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Fouling Intensity of Three Indian Coals

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ABSTRACT

Ash particles can arrive at heat-transfer surfaces either in solid (solidified) state or in molten state, depending on the factors such as location inside the boiler, temperature, and residence time. In this study, arrival of ash particles in solid state, which can occur in the convective section of the boiler, was considered. Apart from the inertial force that drives particles $>10\ \mu\text{m}$ to the surface, the low-melting inorganic alkali vapors play a vital role in deposit formation by promoting sticking. Chemical equilibrium calculations were performed to calculate the equilibrium composition of flue gas, as well as the amount of condensable inorganic alkali vapors at any particular temperature. Condensed alkali liquids act as “glue” in holding together impacting fly ash particles. Eutectic formation between alkali salts was considered to accurately predict the condensation onset temperature. Using the glue volume fraction obtained as a function of temperature, we adopted a self-regulated deposit growth model to predict deposit growth rate. The uniqueness of the model is that it simultaneously incorporates sticking and particle-particle erosion, where both are dependent on available liquid fraction, to predict fouling intensity. The deposit growth rate of three Indian coals was simulated and compared with coal having lower ash content.

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1. Introduction

Coal-fired thermal power plants address 70% of electricity needs and 60% of commercial energy needs in India (Mishra, 2004; Chikkathur et al., 2009). Coal is a major fossil fuel that will continue to play a vital role in the Indian energy sector. India has 253 Gt of coal reserves, and out of these reserves, 89% are non-coking coal having an inorganic noncombustible content, ash, from 40% to 45% by weight (Mishra, 2004; Biswal et al., 2005). These inorganic components undergo physical and chemical transformations during coal combustion and are converted into fly ash and bottom ash (Damle et al., 1982; Benson et al., 1995). Fly ash particles rise with the flue gas and collide with the heat-transfer surfaces. During impact, some of the ash particles stick to the surfaces and others bounce off. Deposition of ash particles

results in reduced heat transfer (Rosner and Nagarajan, 1987; Nagarajan and Anderson, 1988; Ross et al., 1988; Richards et al., 1993; Erickson et al., 1995; Wang and Harb, 1997), interferes with the aerodynamic flow of flue gas, diminishes the flow area (Smith et al., 1985), and causes corrosion and erosion of boiler tubes (Wang and Harb, 1997), thereby affecting the normal functioning of the boiler.

In the present study, with the objective of predicting the fouling intensity of Indian coals, ash particles arriving in solid state are considered. Hence, hereafter, ash deposition refers to ash particles arriving in solid state, unless otherwise specified. Deposition of ash has been studied for many years due to its direct impact on electricity generation. Due to complexity of and variations in deposition mechanisms, prediction of ash deposition requires a thorough knowledge of ash chemistry, transport phenomena, and deposit properties (Erickson et al., 1995) and thus provides the motivation of the present pioneering study on fouling tendency of Indian coals, even though similar studies have been undertaken for foreign coals

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(e.g., Rosner and Nagarajan, 1987; Nagarajan and Anderson, 1988; Walsh et al., 1992; Richards et al., 1993; Erickson et al., 1995).

Primary mechanisms involved in the transport and deposition of ash particles onto a surface include inertial transportation and impaction, thermophoresis, condensation, and chemical reaction (Baxter and DeSollar, 1993). Inertial impaction is significant for particles $>10 \mu\text{m}$ in diameter (Adamczyk et al., 1983), whereas thermophoretic transportation is dominant for submicrometer-sized particles (Byers and Calvert, 1969). Studies have concluded that for Indian fly ash particles, the average mean diameter varies from 19 to 260 μm (Sarkar et al., 2005). Large ash particles in solid state are affected less by the thermophoretic force; therefore, thermophoretically transported ash particles are few in number and may be considered negligible.

During combustion, alkali salts present in ash are vaporized and carried away along with flue gas. When the mixture of gases (flue gas + alkali salt vapors) comes into contact with the cooled heat-transfer surfaces, the condensable alkali salts condense. These molten alkali salts, referred to as "glue," condense at surface temperatures above the freezing point of alkali salts but below the dew point temperature (Rosner and Nagarajan, 1987), acting as a glue in bonding particles together. Based on experimental results and theoretical understanding, the dependence of sticking coefficient and erosion coefficient on the glue volume fraction was investigated (Rosner and Nagarajan, 1987; Nagarajan and Anderson, 1988; Ross et al., 1988).

The amount of liquids present on the surface at any given temperature has a significant effect on sticking of ash. Hence, the complex interplay of condensable liquids in holding the particles together plays a key role in fouling deposition. One way to quantify the amount of condensable liquids of selected ash species is by performing chemical equilibrium calculations. This method is well established, frequently adopted for complex systems, and has been proven to be effective in modeling complex processes inside the boiler (Smith et al., 1985; Nagarajan and Anderson, 1988; Harb et al., 1993). Chemical reaction is considered to be a negligible contributor, because reaction between alkali salts and silica occurs at temperatures $>1800 \text{ K}$ (Nagarajan and Anderson, 1988).

In this study, inertial force was considered to be predominant in transporting ash particles to the surfaces, and the presence of liquids, condensed from the flue gas, was considered the main factor in holding the impacting particles together. To quantify the amount of condensable alkali liquids, chemical equilibrium calculations were performed, and eutectic formation information was incorporated to accurately predict the condensation onset temperature. Furthermore, the self-regulated deposit growth model was adopted to simulate deposit growth for three Indian coals of varying ash and carbon contents.

2. Chemical Equilibrium Model

The objective of the equilibrium calculation is to minimize the Gibbs free energy of the system (Smith et al., 2005). Applying material balance for the k th element in species i :

$$\sum_i n_i e_{ik} = E_k \quad (1)$$

Total number of atomic masses (E_k) of element k present in the mixture is equal to the summation of product of moles (n_i) of chemical species i and number of atoms of the k th element (e_{ik}) present in the chemical species i . The k varies from 1 to S , where S is the total number of elements present in the mixture.

With the aim of minimizing the Gibbs free energy, and assuming ideal gas, the LaGrangian function for gaseous species can be written as follows:

$$\mu_i^0 + RT \ln \left(\frac{n_i}{\sum_i n_i} \right) + \sum_k \beta_k e_{ik} = 0 \quad (2)$$

For condensable pure species, Eq. 2 reduces to

$$\mu_i^0 + \sum_k \beta_k e_{ik} = 0 \quad (3)$$

where μ_i^0 is the chemical potential at standard conditions, R is universal gas constant, T is the prevailing temperature, and $\beta_k e_{ik}$ is the LaGrangian multiplier. Eq. 2 and 3 represent a system of N equations, where N is the total number of species present in the gas phase. S equations can be written from Eq. 1, one for each element. This system implies that totally $N + S$ equations are available and that there will be N number of n_i unknowns and S number of β_k unknowns. Total number of unknowns ($N + S$) is equal to the number of equations; hence, the system is solvable with unique and finite solutions. A computer program developed by the National Aeronautics and Space Administration, Chemical Equilibrium with Applications (CEA), was used in this study to perform the equilibrium calculations. This software uses the aforementioned equations to calculate the equilibrium compositions, and free energy values available in an associated database are taken directly for the calculations.

The CEA software has a built-in capability to include phase transition. It is assumed that the condensing phases are pure. Hence, possibilities of phase transition between solids and liquids and between two stable solid phases are accounted for in the calculations. When the temperature is assigned, it is possible to consider the phase transition and assign the phase of the species at the particular temperature. The criterion used by the software to allow phase change is that if the temperature difference between surface temperature and the phase change temperature (melting point or boiling point) is of the order of 50 K, the switch from one phase to another phase is activated. The condensable alkali salts considered in the present study were alkali sulfates, carbonates, chlorides, and hydroxides.

With the above-mentioned protocols, CEA analyses were performed for four coals whose compositions are given in Table 1. Among these coals, coal 1 (lignite), coal 2 (bituminous), and coal 3 (bituminous) are Indian coals with varying ash content, fixed carbon contents, and calorific values. Temperatures were varied from 600 to 1700 K in steps of 100 K. The reason for performing equilibrium calculations from 600 K is explained later in this section in the context of eutectoids. All coals were burnt with 20% excess O_2 . The theoretical amount of air required for complete combustion was calculated manually, and 20% excess air was taken for equilibrium calculations. Conversion of C and H_2 to carbon dioxide and water, respectively, were considered to calculate the theoretical amount of O_2 required. In thermal power plants, generally, air from the atmosphere is preheated and used for combustion. Eventually, some of the pollutants (e.g., S, Na) present in the air, unless it is purified, find their way into the combustion zone and thus actively take part in the chemical reaction during combustion. An important constituent that cannot be neglected, especially when a thermal power plant is located on the seashore, is sodium chloride (NaCl). Because of its proximity to the harbor, the seashore is a preferred location for a thermal

Table 1
Proximate analysis of select coals and their ash composition

	Coal 1 (Irdi et al., 1993)	Coal 2 (Irdi et al., 1993)	Coal 3 (Roy, 1940)	Coal 4 (Senior et al., 2000)
Proximate analysis (wt%)	Basis 100%			
Fixed carbon	35.1	34.7	56.34	61.99
Moisture	14.9	4.3	0.8	1.44
Ash	7.0	37.6	18.1	7.01
Volatile matter	Rest	Rest	Rest	Rest
Heating value (MJ/kg)	21.3	18.8	25.1	30.5
Ash composition (wt%)	Basis 100%			
Al ₂ O ₃	15.3	23.3	22.54	22.87
Lime (CaO)	14.7	1.4	2.58	1.84
Iron (III) oxide (Fe ₂ O ₃)	5.5	11.4	10.10	19.18
Potassium oxide (K ₂ O)	—	1.7	1.48	1.53
Magnesia (MgO)	3.1	0.5	2.58	0.60
Na ₂ O	0.9	0.1	0.30	0.32
SiO ₂	32.0	54.7	57.61	42.92
Titania (TiO ₂)	2.3	1.3	1.52	1.71
Sulphur oxide (SO ₃)	—	—	0.25	—
From ultimate analysis				
S	1.9	0.5	—	1.64

power plant. Because the number and size of sea salt particles in marine air varies with altitude, position, and weather (Woodcock, 1953), it is necessary to consider sea salt (mostly NaCl) along with the alkali constituents of coal to predict the formation of condensable alkali salts. The concentration of sea salt in the marine air reportedly varies from 0.01 to 10 parts per million (ppm) by weight. In this study, all coals were subjected to combustion in air ingested with 10 ppm NaCl.

Based on the equilibrium thermodynamic calculations, the condensation onset temperature of alkali salts without eutectoids is identified (Figure 1), and the first condensation of alkali salts is observed to occur at 1200 K. Smith et al. (1985) reported that formation of eutectoids in the condensing species could substantially reduce the condensation onset temperature, to as low as 1000 K. Hence, eutectic formation was incorporated in the present

Table 2
Various coals and their eutectic formation information

Coal	Salt formation by CEA	Eutectic information
1 and 2	NaCl and Na ₂ SO ₄	Eutectic point of 891 K and 0.474 mole fraction of Na ₂ SO ₄
3 and 4	Potassium chloride (KCl) and K ₂ SO ₄	Eutectic point of 900 K and 0.56 mole fraction of K ₂ SO ₄

equilibrium calculations. When equilibrium calculations are performed at temperatures as low as 600 K, almost all of the condensable alkali salts are present in solid state. Among the alkali salts in the mixture, it is necessary to determine which salts can form eutectoids. The various binary mixtures and corresponding eutectic information—temperature and composition—for each coal are shown in Table 2. The binary mixture phase diagram of these alkali salts was used to determine the eutectic temperature and composition. From the equilibrium calculations, the temperature and the corresponding composition of the two species, in either weight percent or mole percent, are known. With the help of the binary mixture phase diagram, and by knowing the temperature and composition, one can infer what fraction of the constituents will be in solid state or in liquid state. In the same way, calculations were performed at successive temperatures until the melting point of the individual species, beyond which complete liquid formation occurs, was reached. The results of the CEA calculations with and without eutectic formation are shown in Figure 1.

In any given coal, depending on the combustion conditions and the availability of species, some but not all coals condense. Importantly, not all coals yield the same condensable species. The quantity of the condensable species depends on the temperature, pressure, and availability of precursors in the flue gas and in the coal for the formation of the condensable species. The ash content in coal 2 is higher than the ash content in the other coals. Based on the ash content, the coals are ranked as coal 2 > coal 3 > coal 1 > coal 4. Formation of initial deposits, condensation of alkali salts, and ash arriving rate are to be understood, apart from ash content, to study fouling deposition.

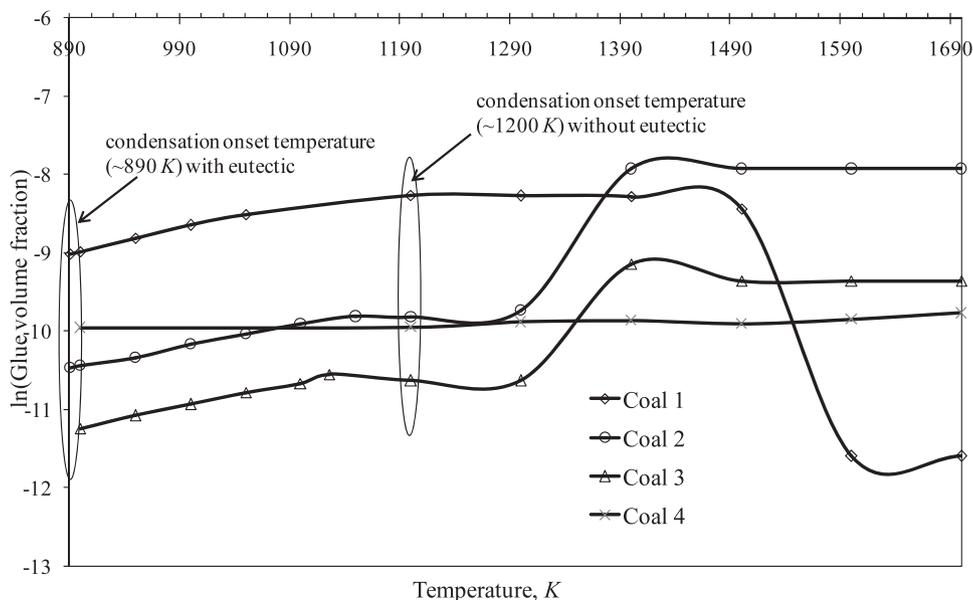


Fig. 1. Semi-log plot of predicted values of condensable alkali salts as a function of surface temperature for four selected coals.

With coal 1 having the highest Na content, the following ranking has been assigned based on Na present: coal 1 > coal 4 > coal 3 > coal 2. No potassium content is reported in coal 1; in the remaining three coals, potassium content is comparable. Therefore, the overall alkali content in coal 1 is lower than in all other coals. However, the alkali contents of the remaining three coals (coals 2–4) are comparable. The chemical equilibrium calculations indicate that carbonates [e.g., sodium carbonate (Na_2CO_3)] occur chiefly at lower temperatures (1100 K), sulfates [e.g., sodium sulfate (Na_2SO_4) and potassium sulfate (K_2SO_4)] are predominant at intermediate temperatures (1100–1200 K), and oxides [e.g., alumina (Al_2O_3) and silica (SiO_2)] are significant at the highest temperatures (>1600 K). These calculations match well with literature values (Smith et al., 1985). In addition, in all the three coals, alkali salts start condensing at 890 K, and vapor condensation continues up to 1600 K.

There is no reported potassium in coal 1; hence, there is no significant glue volume fraction observed above 1600 K. Because of the condensation of Na salts, the glue volume fraction is maintained nearly constant from 890 to 1500 K. Sodium salts start vaporizing above 1500 K, and the nonavailability of potassium makes the glue volume fraction drop beyond 1500 K. Notably, there is a significant amount of molten ash present above 1800 K, a range not included in this study. The actual amount of alkali content in coal 2 (0.007) is almost twice the amount of alkali in coal 3 (0.003). Sulfur, which is required for the formation of sulfates, is an order of magnitude higher in coal 2 (0.005) compared with coal 3 (0.0002). High alkali and S content in coal 2 leads to increased formation of alkali salts compared with that of coal 3. Sodium content in sodium oxide (Na_2O) in coal 2 (0.0003) is half the amount of Na in coal 1 (0.0007). Therefore, the amount of Na salts condensing in coal 1 is highest at lower temperatures compared with the other coals. All three coals are compared with coal 4; coal 4 has less ash content and is considered to be a clean coal in terms of fouling tendency. However, it is difficult to draw a conclusion regarding the relative fouling intensity of these coals, since the coal that shows a low glue volume fraction at the lower temperature turns out to have a high glue volume fraction in the higher temperatures (Figure 1). From Figure 1, it can be inferred that, without considering eutectoids, liquid formation starts at ~ 1200 K, whereas when considering eutectic formation, the liquid formation is predicted to begin at ~ 890 K. Also, coal 1 shows lowest glue effect above 1500 K, due to no reported potassium; nonetheless, the presence of potassium would significantly improve the amount of glue present above 1500 K. Calcium sulfate gluing effect is not considered in the present study; however, it is possible that presence of Ca can result in low-melting eutectoids; this relationship will be studied in future work. In this study, only binary mixtures of alkali salts were considered in eutectic formation. Since the liquid alkali salts present on the surface hold the impacting ash particles, the above-mentioned information's effect on the liquid fraction as a function of surface temperature is crucial to simulate deposit growth on boiler tubes.

3. Self-Regulated Deposit Growth Model

The evolution of ash deposit thickness with time is a function of sticking coefficient (s) and erosion coefficient (e) (Rosner and Nagarajan, 1987). The s and e depend on the available glue volume fraction, ash arrival rate, and the deposit surface temperature. In the convective section, due to the low temperature (~ 500 K) of heat-transfer surfaces, deposition is expected to be initiated by dry

deposition. In the absence of a liquid phase, particle adhesion occurs primarily by attractive intermolecular van der Waals forces and Coulombic forces. Thus, the dry deposition sticking coefficient (s_{dry}) rarely exceeds 0.1 (Nagarajan and Anderson, 1988). In dry deposition, the sticking coefficient is defined as the product of impaction efficiency and capture efficiency. Impaction efficiency is a function of Stokes number. Israel and Rosner (1982) developed a correlation for calculating impaction efficiency for effective Stokes number (St_{eff}) > 0.14. The effective Stokes number for impacting fly ash particles was calculated, and hence impaction and collection efficiency values were obtained (Rosner and Tandon, 1995).

The surface temperature of the deposit increases as the deposit grows. This increase in deposit surface temperature eventually causes the deposit to enter into the wet-deposition regime. Above 890 K, the formation of condensable alkali salts becomes significant. The presence of alkali liquids enhances deposit growth by acting as a glue in bonding ash particles together. Thus, the sticking coefficient of wet deposit is expected to be greater than that of the dry deposit. As the deposit surface temperature increases further, the ash particles start to deform, sinter, and flow like a liquid, and at this stage, the sticking coefficient nearly equals unity ($s_{wet} = 1$). Because of a lack of strong adhesion among the particles, as the deposit grows, the loosely packed deposited particles are dislodged by the impacting particles. Hence, the actual growth rate is a function of the difference between the sticking and erosion coefficient. The self-regulated deposit evolution model is given by the following equation (Rosner and Nagarajan, 1987):

$$\frac{d(\Delta/a)}{d\tau} = s(T_s(\Delta)) - e(T_s(\Delta)) \quad (4)$$

where τ , the dimensionless time = $m_f' t / a \rho_d$, T_s is the deposit surface temperature in kelvins, Δ is deposit thickness in meters, a is the tube diameter in meters, m_f' is the fly ash flow rate in kilograms per second, and ρ_d is the density of the deposit in kilograms per cubic meter. The relationship between sticking coefficient and erosion coefficient on the glue volume fraction is shown in Figure 2. The sticking coefficient is a function of adhesion force and directly proportional to glue volume fraction, whereas the erosion coefficient is inversely proportional (Rosner and Nagarajan, 1987; Nagarajan and Anderson, 1988) to liquid fraction.

3.1. Thermal conductivity

To predict the deposit surface temperature, thermal conductivity and porosity must be known. Robinson et al. (1998) showed that the deposit thermal conductivity (in watts per meter kelvin) in the dry regime is less than the thermal conductivity in the wet regime. In the dry deposit, the lack of interconnectedness among the particles leads to lower thermal conductivity (Kweon et al., 2003). In the wet deposit, the glue plays the role of bridging the particles; hence, thermal conductivity is a strong function of the glue volume fraction. Ross et al. (1987) proposed a model for thermal conductivity dependence on the glue volume fraction, and the same model was used in the present calculations.

3.2. Procedure for estimation of surface temperature

The heat transferred by conduction through the deposit must be equal to heat transferred by convection and radiation to the deposit

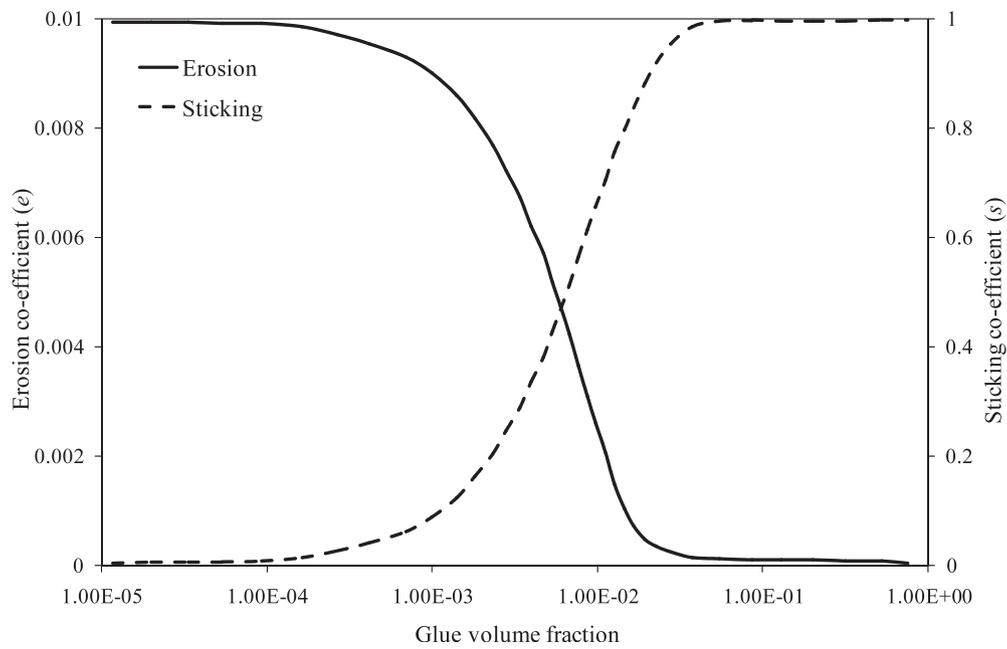


Fig. 2. Dependence of sticking coefficient on the glue volume fraction (from Rosner and Nagarajan, 1987).

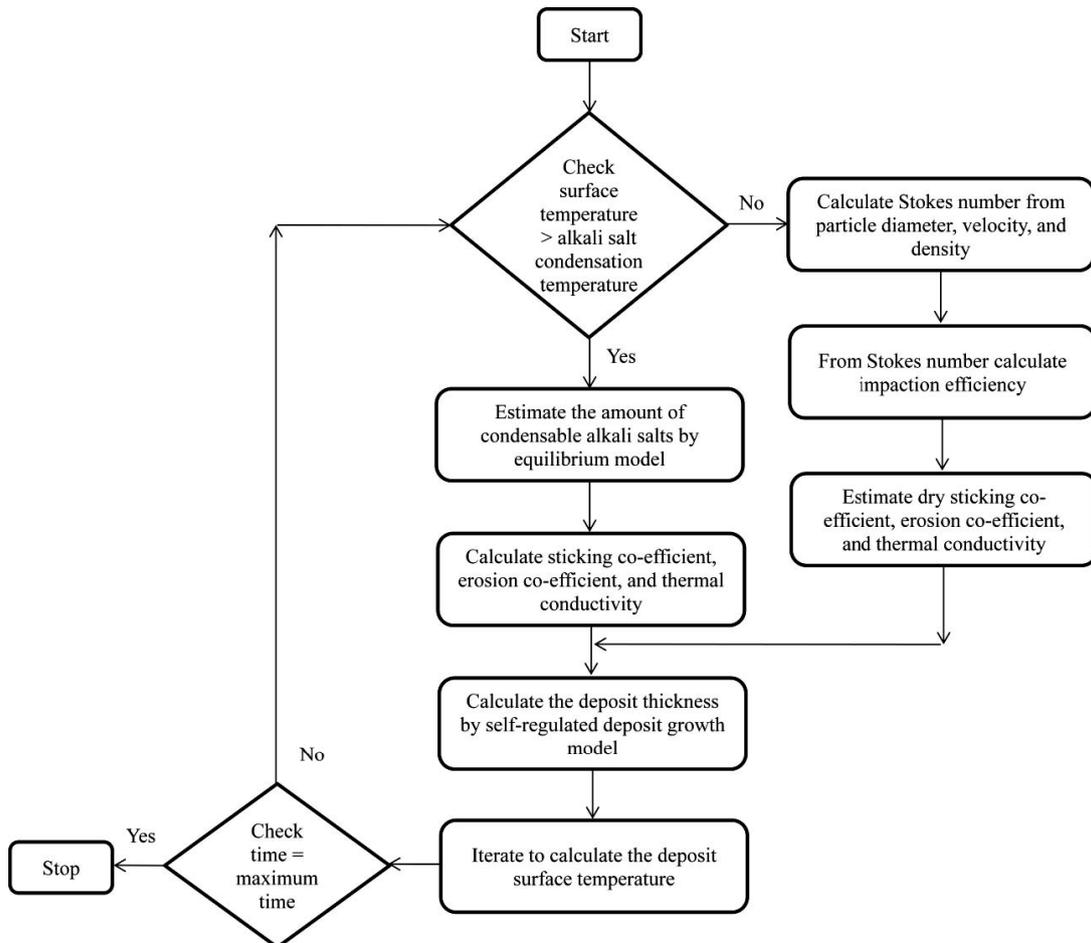


Fig. 3. Flow chart illustrating the procedure followed to simulate the growth of the fouling deposit.

Table 3
Conditions chosen for simulating deposit growth

Parameter	Value
Overall surface area (m ²)	2135
Efficiency of power plant	0.34
Tube diameter (m)	0.05
Ratio of fly ash to bottom ash	0.7:0.3
Porosity of deposit	0.4
Density of deposit (kg/m ³)	1680
Particle diameter (μm)	20
Velocity of flue gas (m/s)	10
Density of particle (kg/m ³)	2800
Thermal conductivity of dry deposit (W/m K)	0.14
Emissivity	0.75
Heat transfer coefficient (kW/m ² K)	25
Heat flux, Q_{in} (kW/m ²)	292
Flue gas temperature, T_g (K)	1600
Tube wall temperature, T_w (K)	500

surface (Richards et al., 1993). Conductive rate of heat transfer through the deposit can be written as $Q_{cond} = (T_s - T_w)/R$, where R is the resistance offered by the deposit, and it is the ratio of deposit thickness to the thermal conductivity of the deposit. The sum of convective and radiative rate of arrival of heat is given by the formula $Q_{c+r} = h(T_g - T_s) + \varepsilon(Q_{in} - \sigma T_s^4)$, where h , ε , σ , and Q_{in} are heat transfer coefficient of the tube, emissivity of the deposit, Stefan-Boltzmann constant, and incident heat flux, respectively. At any given time, $Q_{cond} = Q_{c+r}$, this constraint will give a fourth-order polynomial equation for T_s that can be solved by the Newton-Raphson technique to calculate surface temperature.

4. Deposit Growth Simulation

The procedure followed to simulate the growth of the fouling deposit is schematically represented in Figure 3. The deposit thickness of four coals as a function of time (8 hours) for a 210-MW power plant, and the parameters listed in Table 3, is shown

in Figure 4. The amount of coal required to generate 210 MW of power is calculated on the basis of the calorific value of the corresponding coal (see Table 1). Coal 2 has high ash content but the lowest calorific value. Hence, the amount of coal 2 required to generate equivalent power is higher compared with other coals. Coal 1, however, has low ash and alkali content but high moisture content, resulting in reduced calorific value. Therefore, the amount of coal 2 required to generate the same power is high, but not as high as that of coal 1. Similarly, although the ash and alkali contents are high for coal 3, this coal has a relatively high calorific value; therefore, the amount of coal 3 required is less than that of coal 1 and coal 2. The amount of coal needed to produce the required energy for coal 4 is the least compared with that of the other three coals, because of the lower ash content and high heating value.

With this information and the equilibrium glue composition, deposit thickness evolution for four coals was modeled with the constraint of equivalent power generation. Coal 2 has high ash content and shows rapid deposit growth compared with other three coals. At the end of 8 hours, deposit thickness is nearly 17 cm, indicating that when this coal is fired, the boiler will need periodic shutdown to remove the deposits. Even though coal 1 has lower alkali and less ash content, the deposit thickness associated with coal 1 is comparable to that of coal 3. Because of the high calorific value, the high ash in coal 3 is compensated by high carbon content, resulting in deposit thickness of ~5 cm (for coal 1, ~2.5 cm). In comparison, coal 4, with less ash and high carbon content, deposits ~1.5 cm at 8 hour. Owing to the constant ash arrival rate, all coals show a linear deposit growth profile. Such behavior also was been observed by Walsh et al. (1992) and Richards et al. (1993).

The temperature profiles during the deposit growth are shown in Figure 5. As explained in Section 3.2, the temperature increase follows a fourth-order polynomial equation. During deposit growth, the temperature increased from 500 K, starting at the temperature of the tube wall, to a temperature approaching the flue

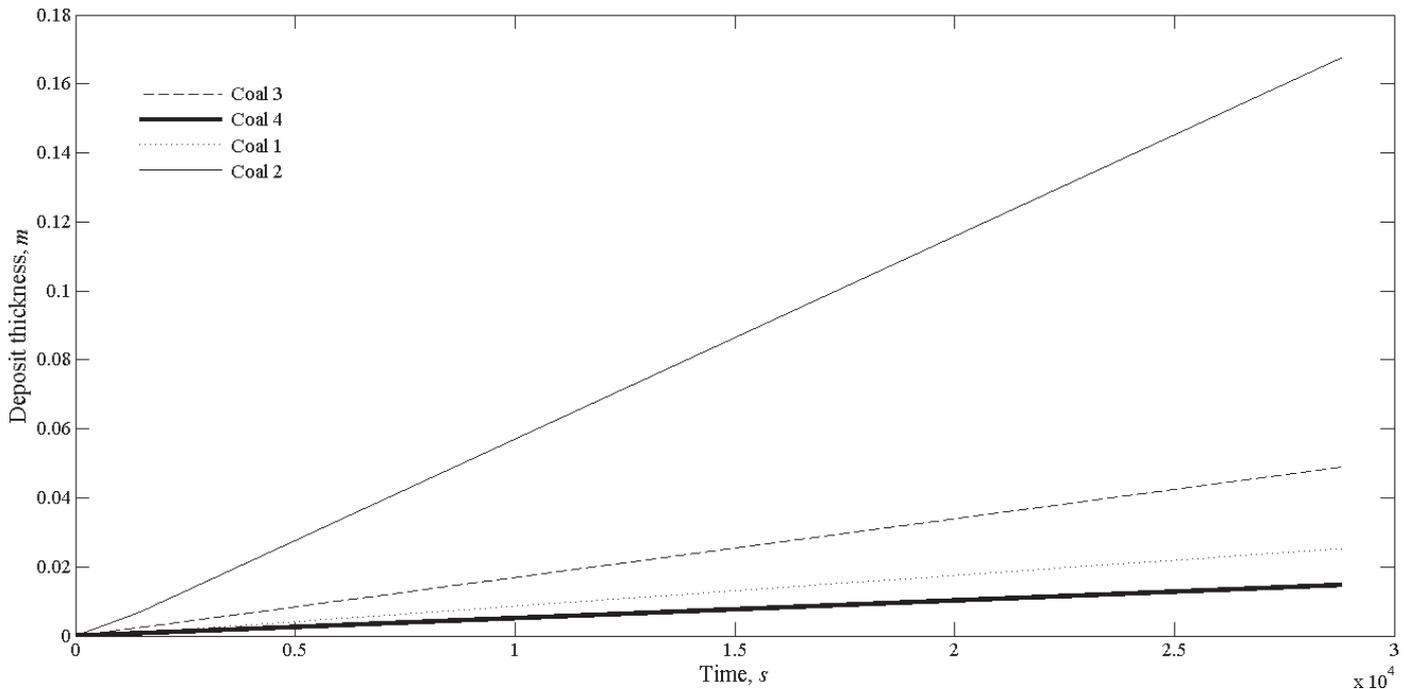


Fig. 4. Deposit thickness as a function of time (up to 8 hours) for four selected coals for a 210-MW power plant running with 34% efficiency.

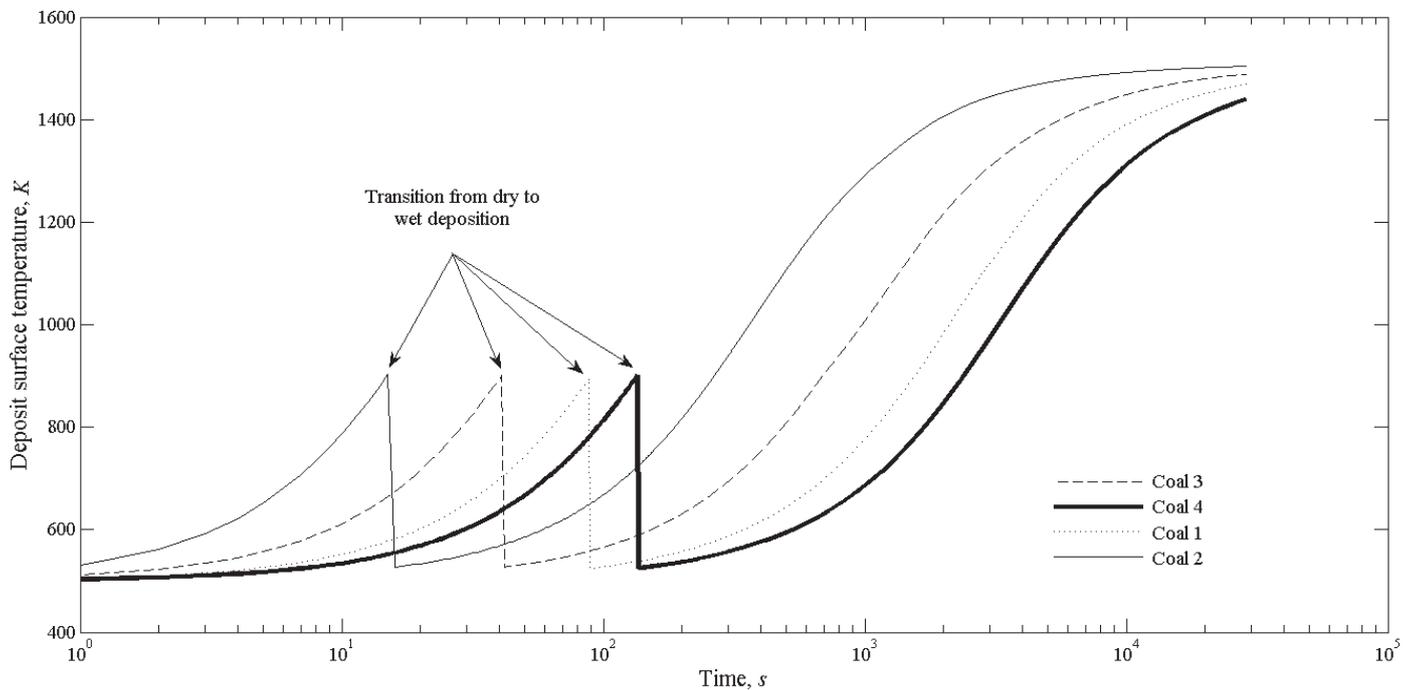


Fig. 5. Evolution of deposit surface temperature with time.

gas temperature, 1600 K. Figure 5 also shows that in the initial dry-deposition period, the temperature increase is rapid due to highly porous deposits. The loosely packed deposit offers more resistance to heat transfer and hence exhibits lower thermal conductivity. As the temperature approaches the alkali condensation threshold, the deposit surface temperature drops, followed by an increase in temperature. The mechanism of increase in temperature in wet deposition, however, is different from that in dry deposition. The drop in deposit outer surface temperature, during transition from dry to wet deposition, is attributed to the increase in interconnectedness among the fly ash particles in the presence of condensed alkali salts. The primary reason for the drop in deposit surface temperature is that the thermal conductivity of wet deposit is greater than that of dry deposit.

5. Conclusions

Three Indian coals of varying ash content were studied in comparison with one low-ash and high-carbon coal. Chemical equilibrium calculations were performed as a function of temperature to quantify the amount of condensable alkali salts. These condensable alkali salts act as glue in holding together impacting ash particles. The amount of alkali salts condensing, as estimated by equilibrium calculations, is in accordance with the amount of alkali present in the coal. Furthermore, by including the binary mixture eutectoid, the condensation onset temperature is reduced from ~ 1200 to ~ 890 K. Based on deposit growth rate, the following ranking has been assigned in terms of fouling intensity: coal 2 > coal 3 > coal 1 > coal 4. Hence, a simple simulation procedure may be applied in power plants to rank the coals and, accordingly, schedule boiler maintenance to remove the fouling deposit.

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References

- Adamczyk, Z., Dabros, T., Czarniecki, J., deVen, T.G.M.V., 1983. Particle transfer to solid surfaces. *Advances in Colloid and Interface Science* 19, 183–252. doi: 10.1016/0001-8686(83)80001-3
- Baxter, L.L., DeSollar, R.W., 1993. A mechanistic description of ash deposition during pulverized coal combustion: predictions compared with observations. *Fuel* 72, 1411–1418. doi: 10.1016/0016-2361(93)90417-Z
- Benson, S.A., Sondreal, E.A., Hurley, J.P., 1995. Status of coal ash behavior research. *Fuel Processing Technology* 44, 1–12. doi: 10.1016/0378-3820(95)00020-8
- Biswal, S.K., Das, S.P., Reddy, P.S.R., Misra, V.N., 2005. Prospects of beneficiation of high ash non-coking coals. In: *Emerging Trends in Mineral Processing and Extractive Metallurgy* (Misra, V.N., Das, S.C., Subbaiah, T., eds.). Allied Publishers, New Delhi, India, pp. 61–71.
- Byers, R.L., Calvert, S., 1969. Particle deposition from turbulent streams by means of thermal force. *Industrial and Engineering Chemistry Fundamentals* 8, 646–655. doi: 10.1021/i160032a008
- Chikkathur, A.P., Sagar, A.D., Sankar, T.L., 2009. Sustainable development of the Indian coal sector. *Energy* 34, 942–953. doi: 10.1016/j.energy.2008.12.014
- Damle, A.S., Ensor, D.S., Ranade, M.B., 1982. Coal combustion aerosol formation mechanisms: a review. *Aerosol Science and Technology* 1, 119–133. doi: 10.1080/02786828208958582
- Erickson, T.A., Allan, S.E., McCollor, D.P., Hurley, J.P., Srinivasachar, S., Kang, S.G., Baker, J.E., Morgan, M.E., Johnson, S.A., Borio, R., 1995. Modelling of fouling and slagging in coal-fired utility boilers. *Fuel Processing Technology* 44, 155–171. doi: 10.1016/0378-3820(95)00014-X
- Harb, J.N., Munson, C.L., Richards, G.H., 1993. Use of equilibrium calculations to predict the behavior of coal ash in combustion systems. *Energy & Fuels* 7, 208–214. doi: 10.1021/ef00038a008
- Irdi, G.A., Booher, H.B., Martello, D.V., Frommell, E.A., Gray, R.J., 1993. The petrography and mineralogy of two Indian coals. *Fuel* 72, 1093–1105. doi: 10.1016/0016-2361(93)90314-R
- Israel, R., Rosner, D.E., 1982. Use of a generalized Stokes number to determine the aerodynamic capture efficiency of non-Stokesian particles from a compressible gas flow. *Aerosol Science and Technology* 2, 45–51. doi: 10.1080/02786828308958612
- Kweon, S.C., Ramer, E., Robinson, A.L., 2003. Measurement and simulation of ash deposit microstructure. *Energy & Fuels* 17, 1311–1323. doi: 10.1021/ef020277f

- Mishra, U.C., 2004. Environmental impact of coal industry and thermal power plants in India. *Journal of Environmental Radioactivity* 72, 35–40. doi: 10.1016/S0265-931X(03)00183-8
- Nagarajan, R., Anderson, R.J., 1988. Effect of coal constituents on the liquid-assisted capture of impacting ash particles in direct coal-fired gas turbines. In: Proceedings of ASME International Gas Turbine and Aeroengine Congress and Exposition, Amsterdam, The Netherlands, 6–9 June 1988, pp. 1–9.
- Richards, G.H., Slater, P.N., Harb, J.N., 1993. Simulation of ash deposit growth in a pulverized coal-fired pilot scale reactor. *Energy & Fuels* 7, 774–781. doi: 10.1021/ef00042a012
- Robinson, A.L., Buckley, S.G., Baxter, L.L., 1998. *In situ* measurements of the thermal conductivity of ash deposits. In: Proceedings of the 27th International Symposium on Combustion, Boulder, CO, 2–7 August 1998, pp. 1727–1735.
- Rosner, D.E., Nagarajan, R., 1987. Toward a mechanistic theory of net deposit growth from ash-laden flowing combustion gases: self-regulated sticking of impacting particles and deposit erosion in the presence of vapor deposited – or submicron mist – ‘glue.’ In: Proceedings of the AIChE Symposium Series Heat Transfer, Pittsburgh, PA, 9–12 August 1987 (Lyczkowski, R.W., ed.), pp. 289–296.
- Rosner, D.E., Tandon, P., 1995. Rational prediction of inertially induced particle deposition rates for a cylindrical target in a dust-laden stream. *Chemical Engineering Science* 50, 3409–3431. doi: 10.1016/0009-2509(95)00161-W
- Ross, J.S., Anderson, R.J., Nagarajan, R., 1988. Effect of sodium on deposition in a simulated combustion gas turbine environment. *Energy & Fuels* 2, 282–289. doi: 10.1021/ef00009a010
- Ross, J.S., Ramezan, M., Anderson, R.J., Nagarajan, R., 1987. Prediction and *in situ* measurement of the thermal conductivity of multiphase fouling deposits formed in direct coal-fired combustors. In: ASME Winter Annual Meeting, Boston, MA, 13–18 December 1987, pp. 1–8.
- Roy, R.K.D., 1940. A critical study of some Indian coal ashes. *Geological Survey of India* 4, 539–548.
- Sarkar, A., Rano, R., Mishra, K.K., Sinha, I.N., 2005. Particle size distribution profile for some Indian fly-ash—a comparative study to assess their possible uses. *Fuel Processing Technology* 86, 1221–1238. doi: 10.1016/j.fuproc.2004.12.002
- Senior, C.L., Zeng, T., Che, J., Ames, M.R., Sarofim, A.F., Olmez, I., Huggins, F.E., Shah, N., Huffman, G.P., Kolker, A., Mroczkowski, S., Palmer, C., Finkelman, R., 2000. Distribution of trace elements in selected pulverized coals as a function of particle size and density. *Fuel Processing Technology* 63, 215–241. doi: 10.1016/S0378-3820(99)00098-3
- Smith, J.M., Ness, H.C.V., Abbott, M.M., 2005. *Introduction to Chemical Engineering Thermodynamics*, 7th ed. McGraw-Hill, New Delhi, India, 488 pp.
- Smith, M.Y., Beck, W.H., Hein, K., 1985. Equilibrium calculations of fireside products formed during the combustion of Rhineland brown coals with special emphasis on fouling constituents. *Combustion Science and Technology* 42, 115–130. doi: 10.1080/00102208508960372
- Walsh, P.M., Sarofim, A.F., Beér, J.M., 1992. Fouling of convection heat exchangers by lignitic coal ash. *Energy & Fuels* 6, 709–715. doi: 10.1021/ef00036a004
- Wang, H., Harb, J.N., 1997. Modeling of ash deposition in large-scale combustion facilities burning pulverized coal. *Progress in Energy and Combustion Science* 23, 267–282. doi: 10.1016/S0360-1285(97)00010-5
- Woodcock, A.H., 1953. Salt nuclei in marine air as a function of altitude and wind force. *Journal of Meteorology* 10, 362–371. doi: 10.1175/1520-0469(1953)010<0366:SNIMAA>2.0.CO;2