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ANALYTICAL TOOL FOR ANALYSING SLAGGING CHARACTERISTIC OF HIGH ASH COALS IN UTILITY BOILERS

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ABSTRACT

In today's competitive market, the performance of electric utility industry is a serious concern to the nation. Majority of power plants are Coal-Fired Power plants in India. Due to the wide variation in the quality of coal being fired, it affects the performance of the power plant like furnace wall slagging, convective pass slagging (both Low and High Temperature), soot blower effectiveness, erosion and grindability. At this juncture, a reliable prediction is needed to assess the slagging problem which in turn affects the performance parameters of power plant like heat transfer rate, exit gas temperature, surface corrosion and frequency of soot blowing.

Though conventional indices and ash fusion temperature measurement techniques do not aid in predicting slagging condition with field performance hence, it is reported to be highly subjective in nature and poor accuracy.

In this work an alternative approach is made based on shrinkage measurement up to 1400 °C of coal ash prepared at 800 °C. Sensitive shrinkage measurements indicate temperatures of rapid change which correspond to the formation of liquid phases.

A preliminary evaluation of shrinkage data for coal ash collected at different power stations firing wide variety of coal indicates that, the shrinkage profiles of the ashes are differing widely and rate of shrinkage measurement can provide an alternative approach to characterize/assess the slagging potential. Shrinkage measurement of coal ash has been carried out for the coal ashes collected at different power stations using different quality of coal.

Key words: Utility Boiler; Slagging; Prediction; Energy; Thermal; Shrinkage; TMA etc.,

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1. INTRODUCTION

A pulverized coal-fired Boiler is an industrial or utility Boiler that generates thermal energy by burning pulverized coal (Fossil Fuel) into the furnace. The basic idea behind pulverized coal firing system is to use the whole volume of the furnace for combustion. Pulverised Coal firing is a dominant technology for generating electric power in our country which contributes 60% of total installed capacity in thermal as on August 2015.Pulverised coal provides the thermal energy which produces about 50% of world's electric supply.

Pulverised fuel Boilers are principally a combustion chamber enclosed by vertical wall tubes. Pulverised coal enters into the combustion chamber through the burners, combusts and heat the water in the vertical tubes. Steam produced from heating the water produce electricity through turbo-generator sets. The mineral matter in coal is converted into ash during combustion. (A coal particle entering the combustion chamber will be subjected to a temperature of 1500° C). Ash, a by-product of combustion either accumulates onto the Boiler tubes as "Slag" or is collected by Electrostatic Precipitators, attached to the backend of the Boiler.

On entering the Boiler, mineral matter in coal undergoes high complex mineral transformation to produce ash of varying elemental compositions, morphological features (size and shape) and physical characteristics (viscosity and density).Flue gas a by-product of combustion carries ash particles (fly ash) to the dust collecting facility at the Boiler end. Ash thus formed from combustion creates severe problems like slagging, fouling, erosion, particulate emissions etc., Slagging is a complex phenomenon seen in radiative heat transfer section in boiler. The mechanism of the growth of the ash deposits on the surface of the tube is mainly because of molten condition of the ash particles in the flue gas stream. When the particle approach the tube initial layer formed by the condensation of low melting minerals, therefore it acts as a glue to capture other particles arriving in partially molten state deposit over the initial layer and provides a sticky surface for other particles leads to sintering. As the deposit grows further and temperature becomes high the proportion of the liquid increases which cause to collapse later.

2. PRELIMINARY ANALYSIS

All individual coal samples used in this work were characterized with proximate, ultimate chemical composition of ash and calorific value analysis. The analysis were done as per standard ASTM standards and summarized in Table(s) 1, 2 and 3

Table 1 Proximate analysis are done for different coal samples

Coal	Moisture	Volatile matter	Ash	Fixed Carbon	Sulphur	Gross Calorific value
A	3.70	20.40	52.40	23.50	0.44	3026
B	10.80	43.90	4.60	40.70	0.34	5760
C	7.30	26.20	34.60	31.90	0.46	4058
D	10.06	22.75	43.19	24.00	0	3337
E	9.74	33.85	19.75	36.70	0.60	5069
F	25.0	37.17	2.50	35.30	0.30	4961

Table 2 Ultimate analysis are done for different coal samples

Coal	C	H	N	S
	% by Weight			
A	32.12	2.04	0.98	0.44
B	62.23	3.69	1.04	0.34
C	41.76	2.74	1.01	0.46
D	35.82	1.68	0.69	1.09
E	54.81	3.18	1.22	0.58
F	51.32	4.02	1.09	0.27

Table 3 Chemical composition of coal ashes for different coal samples

Coal	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Cao	MgO	Na_2O	K_2O	P_2O_5	SO_3
	% by Weight									
A	64.80	26.10	4.30	1.60	0.60	0.50	0.60	1.20	0.20	0.10
B	36.20	19.20	18.60	1.20	10.70	3.20	0.80	0.90	0.30	8.90
C	63.40	26.20	5.90	1.70	1.20	0.60	0.10	0.70	0.10	0.10
D	65.25	20.30	8.23	1.13	1.70	1.19	0.15	1.58	0.27	0.20
E	61.60	20.80	7.20	1.40	3.40	2.60	0.40	1.10	0.20	1.30
F	35.60	16.42	18.89	1.04	15.70	7.97	0.03	0.95	0.15	3.27

3. EMPIRICAL RATIO TO ASSESS SLAGGING

The conventional predictive slagging indices namely Base to acid ratio, Slagging factor R_s, Iron oxide to calcium oxide ratio, Silica to alumina ratio, Sodium content of coal ash, Sodium to potassium ratio and Iron oxide are done for the coal ash samples and are shown in Table 4. The low, medium and high slagging stands for the prediction of coal behavior w.r.t slagging in the Boiler during the combustion. Low slagging means there is non-problematic combustion and the deposition does not affect the heat transfer and cleaning up is not necessary. High slagging refers to formation of thick layer ash deposit on the Boiler heat transfer section which will retard the heart transfer in boiler tubes.

Table 4 Slagging performance prediction based on conventional indices

Conventional Indices C.I	A	D.S	B	D.S	C	D.S	D	D.S	E	D.S	F	D.S
Base/Acid ratio	0.08	L.S	0.60	H.S	0.09	L.S	0.15	L.S	0.18	L.S	0.82	L.S
Slagging Rs index	0.03	L.S	0.21	L.S	0.04	L.S	0.07	L.S	0.26	L.S	2.79	S.S
Iron/Calcium Ratio	7.17	H.S	1.74	H.S	4.91	H.S	4.84	H.S	2.12	H.S	1.20	H.S
Silica Aluminum Ratio	2.48	M.S	1.88	M.S	2.42	M.S	3.21	H.S	2.96	H.S	2.17	H.S
Sodium Oxide	0.60	L.S	0.80	L.S	0.10	L.S	0.15	L.S	0.40	L.S	0.03	L.S
Sodium and Potassium oxide	1.80	L.S	1.70	L.S	0.80	L.S	1.73	L.S	1.50	L.S	0.98	L.S
Iron oxide	4.30	L.S	18.60	M.S	5.90	L.S	8.23	L.S	7.20	L.S	18.89	M.S

C.I Conventional indices, L.S low slagging, M.S medium slagging, H.S high slagging and S.S Severe slagging, D.S Degree of Slagging

3.1. Base to Acid Ratio (B/A)

The base-to acid ratio is the ratio of total base to total acid components in the coal ash. Since it is a ratio, its lower limit can approach but never be zero and its upper limit approach to infinity. It is generally used only in the range of 0.1 to 1. The base-to acid ratio has been empirically correlated with ash melting, viscosity properties and other problems.

$$(B/A) = Fe_2O_3+CaO+MgO+Na_2O+K_2O/SiO_2+Al_2O_3+TiO_2 \quad (1)$$

3.2. Slagging Factor R_s

The B/A ratio provides an indication of the melting point and viscosity of the slag while % Sulphur gives an indication of the quantity of pyritic iron present which influences the state of oxidation of the iron in the slag and thus its plastic range. The overall R_S parameter has no theoretical basis, however it develops report that it gives a reasonable correlation with the slagging problems, particularly for dry bottom furnaces.

$$R_s = B/A \text{ x Sulphur \% in dry coal} \quad (2)$$

3.3. Iron Oxide to Calcium Oxide Ratio

The iron oxide to calcium oxide ratio is the ratio of iron present in the ash calculated as Fe2O3 divided by the percentage of calcium calculated as CaO. This parameter is used as an indicator of furnace slagging in dry bottom furnaces.

$$= Fe_2O_3 / CaO \quad (3)$$

3.4. Silica to Alumina Ratio

The Silica-to-Alumina ratio is the %SiO_2 in the ash divided by % Al_2O_3 in the Ash.

$$= SiO_2 / Al_2O_3 \quad (4)$$

3.5. Sodium Content of Coal Ash

Sodium oxide contributes to corrosion and slagging and is one of the parameter used to judge the slagging potential problem. Some forms of sodium in coal are vaporized in the flame and condense out on heating surfaces of the furnace producing alkali-matrix deposits. Since the quantity of sodium that can be vaporized per unit of coal burned is a function of the total ash content and of the form in which the sodium is present, additional information on the coal source is needed for proper interpretation of results.

3.6. Sodium to Potassium Ratio

The sodium-to-potassium ratio is the molar ratio of Na_2O to K_2O in the coal. It is most useful when determined on actual convection section deposits.

$$= Na_2O / K_2O \quad (5)$$

3.7. Iron Oxide

The presence of high iron oxide content in coal ash leads to slagging in radiative heat transfer section in boiler.

4. INFLUENCE OF CALORIFIC VALUE BY ASH AND MOISTURE CONTENTS IN COAL

Figure 1 shows that, if we have a certain correlation among ash content, moisture and calorific value then it is easy to relate coal quality with slagging propensity index. The calorific value has a linear dependence on the ash content in coal. However the results matches with medium moisture samples, but the error was big in case of smaller moisture and bigger than medium moisture coals samples. According to this situation, we have to consider moisture data for determination of slagging propensities.

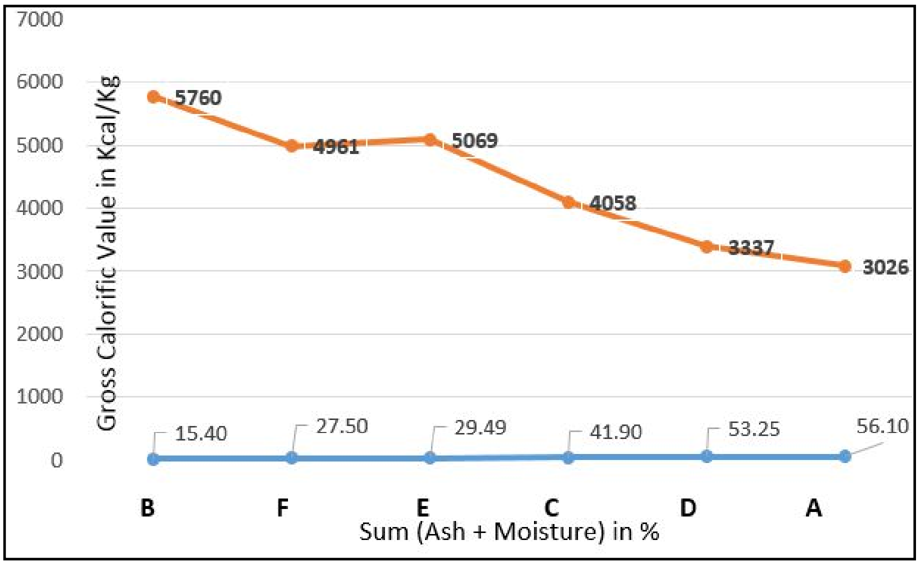

Figure 1 Correlation between Gross Calorific Value and Sum of Ash and Moisture contents in coal samples

5. ASH FUSION TEST (AFT) STUDIES

Ash fusion temperatures are determined in order to provide an indication of how the mineral matter in coal may behave in the furnace. The standard AFT was carried out to determine the initial deformation temperature, softening temperature, hemispherical temperature and fluid temperature and the ash fusibility temperatures are shown in Table 5.

Table 5 Ash fusion test studies for the coal ash samples

Parameters	Unit	A	B	C	D	E	F
Initial Deformation Temp.	Deg. C	1450	1220	1450	1340	1264	1229
Softening Temp.	Deg. C	1450	1275	1450	1445	1316	1242
Hemispherical Temp.	Deg. C	1450	1283	1450	1450	1385	1251
Fluid Temp.	Deg. C	1450	1301	1450	1450	1435	1281

5.1. Initial Deformation Temperature

Initial deformation temperature is the temperature at which a prepared standard cone of ash just begins to fuse or show evidence of deformation at the top of the cone as it is being to heated in a standard test furnace. This would correspond to the temperature in the operating furnace at which the particles of the coal ash, in transit through the furnace, have been cooled to a point where they still retain a slight tendency to stick together or slowly to build upon heat-adsorption surfaces. When the temperatures in an operating furnace are such that the ash particles have cooled to a temperature lower than their initial deformation temperature, they tend to accumulate as a "dry" product.

5.2. Softening Temperature

The softening temperature corresponds to an observed condition between initial deformation and fluidity. Softening temperature is the temperature at which the test under observation has deformed to a spherical form where height is equal to width.

5.3. Hemispherical Temperature

The hemispherical temperature is read when the cone has further deformed to the point where it assumes a hemispherical shape and its height equals one half of its width. Both softening and Hemispherical temperature are related to appoint at which the fuel shows a greatly accelerated tendency to mass together and stick in large quantities to heat-absorbing surfaces.

5.4. Fluid Temperature

The fluid temperature is the temperature at which the test cones flattens out to a pancake shape on the plaque. The fluid temperature is related to the temperature at which the coal ash may be expected to flow ion streams or drip from heat-absorption surfaces or the temperature at which heavy clinker forms on the grates under a fuel bed.

6. THERMOMECHANICAL ANALYSIS (TMA) STUDIES

TMA is used to determine the linear thermal expansion of the coal-ash as a function of temperature. A small constant load acts on the coal specimen which is used to measure the expansion and thereby co-efficient of linear thermal expansion is determined. The first heating phase yields information about the actual state of the coal-ash, including its thermal and mechanical history. When the thermoplastics soften, stress may relax as a result of which post crystallization and recrystallization processes may occur. On the other hand, specimen with deform for the load applied.

6.1. Experimental Studies

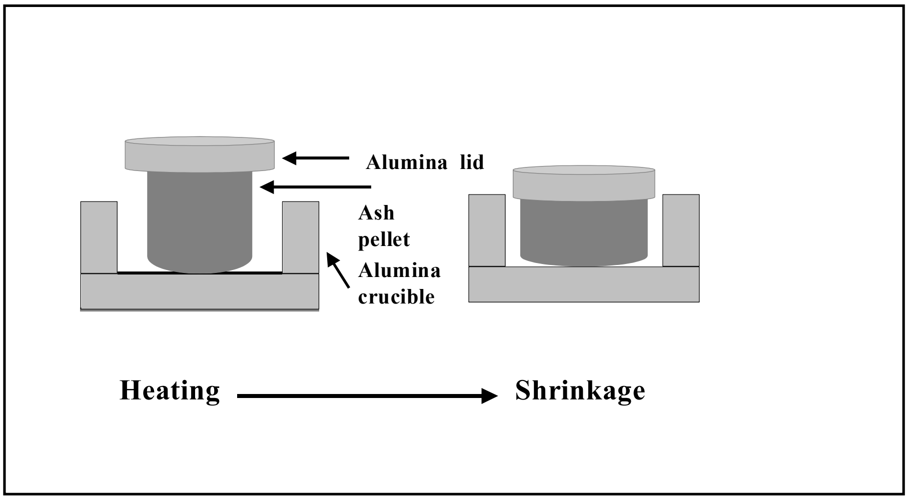

Figure 2 Description of TMA test

Thermo-mechanical analysis measures linear or volumetric changes in the dimensions of the sample as a function of time, temperature and force in a controlled atmosphere. Thermo mechanical analyzer of SETRAM make Model Setsys-18 with resolution of 0.004micron is used. The representative raw coal sample was crushed and fine grounded in a mini pulveriser to pass through 200 mesh (75 microns) similar to the pulverized coal. The –-200 mesh coal sample was heated in a furnace at 900°C to completely burnout the combustible matter. About 500 mg of the residual ash is mixed with 2 drops of 10% dextrin solution and pressed into pellet of the size (7mm x 5 mm dia) in a specially designed pelletizer by applying constant pressure. The ash pellet is dried in an oven at 100°C and the height of the pellet is measured to an accuracy of 0.01 mm. The ash pellet is placed in an alumina crucible of 6.8 mm dia and a suitable alumina disc (cover) is placed over the top of the pellet as shown in the Fig. 2

The whole sample assembly is placed between the push rod and the sample holder in the TMA instrument and inserted into the furnace. Adjustments are done in such a way that the push rod just rests on the alumina cover and 10g load is applied on the push rod and the displacement of the push rod is targeted to "zero". The actual length of the ash pellet is fed into the computer as input.

The furnace is heated at the rate of 10°C per minute from room temperature to 1400°C in nitrogen atmosphere. The ash pellet undergoes dimensional changes as it is heated. The displacement of the push rod, i.e, shrinkage pattern, time and temperature are recorded continuously. At the end of the run, the absolute shrinkage%, as well as the rate of shrinkage %/min are plotted against temperature. Under the standard experimental conditions, the repeatability has been found to be good, with peaks in derivative curves being reproducible to within about 5°C. Whenever there was a steep drop in the 2nd stage shrinkage at temperatures ≤ 1200°C the heating of crucible was limited to 1300° C in order to protect the alumina push rod from being fused with the ash melt.

6.2. Shrinkage Curves based on TMA

The review of shrinkage curves of all coal ashes shows that different stages of shrinkage pattern have been occurring, when the ash pellet is subjected to heating from ambient to 1400 oC. The first stage of shrinkage of less than 2 to 3 % is observed for all the coal ashes around the temperature range of 800oC to 1000oC. The second stage of shrinkage of 5 to 40% range appears to be a prominent phase observed in almost all coal ashes within the short temperature range of 1150 oC to 1350 oC. The different stages of shrinkage, representing the various events are clearly exhibited by the peaks on the differential curve (rate of shrinkage). The temperatures with respect to specific amount of shrinkage can be derived from TMA curve. The initial stage of shrinkage or the first derivative peak occurs at temperatures less than 1000 oC in all the samples, which may probably be primarily due to particle deformation rounding of corners and secondarily due to sintering. As the temperature increases, more particles become fully molten depending on the mineral phase changes and the proportion of liquid formation increases significantly exhibiting the steep rise in the rate of shrinkage as shown by the second peak.

It is important to note that all the conventional slagging indices namely percentage iron oxide, base to acid ratio, slagging index based on AFT, silica ratio and viscosity are ultimately linked to liquid formation tendencies of the ash. It is well established that the buildup of ash deposit on waterwalls is dependent on the ash particle remaining partially in the liquid stage on arrival at the tube surface. Analysing the shrinkage curves of TMA analysis, the 2nd peak is significant since it captures major portion of shrinkage occurring due to liquid formation in ash. Though the maximum rate of shrinkage is observed to be different for different coal ashes and the temperature at which the peak rate of shrinkage is also observed to be varying between coal ashes. In order to rationalize the above two characteristic data namely, peak shrinkage rate and temperature corresponding to the peak rate are normalized by dividing the rate by temperature to arrive at relative shrinkage rate for all the coal ashes. In spite of having higher relative shrinkage rate of the ash, the quantum of ash or concentration of ash particle in the furnace also matters. If it is less for corresponding coal the overall effect of slagging in the furnace dynamic condition may not be significant. On the other hand if both the relative shrinkage rate and quantum of ash are high then, there will be a pronounced synergistic effect on slag formation.

6.3. Formulation of New Slagging Index

In order rationalize different peak shrinkage rate (Rm) and the temperature corresponding to the peak rate (Tm) for different coal ashes, the same is been normalized by dividing the Shrinkage rate by temperature to arrive a relative shrinkage rate. It is worthwhile to consider the concentration of the ash particles or the ash content in coal because the overall effect of the slagging depends upon the percentage of ash in the coal.

Based on the above new Slagging Index,

$$SI_{New} = \left[\frac{R_m}{T_m}\right] \times \left[\frac{Ash}{GCV}\right] \times 10^7 \quad (6)$$

R_m - Maximum rate of shrinkage for the second peak

T_m - Temperature corresponding to Rm

R_m/T_m - Relative shrinkage rate

Ash - Ash in percentage

GCV - Calorific value of coal in Kcal/Kg

Based on the above slagging index by TMA for the coal ash samples, Table 6 shows the slagging performance prediction with power plant performance.

Table 6 Slagging prediction based on TMA and validation with power plant performance

Coal	Relative Shrinkage Rate (R_m/T_m) 10^{-5}	Ash per million Kcal g x 10^3	New Slagging Index SI_{New} (6)	Power plant Performance
A	48.60	173.16	84.11	Slagging
B	641.40	7.98	51.22	No Slagging
C	51.20	85.26	43.64	No Slagging
D	82.30	129.42	106.49	Slagging
E	280.10	38.96	109.13	Slagging
F	275.60	5.04	13.89	No Slagging

7. RESULTS AND DISCUSSIONS

There is positive correlation between the new slag index and actual observation made in a few higher capacity boilers. The field data indicated slagging tendency for coals having slag index more than 80. The data also reveals that if either of the parameters ie, relative shrinkage rate or ash in g per million kcal alone is very low comparatively for a particular coal then that coal is not likely to exhibit slagging eg coal-C. It is very clear that slagging in boiler furnaces depends on the combined effect of the liquid forming tendency of the ash, temperatures experienced in furnaces and ash loading. It is also evident from the Table-4 that the indices derived from chemical composition do not reliably correlate with the power plant performance. Slagging index based on ash fusion temperatures, which was carried out for coal ashes also do not reliably reflect the power plant thermal observation with respect to slagging.

The proposed new index takes into account both the liquid forming tendency of the ash ie, the relative shrinkage data from TMA of the ash as well as ash loading ie, weight of ash per million kcal derived from proximate and calorific value. The conventional slagging indices that are derived from Ash fusion temperatures and chemical compositions of ash do not take into account the ash loading of high ash coals and hence conventional indices are not reliably correlating with actual performance. The new slagging index provides a better tool for assessing boiler slagging than the conventional indices derived from chemical composition of ash and ash fusion temperatures.

It is well known fact that the slagging phenomena in boilers not only depends on coal quality but also the boiler design such as volumetric heat loading and operational regimes like excess air, fineness of coal particles etc. However, for a given boiler, the boiler-operating regime cannot be adjusted beyond certain range to alleviate slagging without compromising on combustion efficiency if the coal exhibits very high slagging index. For a given new coal, proper sizing of boiler furnace can be done, based on the comparison of new slagging index of the coal against a reference coal for which the correlation between slagging index and power plant performance is well understood.

7.1. Coal-Ash A, D and E

The relative shrinkage rate of ash and ash content in coals are varying between moderate to high and hence due to the combined effect of the liquid forming tendency and high ash loading, the effect on slagging is high and same matches with power plant performance.

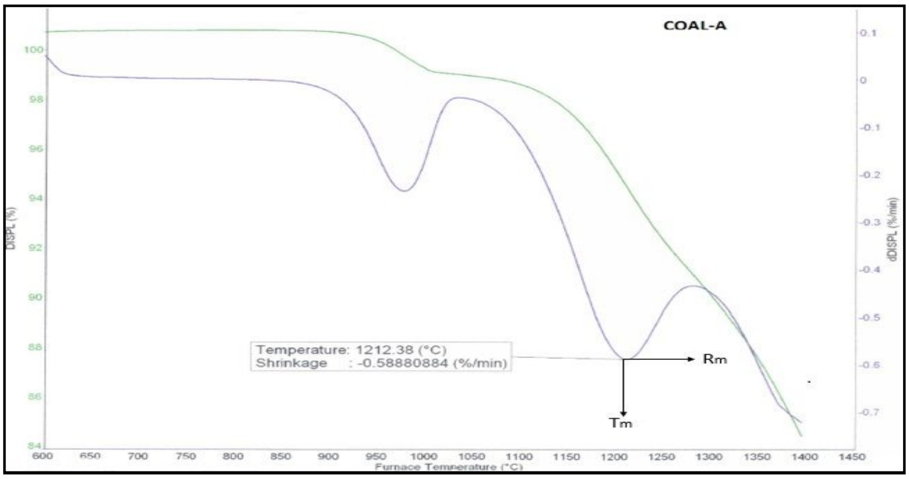

Figure 3 Shrinkage % and rate of shrinkage%/min of coal-ash A

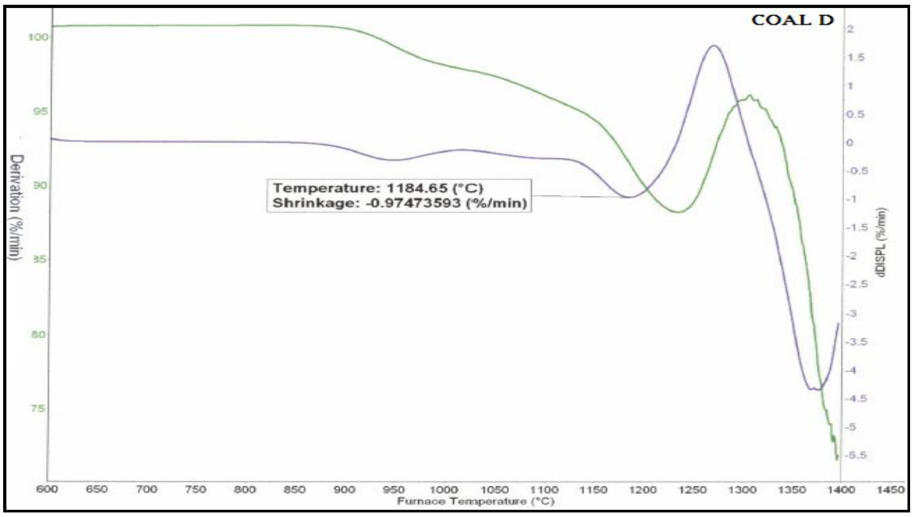

Figure 4 Shrinkage % and rate of shrinkage%/min of coal-ash D

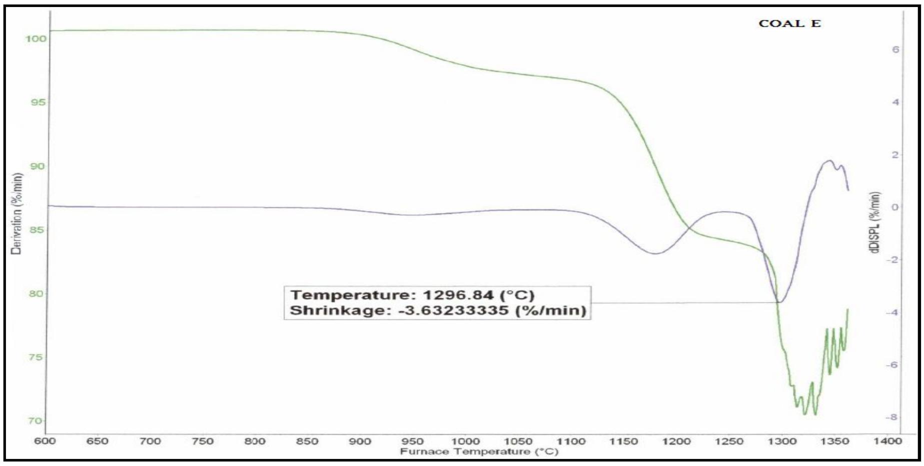

Figure 5 Shrinkage % and rate of shrinkage%/min of coal-ash E

7.2. Coal-Ash B and F

High Iron oxide content of the ash shows high slagging nature as per the conventional indices. Though the relative shrinkage rate of coal ashes is high, the ash content in is low and hence it is less propensity towards slagging.

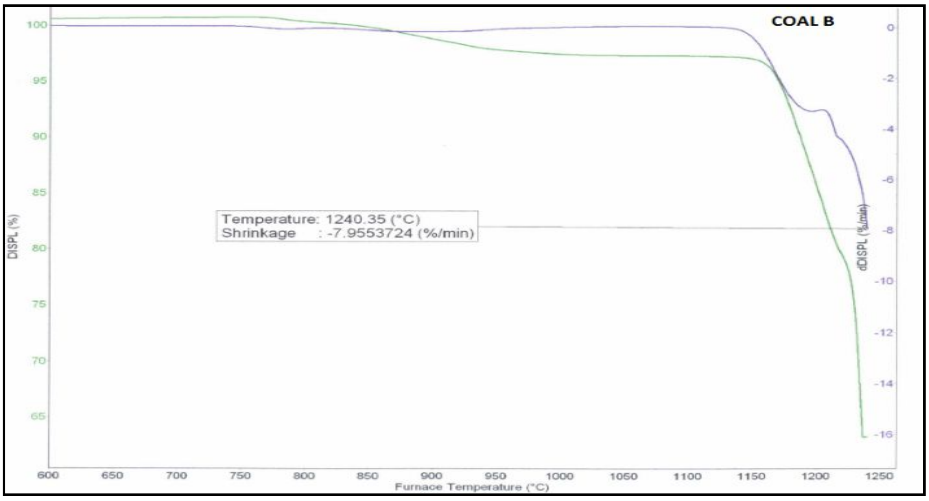

Figure 6 Shrinkage % and rate of shrinkage%/min of coal-ash B

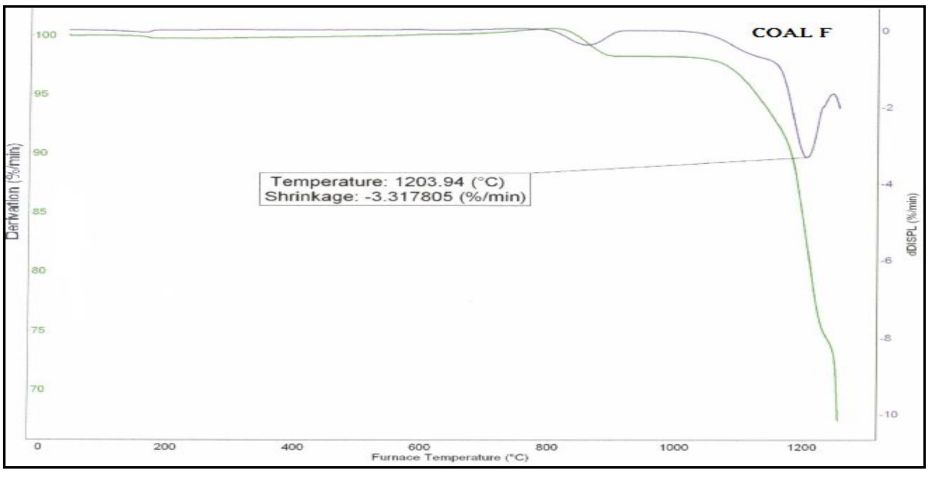

Figure 7 Shrinkage % and rate of shrinkage%/min of coal-ash F

7.3. Coal-Ash C

The relative shrinkage rate of ash and ash loading in the furnace is moderate, hence there is less effect on slag formation and same matches with power plant performance.

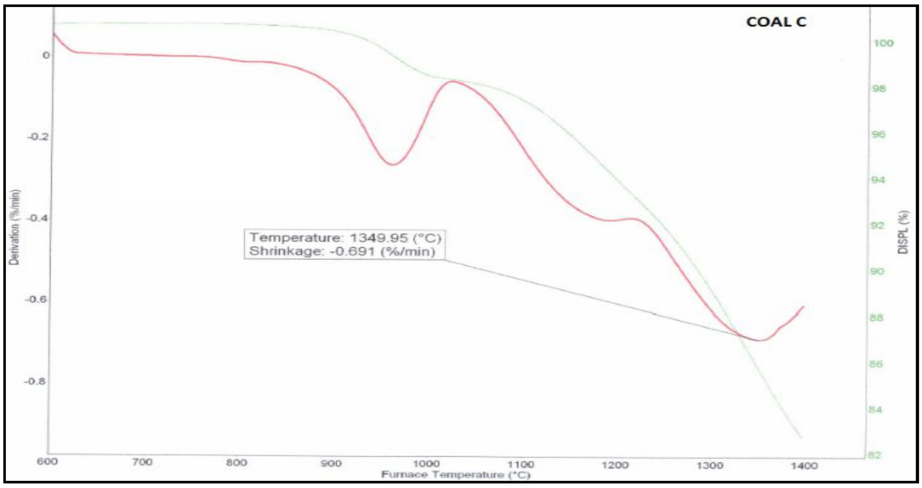

Figure 8 Shrinkage % and rate of shrinkage%/min of coal-ash C

8. CONCLUSION

1. The development of new methodology of calculating slagging index based on maximum shrinkage rates measured in a Thermo-Mechanical Analyser (TMA) offers a reliable correlation with the reported slagging intensities in the power plant.
2. The new index based on TMA is found to be a better predictive tool for assessing boiler slagging than conventional indices derived from chemical composition of ash and ash fusion temperatures.
3. The work described in this paper though with the limited data, has provided a foundation for a comprehensive coal quality research program for characterization towards better slagging potential prediction.

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