion is due to ash in the flue gas stream directly impact and flow over the tube. In the case of (iv) and (vi) it is more due to ash collected in this region sliding over the tubes. In the bottom hopper impact of the water wall deposit is predominant. In the case of (v) and (vi) it is more due to entrained ash / fuel causing erosion due to eddies formed in this area [1].

PREVENTIVE MEASURES

To reduce the erosion

(a) Reduced gas velocity in second pass
(b) Use Inline arrangement for all second pass heat transfer surface
(c) Provide shield in places prone for higher erosion

(d) Provide cassette baffles for LTSH and economizer bends
(e) Go for refractory lining in areas of high erosion where shields cannot be provided.

As low grade coals are now emerging to be used in large quantity in boilers for power generation and process steam requirement, it has become necessary to protect the pressure parts from ash erosion. It can be said with confidence that in the case of high ash coals, erosion cannot be avoided; it can be only minimized to an optimum level. However data show that the boiler pressure parts in the second pass like LTSH and Economizer may need replacement in full from about 10-15 years of operation depending upon the nature of the ash, the type of operating regime maintained, etc [1]. It is important to differentiate between various modes of wear, and to understand which mode is the primary driver for tube failures in a given location. A material that withstands corrosive attack in a water wall application may be a poor choice for protecting superheater tubes against fly ash entrained flue gas erosion. For example, 316 Stainless Steel may perform reasonably well at protecting against Nitric Acid attack, but does not provide notable protection against high velocity fly ash erosion. The same can be said for most weld overlay materials, which typically do not have a sufficient density of hard particles to qualify them as high performance erosion resistant materials.

Extreme temperatures, thermal shock, and the possibility of impact from clinkers are all factors confronting wear protection methods in a power generation steam boiler. A material must possess the following characteristics to defend against high velocity fly ash erosion in this severe environment [11]:
1. Ultra high density of hard particles to withstand extreme ash particle impingement energies
2. Extreme inter particle bond strength to ensure that the hard particles remain in place, even in the presence of corrosive agents
3. Toughness to withstand large particle impact and extreme thermal shock.

SHIELDING OF TUBES

Virtually every boiler maintenance team is familiar with the use of shields for the protection of boiler tubes. Shields may be as simple as a sacrificial contoured plate of carbon steel welded in place, or as complex as a "hand-cuffed" super alloy with sophisticated spray coatings. Tube shields may reduce the frequency of tube leaks and the opportunity for collateral damage caused by high-velocity steam cutting. The objective of tube shields, to prevent hot gas from contacting the heat exchanger tubes of the boiler, it significantly reduces the efficiency of the unit by impeding heat transfer. This heat transfer degradation is caused not only by the increased material of the shield, but also by the shield's tendency to entrap "dead" air between itself and the tube that it is protecting.

EXPERIMENTAL PROCEDURE
Drafting Model

From the given dimensions of a standard sized boiler tube, we have drafted the model of the shield using Pro-E software.

The image below give a diagrammatic representation of the erosion protection shield. When flue gases come in contact with the bend of the boiler tube, the surface of the bend becomes eroded. Erosion shields are used in high temperature applications and to avoid the erosion rate in boiler tubes at the bend, the shield is used to protect the boiler tubes. The shield is used to improve the efficiency of the boiler by avoiding the boiler tube failure, this show how the placement of shield at the bend in order to avoid the erosion. While tube shields may reduce the frequency of tube leaks and the opportunity for collateral damage caused by high-velocity steam cutting. The shield is placed above boiler tubes by using clamps. Clamping is used to avoid the problems caused by wedding process. If wedding process is suggested, then boiler tubes subjected to formation of minute holes leads to another failure.

The placement of shield is playing major role in increase resistance to the erosion caused by the flue gas. The shield is formed by using the erosion resistance materials.

MATERIAL SELECTION PARAMETERS

Initially the suitable metal is selected by taking chemical composition into consideration. The metal having low carbon content is said to have higher wear resistance. Hence, the metal having lower carbon content is chosen.

From the above table it is clear that ss316 has lower carbon composition and at the same time chromium composition is more when compared to rest of the metals. Hence, according to the study of chemical composition, SS 316 is said to have higher erosion resistance and will be able to provide longer life to the boiler tubes.

Relationship between Erosion resistance and composition of chromium present in the metal

It is seen from the above diagram that chromium content increases with the increase of erosion resistance. The X-axis is chromium content in percent and the Y-axis is erosion resistance in ohm-metre. The presence of molybdenum prevents specific forms of corrosion. In SS 304 molybdenum is not present. Hence, it will not resist corrosion attack. Whereas SS 316 has 2 to 3% of molybdenum in its composition.

FORMULAS USED AND FORMULA EXPANSION

This formulae is been taken form the **HMT** Data Book Seventh Edition. This is used to find out the heat transfer for the composite cylinder with convection condition.
Heat Transfer carried out from outside tube to inside tube,
$Q = \Delta T/R$ (Watts)   (1)

The heat transfer is defined as the ratio of difference in the temperature to the thermal resistance of the material. The unit of the heat transfer is mentioned in Watts

Where,

Q – Heat Transfer (Watts)

ΔT – Temperature Difference (Kelvin)

R= $1/2\prod L$ [$1/h_a r_1$ + $1/k_1*$ln (r_2/r_1) + $1/k_2*$ln (r_3/r_2) + $1/h_b r_3$]   (2)

The thickness resistance is defined as the ratio between temperature drop and the average heat flow across the interface.

Where,

R – Thermal Resistance (K/W)

h_a, - heat transfer coefficient of steel

h_b - heat transfer coefficient of gas

k_1 – thermal conductivity of boiler tube

k_2 - thermal conductivity of shield

r_1 – Inner radius of tube (meter)

r_2 – Outer radius of tube (meter)

r_3 – Outer radius + Thickness of shield (meter)

ANALYSIS APPROACH

Before getting into the analysis part, first we have to know about the geometry of the boiler tube with the bending section. The geometric specification consider for designing the boiler tube at the bends is listed below

At left side bend section:

Bend angle : 120°

Bend radius : 52.5mm

At right side bend section:

Bend angle: 60°

Bend radius: 198mm

Geometry specification

Length X	1079.2 mm
Length Y	1153. mm
Length Z	66. mm

The value of z depends upon the selection of surface at which we going to analysis the heat transfer. Z axis is symbolically show the depthness of the tube. The overall heat transfer rate is mainly depend upon the shielding which is provided additionally to the boiler tube. Different material possess different thermal conductivity value. Based on the thermal conductivity value, the heat transfer is dependent. Lesser the "k" value higher the heat transfer. The temperature range outside the tube is around 700° and the inside temperature is maintain around 540°. But the inlet of the steam having the temperature around 340°.

Also the velocity of the steam entering the tube is around 24.15m/s. the velocity striking on the tube is consider as the main parameter which results in erosion.

The heat transfer is occurring at two stages. Convection and conduction heat transfer is been taking place.

The heat transfer is analyzed by considering the shield and without considering the shield. The comparison between this parameter shows the loss of value that occurs.

Based on the procedure given above the analysis is been carried out. Each and every step is carried out in series. This procedure is repeated for different shield materials.

RESULT AND DISCUSSIONS

The materials provided for an erosion protection shield are given below,

➢ Stainless Steel(Grade 304)

➢ Stainless Steel(Grade 316)

➢ Stainless Steel(Grade 316L)

➢ Alloy Steel

➢ Carbon Steel

The best material is selected based on the following factors,

i. Heat Transfer rate

ii. Erosion rate and Temperature resistance Chemical Composition, particularly carbon content Mechanical Properties, such as hardness

COMPARISON OF HEAT TRANSFER RATES

From the above calculations, the heat transfer is determined and it is observed that SS 316 has a high heat transfer rate compared to the other materials. The new metal selected as the erosion protection shield must have reasonable heat transfer coefficient and the heat received from flue gases must be transferred to the inner walls of the reheater tubes so that the temperature of hot gas flowing inside the tube is maintained.

EROSION RATE AND TEMPERATURE RESISTNCE

The chart above shows the variation of temperatures of the inner and outer diameter of the pipe as well as the tube material. Hence SS 316 can be used as a shield material without any hesitation because it provides reasonable heat transfer along with high resistance to erosion. Therefore it increases the life of the boiler tubes without affecting efficiency of the boiler.

From above results, though both SS 304 and SS 316 have high erosion resistance and high temperature with standing capacity. The heat transfer rate is higher in the case of SS 316 when compare to SS 304. It has been concluded that SS316 is the material which is capable of providing longer life to reheater tubes by resisting erosion to a greater extent. Higher the temperature and erosion resistance of the shield material, better the life of the boiler tubes.

CHEICAL COMPOSITION

From Table 3.1, it is seen that though the carbon content in SS 316 is lower as compared to the other materials, the chromium content is more.

We know that from fig 3.3, chromium composition is directly proportional to erosion resistance. As the chromium content of SS 316 is higher than any other material, it will therefore have the highest erosion resistance which will support its cause as a suitable material for the protective coating around the boiler tubes.

MECHANICAL PROPERTIES

Hardness is a main factor which is taken into account while selecting the type of shield material. The material which has higher hardness will be able to withstand high temperatures and erosion.

Therefore from the above table, it seen that though both SS 316 and SS 316L have the same hardness but SS316 is a more suitable material for an erosion protection shield rather than other materials due to its sufficiency in its physical, chemical and mechanical properties as well as erosion resistance, temperature range and heat transfer.

THERMAL ANAKYSIS
Analysis of Alloy Steel (SA213T11)

Table 1. Ash Content and mineral matter in the suite of coals

Coal	Ash content	Major Minerals	Trace minerals
Indian Coal A	46.7%	Quartz, muscovite, illitic Clay, Kaolinite, siderite	Barites, feldspar, ilmenite, pyrite, rutile, zircon
Indian Coal B	30.3%	Quartz, feldspar, illitic clay, kaolinite, muscovite, siderite	Apatite, garnet, ilmenite, monazite, rutile, zircon
Indian Coal C	45.6%	Quartz, feldspar, garnet, illitic clay, muscovite, kaolinite	Apatite, ilmenite, monazite, pyrite, rutile, zircon

Table 2. Chemical Composition of different types of shield materials

Chemical composition	Low carbon steel	Alloy steel	SS 304	SS 316	SS 316L
Carbon	0.17-0.23	0.3 max	0.08 max	0.08 max	0.09 max
Manganese	0.70-1.00	0.70-1.00	2.00 max	2.00 max	2.00 max
Silicon	0.10	0.20-0.80	0.75 max	0.75 max	0.75 max
Phosphorous	0.04 max	0.04 max	0.045 max	0.045 max	0.045 max
Sulphur	0.05 max	0.045 max	0.03 max	0.03 max	0.03 max
Chromium	n/a	0.35 max	16-18	18-20	16.00-18.00
Molybdenum	n/a	1.00-1.50	n/a	2.00-3.00	2.00-3.00
Nickel	n/a	0.50 max	8.0-10.5	10-14	10.00-14.00

Table 3. Heat Transfer Rates

Type	T_a (K)	T_b (K)	DT (K)	h_a W/m^2	h_b W/m^2	r_1 m	r_2 m	r_3 m	k_1 W/mK	k_2 W/mK	R, Thermal Resistance (K/W)	Q
SS 304	773	973	-200	12.15	56	0.027	0.03	0.033	33	25.4	0.59236405	-338.427
SS 316	773	973	-200	12.15	56	0.027	0.03	0.033	33	22.75	0.57943468	-345.385
SS 316 L	773	973	-200	12.15	56	0.027	0.03	0.033	33	24.5	0.58386842	-344.414
Alloy steel	773	973	-200	12.15	56	0.027	0.03	0.033	33	33	0.57222737	-349.511
Carbon steel	773	973	-200	12.15	56	0.027	0.03	0.033	33	63.9	0.572005096	-342.67

Table 4. Comparison of Erosion Resistance and Temperature Resistance

Material type	Erosion resistance	Temperature resistance
SS304	Medium	High
SS316L	Medium	Medium
SS316	High	High
SA213T11	Low	Low

Table 5. Comparison of Hardness

Material type	Hardness
SS 304	92
SS 316L	95
SS 316	95
SA213T11	85
Low Carbon Steel	79

Table 6. Model (B4) > Mesh

Object Name	*Mesh*
State	Solved
Defaults	
Physics Preference	Mechanical
Relevance	100
Sizing	
Use Advanced Size Function	Off
Relevance Center	Fine
Element Size	Default
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Fast
Span Angle Center	Coarse
Minimum Edge Length	3.0 mm
Inflation	
Use Automatic Tet Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Advanced	
Shape Checking	Standard Mechanical
Element Midside Nodes	Program Controlled
Straight Sided Elements	No
Number of Retries	Default (4)
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Pinch	
Pinch Tolerance	Please Define
Generate on Refresh	No
Statistics	
Nodes	53381
Elements	16823
Mesh Metric	None

Table 7. Model (B4) > Steady-State Thermal (B5) > Convection

Temperature [°C]	Convection Coefficient [W/mm²·°C]
21.	5.e-006

Table 8. Model (B4) > Steady-State Thermal (B5) > Solution (B6) > Results

Results		
Minimum	535.14 °C	9.5602e-004 W/mm²
Maximum	750. °C	1.7718 W/mm²
Minimum Occurs On	Part1	
Maximum Occurs On	insulation	

Table 9. Model (B4) > Steady-State Thermal (B5) > Solution (B6) > Probes

Results	
Y Axis	1.0691 W/mm²
Maximum Value Over Time	
Y Axis	1.0691 W/mm²
Minimum Value Over Time	
Y Axis	1.0691 W/mm²

Material Data
SA213T11
SA213T11 > Constants

Thermal Conductivity	3.3e-002 W mm^-1 C^-1

Table 10:
Model (A4) > Mesh

Object Name	*Mesh*
State	Solved
Defaults	
Physics Preference	Mechanical
Relevance	100
Sizing	
Use Advanced Size Function	Off
Relevance Center	Fine
Element Size	Default
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Fast
Span Angle Center	Coarse
Minimum Edge Length	3.0 mm
Inflation	
Use Automatic Tet Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Advanced	
Shape Checking	Standard Mechanical
Element Midside Nodes	Program Controlled
Straight Sided Elements	No
Number of Retries	Default (4)
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled

Pinch	
Pinch Tolerance	Please Define
Generate on Refresh	No
Statistics	
Nodes	70378
Elements	34108
Mesh Metric	None

Table 11. Model (A4) > Steady-State Thermal (A5) > Solution (A6) > Results

Results		
Minimum	-26.288 °C	8.8151e-009 W/mm²
Maximum	750. °C	5.8001 W/mm²

Table 12. Model (A4) > Steady-State Thermal (A5) > Solution (A6) > Probes

Results	
Y Axis	3.3007 W/mm²
Maximum Value Over Time	
Y Axis	3.3007 W/mm²
Minimum Value Over Time	
Y Axis	3.3007 W/mm²

Material Data
SS304
SS304 > Constants

Thermal Conductivity	2.54e-002 W mm^-1 C^-1

SA213T11
SA213T11 > Constants

Thermal Conductivity	3.3e-002 W mm^-1 C^-1

Table 13.
Model (C4) > Mesh

Object Name	*Mesh*
State	Solved
Defaults	
Physics Preference	Mechanical
Relevance	100
Sizing	
Use Advanced Size Function	Off
Relevance Center	Fine
Element Size	Default
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Fast
Span Angle Center	Coarse
Minimum Edge Length	3.0 mm
Inflation	
Use Automatic Tet Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5

	Growth Rate	1.2
	Inflation Algorithm	Pre
	View Advanced Options	No
Advanced		
	Shape Checking	Standard Mechanical
	Element Midside Nodes	Program Controlled
	Straight Sided Elements	No
	Number of Retries	Default (4)
	Rigid Body Behavior	Dimensionally Reduced
	Mesh Morphing	Disabled
Pinch		
	Pinch Tolerance	Please Define
	Generate on Refresh	No
Statistics		
	Nodes	70378
	Elements	34108
	Mesh Metric	None

Table 14. Model (C4) > Steady-State Thermal (C5) > Solution (C6) > Results

Results		
Minimum	527.08 °C	2.2683e-009 W/mm²
Maximum	750. °C	1.5095 W/mm²

Model (C4) > Steady-State Thermal (C5) > Solution (C6) > Probes

Options	
Result Selection	Y Axis
Display Time	End Time
Spatial Resolution	Use Maximum
Results	
Y Axis	0.89409 W/mm²
Maximum Value Over Time	
Y Axis	0.89409 W/mm²
Minimum Value Over Time	
Y Axis	0.89409 W/mm²

Material Data
SS316
SS316 > Constants

Thermal Conductivity	2.275e-002 W mm^-1 C^-1

SA213T11
SA213T11 > Constants

Thermal Conductivity	3.3e-002 W mm^-1 C^-1

Table 15. Model (D4) > Mesh

Object Name	*Mesh*
State	Solved
Defaults	
Physics Preference	Mechanical
Relevance	100

Sizing	
Use Advanced Size Function	Off
Relevance Center	Fine
Element Size	Default
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Fast
Span Angle Center	Coarse
Minimum Edge Length	3.0 mm
Inflation	
Use Automatic Tet Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Advanced	
Shape Checking	Standard Mechanical
Element Midside Nodes	Program Controlled
Straight Sided Elements	No
Number of Retries	Default (4)
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Pinch	
Pinch Tolerance	Please Define
Generate on Refresh	No
Statistics	
Nodes	53381
Elements	16823
Mesh Metric	None

Table 16. Model (D4) > Steady-State Thermal (D5) > Solution (D6) > Results

Results		
Minimum	\536.2 °C	5.0379e-007 W/mm²
Maximum	750. °C	1.4279 W/mm²

Table 17. Model (D4) > Steady-State Thermal (D5) > Solution (D6) > Probes

Results	
Y Axis	0.91245 W/mm²
Maximum Value Over Time	
Y Axis	0.91245 W/mm²
Minimum Value Over Time	
Y Axis	0.91245 W/mm²

Material Data
SS316L
SS316L > Constants

Thermal Conductivity	2.45e-002 W mm^-1 C^-1

SA213T11
SA213T11 > Constants

Thermal Conductivity	3.3e-002 W mm^-1 C^-1

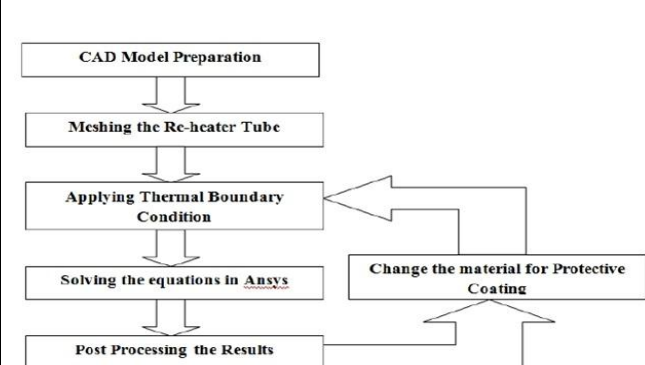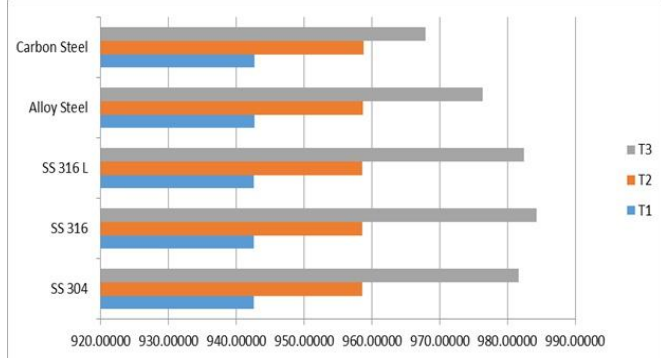|	
Fig 1. Drafting Model of the Shield 	**Fig 2. Shield Placement**
Fig 3. Chromium vs Erosion Resistance 	**Fig 4. Method for Protective Coating**
Fig 5. Variation of Temperatures 	**Fig 6. Alloy Steel**
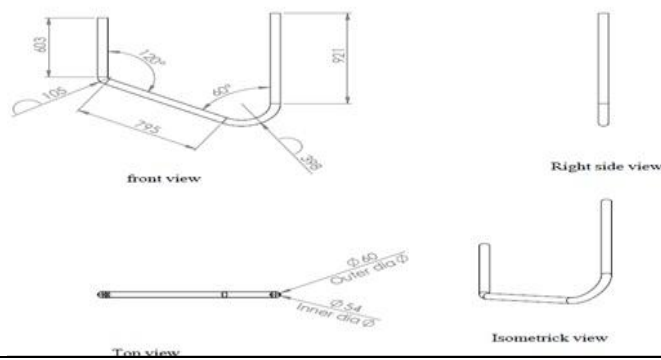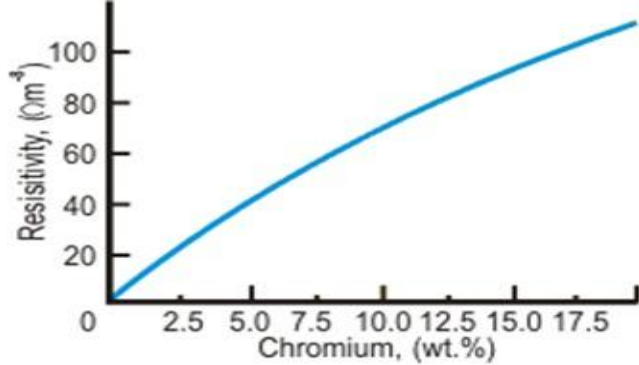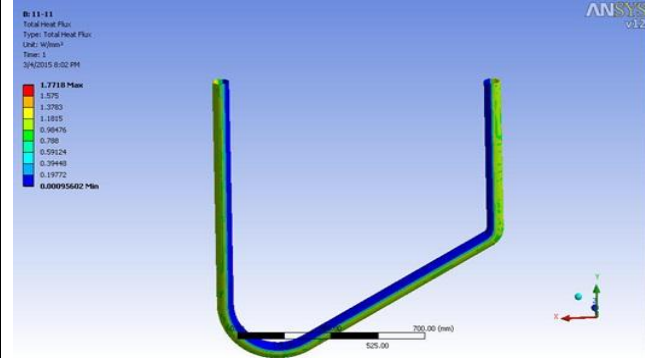
Fig 7. Analysis of Stainless Steel 30
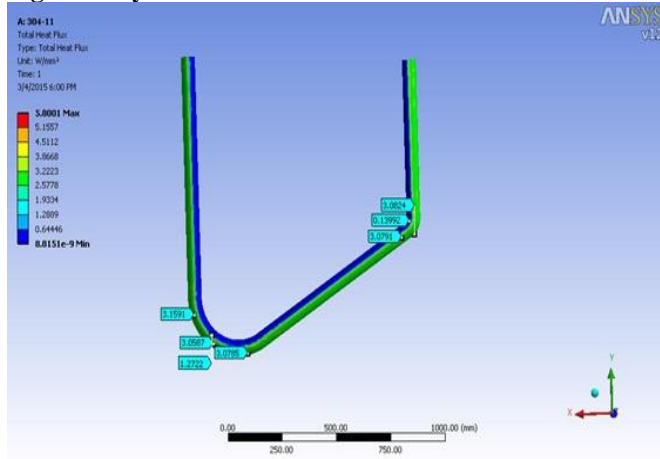
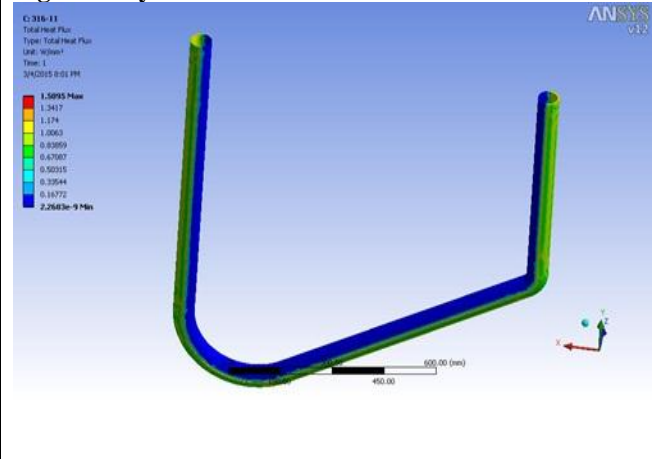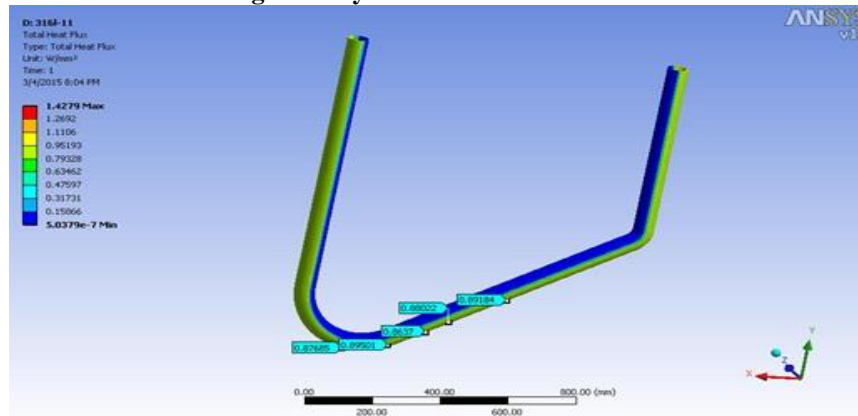**Fig 8. Analysis of Stainless Steel 316**

Fig 9. Analysis of Stainless Steel 316L

CONCLUSIONS

• Out of the four materials chosen to provide as a shielding, SS 316 was found to have a higher heat transfer (Q) value than the other materials. Hence, SS 316 is suggested as a suitable material for shielding.

• The heat transfer co-efficient and the net heat flux is not much affected by adding the protective shield to the eroded portion of the pipe bend. In turn it slightly improves the heat transfer rate. Thus, providing SS 316 as a shielding to the reheater bends prevents the reheater tubes from getting eroded and increases the operational life of the tubes, leading to effective functioning of the plant.

• Though both SS 304 and SS 316 have high erosion resistance and high temperature with standing capacity. The heat transfer rate is higher in the case of SS 316 when compare to SS 304. It has been concluded that SS 316 is the material which is capable of increasing the lifetime of

reheater tubes to a greater extent. Higher the temperature and erosion resistance of the shield material, better the life of the boiler tubes.

• Since, the chromium content of SS 316 is higher than any other material, it will therefore have the highest erosion resistance which will support its cause as a suitable material for the protective coating around the boiler tubes.

• Both SS 316 and SS 316L have the same hardness, but SS 316 is a more suitable material for an erosion protection shield rather than other materials due to its comparable physical, chemical and mechanical properties as well as erosion resistance, temperature range and heat transfer.

• The thermal analysis suggests that the thermal conductivity of SS 316 when compared to the boiler tube material, SA213T11 is minimal therefore SS 316 would be a more suitable material for the protective shield.

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