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High temperature erosion resistance characteristics of boiler tube materials of thermal power plant

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The boiler tubes of Indian thermal power plants are exposed to severe erosive ash environment leading to continuous metal wastage and failure. The erosion resistance of the boiler tube material is affected by hardness, particle velocity, impact angle, particle size and metal temperature. The parameters affecting the erosion resistance properties are required to be evaluated in the laboratory under accelerated condition using a tunnel type erosion test rig. The present paper highlights the results of high temperature erosion of five different widely used boiler tube materials such as T11, T91, T22, carbon steel, and SS304 have been brought out in terms of their erosion resistance properties under different temperature conditions. The properties are compared with that of room temperature erosion resistance properties. The erosion resistance characteristics were studied for different velocity and impact angles around the circumference of the boiler tube. The evolution of surface roughness corresponding to different angles around the boiler tube, upon erosion, in comparison with the carbon steel tube, is presented.

Keywords : *boiler tube, erosion, superheater, reheater, surface roughness, impact angle*

1.0 INTRODUCTION

Indian power station utilizes coal having a high amount of ash up to 50 %. The ash contains predominantly abrasive mineral species such as hard quartz up to 15 %, which increase the erosion propensity of coal. In a coal based thermal power plants, the ash generated after coal combustion process gets carried by the flue gas and pass through various convective heat transfer sections where Superheater (SH), Reheater (RH), and Economizer (ECO) components are located. Finally, the ash particles are collected in the electro-static precipitator and the flue gas is discharged through the chimney.

In the process of coal conversion, all the coal and ash handling components are subjected to severe erosion leading to metal wastage. The components inside the boiler in the particular Water Wall (WW), SH and RH are subjected to erosion at an elevated temperature ranging up to 700 ºC. The flue gas temperature at the SH and RH elevation reach as high as 1050 ºC and the gas velocities reach the maximum of 25 to 30 m/s. Under this high velocity condition, the abrasive ash impacts on to different alloy steel tube surface, leading to metal wall thinning and premature failure of the tube.

Failure of boiler tubes due to impingement of high velocity ash particles in Indian power plants is widely recognized one. The quality of coal used in different power plants is worsening day by day and as per the Annual report of Central Electricity Authority, the forced outage loss due to tube failure accounts for nearly 6 % [1]. Artificial neural network (ANN) model has been

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developed to predict the erosion behavior of these boiler grade steels impacted by boiler fly ash for more realistic characterization of erosion potential using pertinent data. An efficient network training optimization algorithm has been employed for faster convergence and better predictions.

The ANN predictions of erosion rate are found to be in excellent agreement with the actual measured data as reported in the literature [2]. Also, mathematical model embodying the mechanisms of erosion on behavior, has been developed to predict erosion rates of coal-fired boiler components at different temperatures and the results were in good agreement with the experimental data [3]. Computational fluid dynamics simulations carried out on a typical fossil fuel boiler has indicated a orderly low turbulence flow pattern in the 2nd, 3rd and 4th pass as well as at the exit headers where no erosion–corrosion was seen in practice [4-5].

The magnitude of erosion due to soot blowing through spraying on to the tube surfaces using high-pressure steam is much higher than that of the fly ash erosion during the normal boiler operation. The close conformity between the Computational Fluid Dynamics (CFD) modeling results with that of experiments on soot blower erosion indicated that the Computational Fluid Dynamics tools can be effectively applied for erosion prediction in power boilers [6]. Plants which implement an effective tube failure prevention program can minimize the risk of failures [7].

The magnitude of erosion damage depends on the local gas/particle velocity as well as temperature environment, at which the component is working [8]. The velocity reaches a maximum in Reheater and Low-temperature Super heater section in view of their closed arrangement and minimum gap between the tube panels. It is estimated that RH and Final SH tube metal temperature reaches close to 580 ºC, which is in excess of the oxidation temperature of low alloy steel used. Under the conditions of fluctuating fuel quality, the metal temperatures in excess of 600 ºC are experienced [9]. The erosivity of the material depends on upon particle streams, they included shape, mass, size impact velocity and feed rate [10-11]. The impact velocity only increased the erosion rate and did not affect the dependency of erosion behavior on the impact angle for the metallic materials. Several parameters for description of the erosion–oxidation phenomena under different impact angles are proposed and the assessment of their applicability is done [12-13]. Evaluation of boiler tube material for its suitability for high ash coals is still considered important and the erosion resistance data would become an input for the boiler design for the selection of appropriate tube thickness in a different section [14-15].

Much of the reported literature data on the high-temperature erosion of tubes and hard coatings for boiler applications are based on the sample coupons rather than the actual tube [2-3,11,16]. It is emphasized that evaluation of the actual tube specimen under closely simulated test conditions would give more insight into the material removal mechanism in these critical materials.

In the present study, the results of erosion experiments conducted using actual boiler tube specimens of widely used grades are presented. Silica sand of AFS 70 was used as the erodent. The detailed analysis in terms of the changes in surface roughness after erosion was presented in graphical form for easy understanding of surface topography.

2.0 EXPERIMENTAL PROGRAM

2.1 Tube Sample Materials

The boiler samples of T11, T91, T22, Carbon steel (CS), and SS304 are considered. Multiple ring specimens were machined from these tubes. The final finishing of the OD surface was carried out through polishing by 600 grit silicon carbide emery to achieve the uniform initial roughness on all the tubes. Figure 1 shows the view of the various sample boiler tubes used along with the cut ring specimens used for the erosion test.

TABLE 1

STATISTICS OF BOILER TUBE FAILURE DATA [1]

Capacitry (MW)	Total No of Units Reviewed	Water Wall		Super heater		Economise		Reheater	
		Total No of Units involved	Total No of Outages	Total No of Units involved	Total No of Outages	Total No of Units involved	Total No of Outages	Total No of Units involved	Total No of Outages
500	33	21	46	16	20	11	11	9	18
250	13	6	9	3	5	1	1	1	1
200/210	160	106	265	62	110	68	129	52	103
140/150	11	7	40	4	15	4	16	1	2
120	21	12	25	14	50	11	50	8	20
110	40	24	83	22	65	18	56	15	38
100	40	24	83	22	65	18	56	15	38
100	11	5	13	5	49	5	7	0	0
70/80	6	5	50	4	6	3	8	0	0
62.5/57.5	23	17	73	5	5	9	13	0	0
60	25	8	35	12	27	8	24	2	2
50/57.5	24	5	11	3	6	7	15	2	2
20/40	13	2	4	2	3	3	7	1	1
Grand Total	380	218	654	152	361	148	337	91	187

The dimensions of the tube used and the initial surface roughness value (Ra), was measured using Surtronic-25 Taylor Hobson surface roughness tester and the results are given in Table 2. The Ra measurement was done along the axis of the tube with an evaluation length of 4 mm. The tube was marked at different angular positions with an interval of 15° on the wall thickness side for the purpose of Ra measurement. The elemental composition of the tubes analyzed by the Optical Emission Spectroscopy method is given in Table 3.

2.2 Erosion Resistance Evaluation

The high-temperature erosion resistance test was carried out in an indigenously designed tunnel type erosion test rig Figure 2. A rotary blower with the damper control the mechanism at the inlet side is used to supply the required quantity of air and discharges the outlet air into a horizontally supported pipe of 80 mm diameter. The diameter of the pipe at the exit (nozzle) was reduced to a size of 50 mm diameter. The heating up of the air was carried out in a 18 kW fin-type cartridge heater unit, located on the upstream of the discharge end. The schematic arrangements of erosion test setup with tube specimens are shown in Figure 2. The ring specimens were supported on a pedestal and held vertically coinciding with the central axis of the nozzle. The typical test conditions used during the erosion tests are;

FIG. 1. BOILER TUBE SAMPLES AND MACHINED RING TUBE SPECIMENS

TABLE 2

DETAILS OF TUBE MATERIALS

	T11	T91	T22	CS	SS304
Diameter mm)	42	42	48	48	52
Hardness (HRB)	193	223	139	130	162
Surface roughness (µm)	0.61	0.60	0.56	0.58	0.62

TABLE 3
COMPOSITION OF TUBE MATERIALS

COMPOSITION (%)	T11	T91	T22	CS	SS304
C	0.15	0.12	0.15	0.27	0.09
Mn	0.42	0.44	0.45	0.95	1.58
Si	0.67	0.41	0.52	0.12	0.61
Ni	---	---	---	---	8.0
Cr	1.20	9.01	2.15	---	18.0
Mo	0.51	1.02	0.98	---	---
S	0.04	---	0.03	0.06	---
P	0.03	---	0.03	0.52	---
V	---	0.20	---	---	---
Nb	---	0.09	---	---	---

- Abrasive type : Silica sand
- Abrasive size : AFS 70 (375 µm)
- Mass Flux rate : 210 g/min
- Nozzle diameter : 50 mm
- Gap between nozzle tip & sample: 20 mm

The specimen tube samples are exposed to erosion on one side of the ring (0 to 90°) and the tube surface is divided into six different segments of 15° each for change in roughness measurements. The tests were carried out for a period of 30 minutes. Tests were done for three temperatures of Room Temperature (RT), 250 °C & 400 °C. The particle velocity was varied to 20, 25 and 32 m/s for RT conditions and the elevated temperature erosion loss was measured at two velocities of 25 m/s and 32 m/s. In view of the variation in the OD sizes of the tube, the mass loss due to the erosion of the tube specimen was normalized in terms of the kg of abrasive used per square meter area of the tube surface. The tube having the lowest OD has been taken as the reference and increase in impact area for other tubes is calculated for comparative purposes.

The average erosion loss value was reported on an average of two results. The change in surface roughness all around the exposed surface was measured using the roughness tester. Measurements were made on both quadrants of the tube and the average Ra value was reported.

3.0 RESULTS AND DISCUSSION

3.1 Effect of particle impingement velocity on erosion loss at room temperature

Figure 3 and 4 shows the machined tube specimens before and after the erosion test. The change in Ra value is quite evident from the change in morphology coupled with decolorization of the specimen. The rate of erosion of different tubes at room temperature condition for three different particle impact velocities is shown in Figure 5. All the tube materials have show an exponential increase in erosion loss with particle velocity and the velocity exponent is calculated to be in the range of 2.1 to 2.98. The observed lower mass loss of alloyed steel tubes such as T91 and SS304, indicated that an improvement of 27 % to 34 % compared to the reference CS tube.

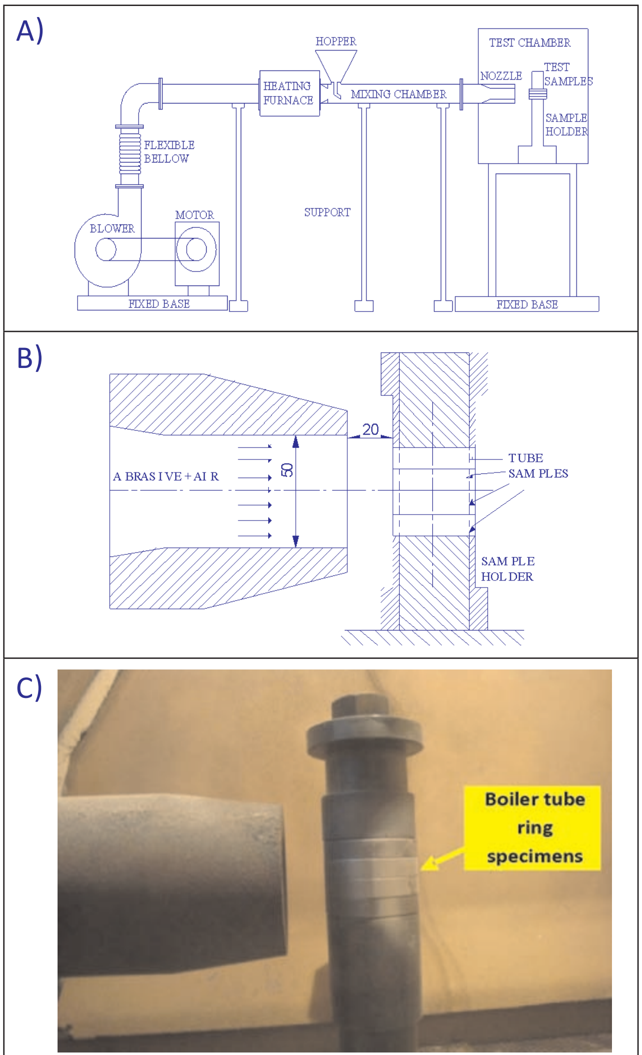

FIG. 2. SCHEMATIC VIEW OF THE EROSION SETUP USED & ARRANGEMENT OF RING SPECIMENS AGAINST THE PARTICLE JET

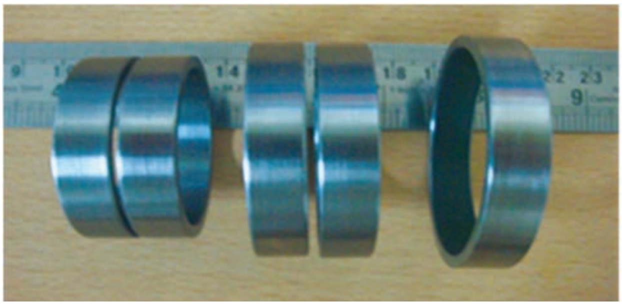

FIG. 3. SAMPLES BEFORE TEST

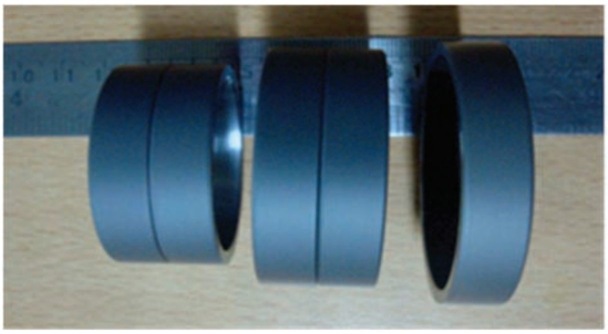

FIG. 4. SAMPLES AFTER TEST

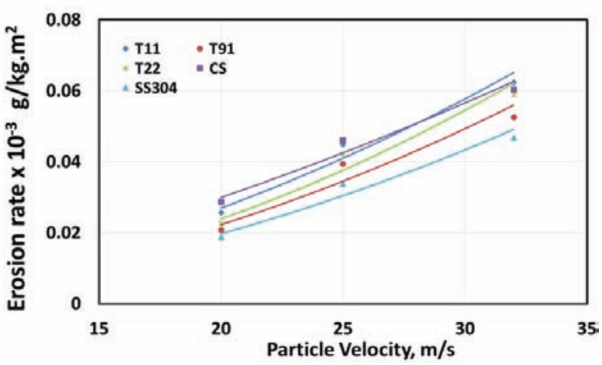

FIG. 5. EROSION RATE OF SAMPLES AS THE FUNCTION OF VELOCITY

3.2 Erosion profile around the circumference

The results of the Ra value around the tube circumference after erosion test for different tube materials is shown in Figures 6 to 9. At room temperature conditions, all the tubes have shown an increase in the roughness value and reaches a maximum value in the angle range of 30° to 45° and decreases subsequently. The Ra value increases gradually around the circumference. The change in roughness is observed to be maximum at 30° for most of the tubes at all the impact velocities This appears possibly due to the cutting action of the hard silica particles at lower impact angles and provides shearing action as it glides over the circumference. The sensitivity of carbon steel and T11 steel is evidently seen at these angles at all the three velocities. At normal impact, the kinetic energy of the particle gets absorbed effectively by the target surface, and the change in Ra value is minimum. The change in Ra value in the case of SS304 tube is quire uniform for particle velocities upto 25 m/s. The lower magnitude of Ra value observed on SS304 and T91 tube material corroborates the findings of metal erosion loss data. The trend observed in the present study is in line with the reported numerical erosion results of tube erosion simulated with ash particles [17]. This is possibly due to the fact that action of particles gliding over the OD surface, induces localized shear force in regions coinciding with angle close to 30°. This observed characteristics of ductile erosion mode shown by all the tube material is typically matching with that of the ductile material. Minimal changes in Ra value was observed after 45° impact angle, implying that the predominant kinetic energy of the impacting particle is absorbed by the tube metal rather than expending the energy in providing the shearing / ploughing action at shallow angles. In actual power plants, the boiler tube experiences erosion due to fly ash particles around half the circumference. Thus, the result of the experiments is considered close to field impact conditions. The change in Ra value around the tube circumference upon eroison is shown in Figure 6. The average value over 0 to 90° on either side of the facing tube is reported. The change in roughness profile over the half circumference eroded region is represented in terms of the original tube geometry is shown in Figures 7 to 9.

Comparison of Ra values of each tube grades for different velocities is shown in Figure 10. The profiles showing the change in roughness due to the removal of material is maximum at 30° for all the three velocities. As can be seen from figures, all the tubes appear to experience uniform pattern in roughness value 'Ra' at lower particle velocity of 20 m/s. As the velocity is increased to 25 and 32 m/s, the change in Ra value appears predominant at 30 and 45° angle around the tube circumference.

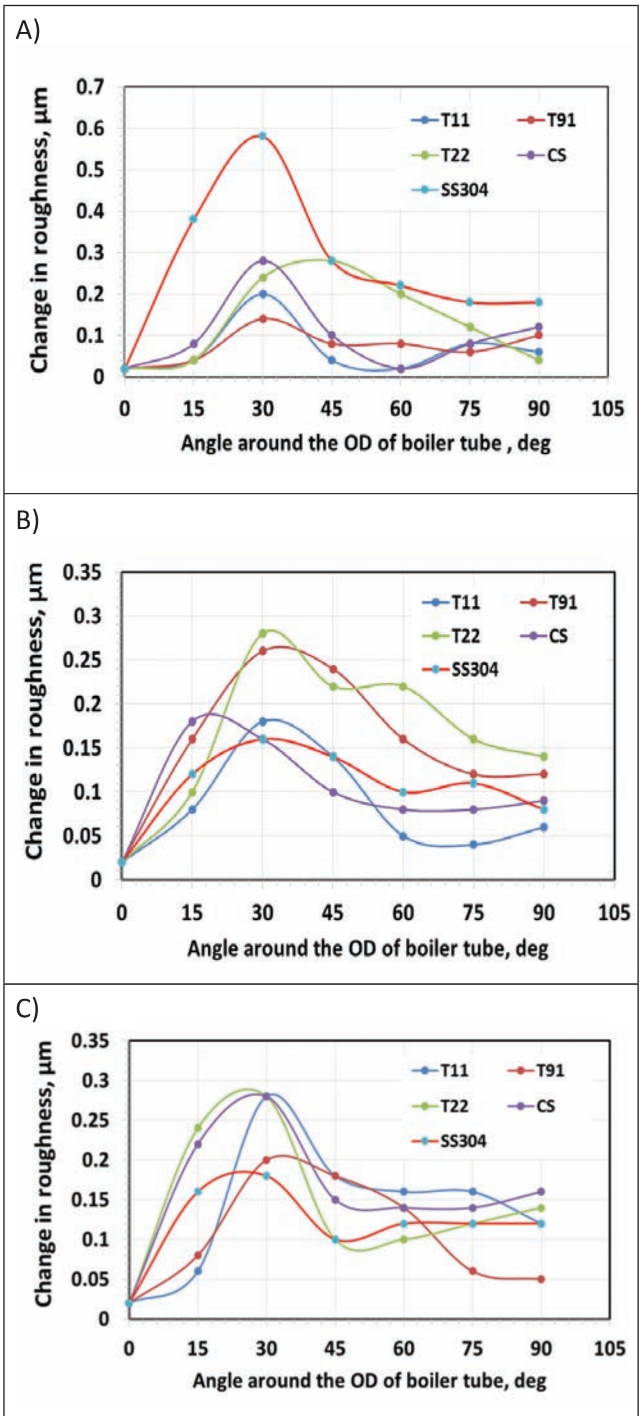

FIG. 6. CHANGE IN ROUGHNESS VALUE AT DIFFERENT PARTICLE VELOCITIES A) 20 M/S B) 25 M/S C) 32 M/S

The flat morphology of the roughness profile on either side close between 60 to 90° of CS and T11 tubes shows that the erosion rate is nearly constant and gets unaffected by the absence of shearing action of the particle. The change in Ra value was maximum at the highest particle velocity of 32 m/s on all the tubes and the pronounced effect could be observed at lower angle close to 30°. Comparative evalauation of change in Ra value was plotted for all the tubes at 32 m/s, as shown in Figure 11. While, the CS and T11 shows erosion sensitive at all the impact angles, maximum erosion is observed close to 30° in all the tubes.

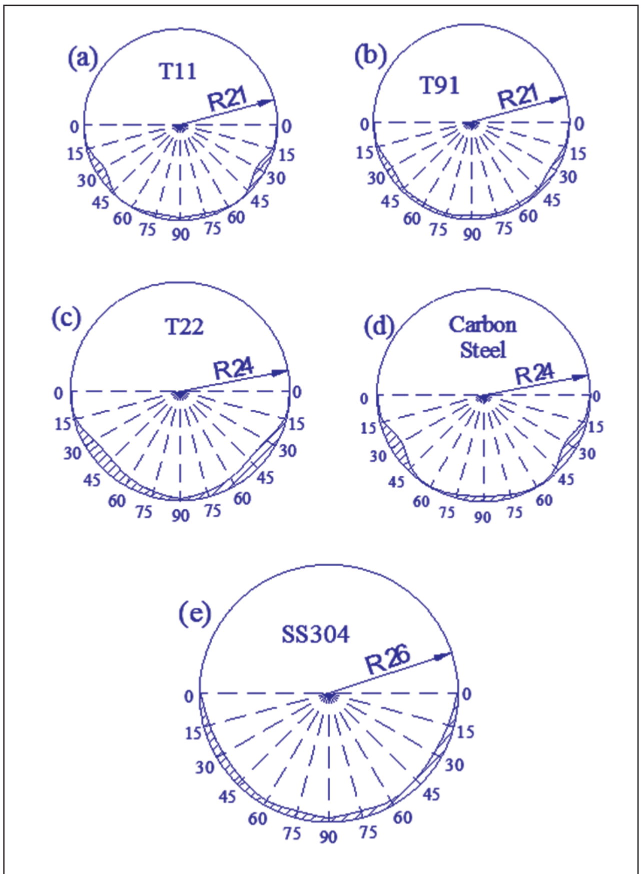

FIG. 7. ROUGHNESS PROFILE AROUND CIRCUMFERENCE AT 20 M/S

3.3 Effect of particle impingment velocity on erosion loss at elevated temperature

The results of the erosion loss of different boiler tubes at 250 °C and 400 °C is shown in Figure 12. While the loss in material at elevated temperature in air environment involves both erosion and erosion-corrosion phenomenon, in the present study, the mass loss is considered as attributed to erosion only. All the tube materials have shown an increase in weight loss with temperature. The sensitivity of CS is observed to be maximum with an increase of nearly 10.2 times more erosion loss compared to the room temperature erosion values. The presence of higher chromium levels in the

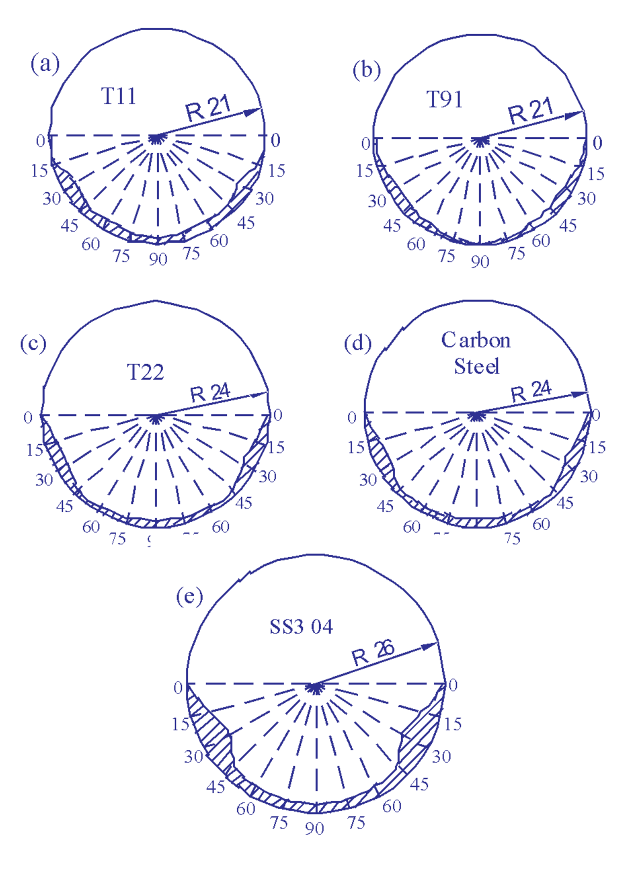

FIG. 8. ROUGHNESS PROFILE AROUND THE CIRCUMFERENCE AT 25 m/s

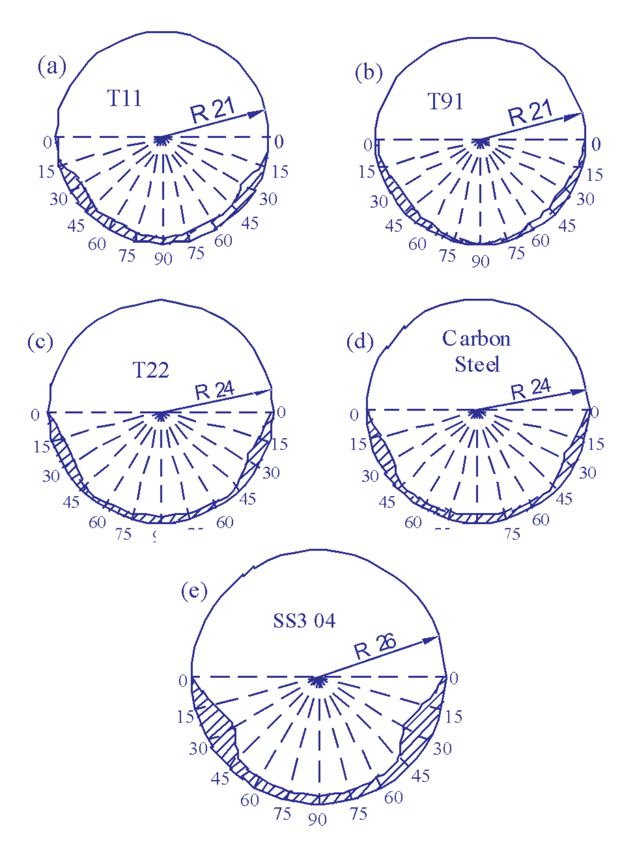

FIG. 9. ROUGHNESS PROFILE ON THE OD AT 32 m/s

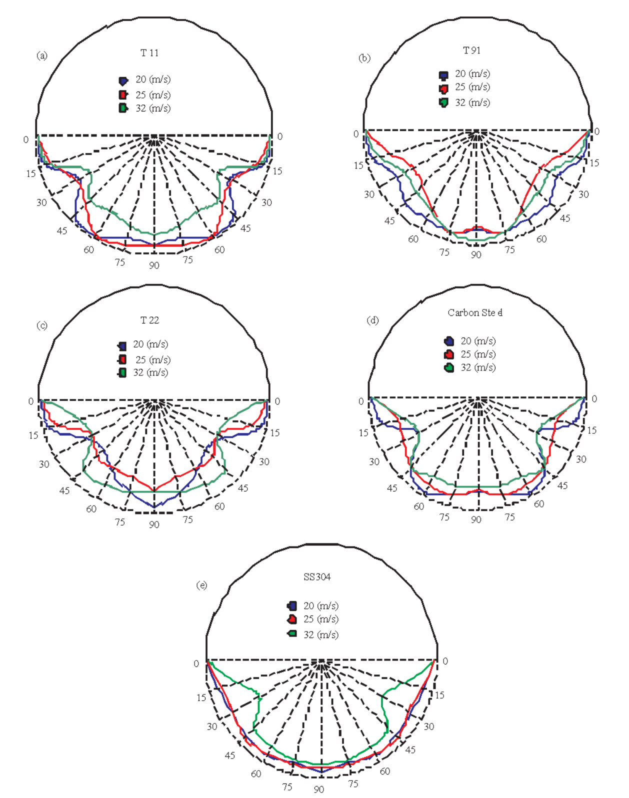

FIG. 10. COMPARISION OF ROUGHNESS PROFILE AROUND THE CIRCUMFERENCE OF THE TUBES

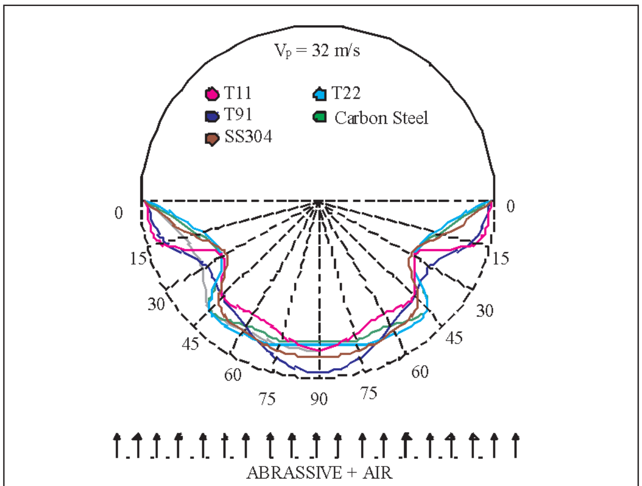

FIG. 11. COMPARATIVE ROUGHNESS PROFILE AROUND THE CIRCUMFERENCE OF DIFFERENT TUBES AT 32 m/s

SS304 steel tube provide the oxidation resistance and the reduction in yield strength properties at 400 °C much low viz. 9.84 % against 26.52 % in the case of carbon steel [18]. The combination of lower yield strength properties of the CS at 400 °C would give rise to more cutting and ploughing action of the particles, especially at 30° impact angle. The change in erosion loss was observed to be minimum, with values up to 2.1 times at 400 °C. Both T11 and T91 have shown similar erosion behaviour and an increase in erosion loss up to 405 % was observed over that of room temperature values.

Among all the tubes evaluated, SS304 has shown lower sensitivity with temperature and thus considered potential candidate material for high-temperature erosion-corrosion resistance applications.

4.0 CONCLUSION

The systematic study on erosion resistance at different temperature conditions indicated the following.

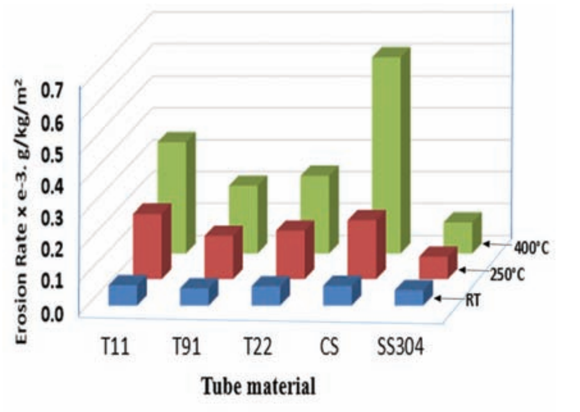

FIG. 12. COMPARATIVE EROSION RATE OF BOILER TUBES AT 32 m/s AND AT 400 °C

- The erosion resistance at room temperature of all steels has shown sensitive to particle impact velocity.
- Carbon steel boiler tube has shown a highest erosive loss at all velocities.
- At low particle velocity (20 m/s), maximum improvement in erosion resistance of SS304 is observed to be 34 % over that of Carbon Steel.
- The erosion resistance characteristics of low alloy steel boiler tubes such as T11, T22 & T91 is observed to be same at all three velocities.
- The test temperature has got a significant effect on the erosion resistance. The tube material loss due to erosion at 250 °C & 25 m/s increases up to 2.4 times higher than that of room temperature resistance properties. The mass loss increases up to 5.6 times at 400 °C.
- Surface roughness measurement of the eroded tube has clearly indicated that the maximum roughness occurs at 30º impact angle, which is typically observed in all ductile materials.
- The change in surface roughness at normal impact angle is found to be minimum indicating that the energy is absorbed by the surface.
- The increase in surface roughness at shallow impact angles (up to 45º), appears due to the particle cutting/scratching over the tube surface leading to increased material removal.
- While the reduction in erosion loss of SS304 was only 54 % at room temperature conditions, significant reduction could be observed (up to 10.2 times lower value) at 400 ºC appears due to the combined effect of minimal changes in yield strength properties and improved corrosion resistance at elevated temperature conditions.
- The carbon steel boiler tube has shown higher sensitiveness to temperature and the material loss increases up to 10.2 times at 400 °C compared to Room Temperature erosion resistance.

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