REVIEW OF ASH AGGLOMERATION CAUSES AND DETECTION IN CIRCULATING FLUIDISED BED COMBUSTION BOILER

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Abstract*—Agglomeration of ash is a major issue in fluidized bed combustion boiler, large agglomeration decreases the bed mixing and result of this activity de-fluidisation take place in the boiler. This cause a shutdown of the combustor because of defluidization. In recent years, significant advances have been made in understanding and predicting the behavior of ash in combustion and gasification systems. In CFBC boilers ash sintering may contribute to deposit formation in the cyclone, return leg and post cyclone flue gas channel. Rapid sintering can lead to heavy agglomerate formation, which may finally inhibit circulation in dense phase areas (such as seal pot and return leg). Hence understanding the sintering behavior before the fuel is used, would be desirable for avoiding problems. A survey of ash agglomeration and deposit formation in industrial boiler found that all the boiler facing some form of bed ash agglomeration. In combustion using Indian coal having high percentage of sulphur ash becomes deposited on the bed particles. After certain temperature (about $800^{O}C$ to $1000^{O}C$) ash showing the sticky behaviour tend to stick ash and form agglomerates. In this study we are trying to find out that what is the causes of this ash agglomeration ? How the agglomeration problem analyzed by different researcher. Which solution or method provide by researcher to reduce ash agglomeration or eliminated from the affect area of fluidized bed boiler.

***Index Terms*— CFBC, Ash agglomeration, ash sintering, ash deposit, CFD model, etc.**

I. INTRODUCTION

Coal is the foremost energy source and one of the major accepted resources available in India. Nearly 55% of country's prime commercial energy supply and about 70% of total electricity generation is from coal. Lignite is fast emerging as an alternate source of fuel for power generation due to a proven potential of – 4177 million tonnes, mostly in discriminating regions such as Gujarat, Rajasthan and Tamil Nadu, where coal availability is scarce. Hence, the share of lignite based pit head thermal projects in Gujarat and Rajasthan are increasing. [2]ON December 16, 1921 a new chapter opened in the history of the energy and power industries by Fritz Winkler. The circulating fluidized bed (CFB) boiler is a member of the fluidized bed boiler family Circulating Fluidized Bed Combustion is the most used & economical technology adopted by the industries.[8] (Fig.1) Combustor is mainly composed of riser, cyclone, downcomer and loop seal. Riser is divided into 5 modules for manufacturing, installation, possible revisions in future and temperature control reasons. J-valve is placed at the return leg of cyclone for sealing the return leg and maintaining the rate of circulation. [9]

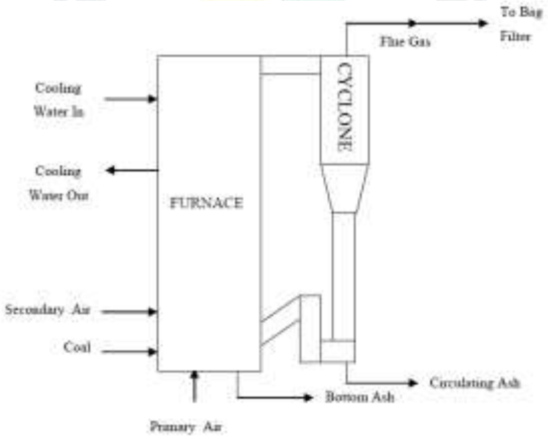

Fig. 1 Schematic diagram of the physical system [9]

Advantages of circulating fluidized bed combustion (CFBC) technology such as the ability to burn a wide variety of fuels efficiently and in an environmentally friendly manner have led to a steady increase in its commercial use over the past decades. Due to wide variations in ash content (5–40%) and sulfur content (0.3–7.0%) of the lignite, in addition to high moisture, CFBC technology is the preferred choice of utility owners for utilizing lignite.[1].

1.1 Cyclone separator

Cyclones are devices that utilize centrifugal force for the separation of solids from a gas stream. Relatively coarse particle of sorbent (limestone) and unburnt char are captured in the cyclone and are recycled back near the base of the furnace. Finer solid residues (ash and spent sorbents) generated during combustion and desulphurization leave the furnace, escaping through the cyclones, but they are collected by a bag-house or electrostatic precipitator locate further downstream. [10] A schematic diagram of a typical cyclone is illustrated in Figure 2.

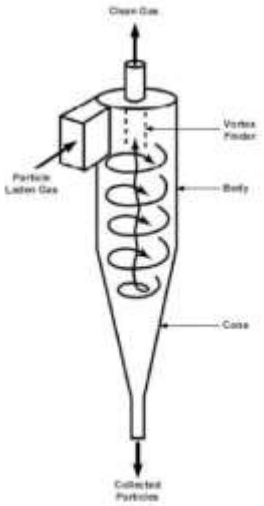

Fig. 2. A typical cyclone [10].

1.2 Ash formation

Depending upon the severity of the process, the inorganic impurities in coal can go through significantly different physical and chemical transformations. Physical transformations involved in high-temperature suspension- or entrainment-type combustion and gasification systems include (1) selective elemental vaporization and subsequent reaction or condensation to form surface coatings or homogeneous fine particulates, (2) coalescence of mineral grains within hot reactive char particles, (3) char fragmentation and partial coalescence of included minerals, (4) shedding of particles from the char surface, (5) fragmentation or fusion of liberated mineral grains, (6) convective transport of volatile species within and between char and mineral particles, and (7) formation of thin-walled ash spheres known as cenospheres. The typical result of these interactions is an ash having a multimodal size distribution, including larger particles that resemble the inorganic constituents in the parent coal and a very fine submicron fractionate resulting from condensation and fragmentation. [11]

1.3 Residence time model

In CFB system, the different size particles may have different residence times; even the same size particles may have different residence times, i.e., different ages. The residence time for multi-size particles will greatly influence the attrition of coal ash particles in the CFB page boiler. Based on such fact, ash particles are classified into size group as well as age group. The size dispersed ash particles are fed into the furnace at feed rate, ˙min (di, t0). In the t0 age group, the di size group particles experience attrition process and the mother particles experience continuous size reduction. The produced fine particles fall into the smallest size group and some mother particles fall into the next size group.

1.4 Agglomeration in fluidized beds

The ash particles are carried by the hot flue gases. Along the way in the boiler, they may suffer coalescence or break-up, depending on the particles mineralogy and flow temperature. Eventually, a reasonable concentration of the ash particles, commonly denominated fly-ash, reaches the tube bundles in the steam superheating section. There, these particles may hit and adhere to the tube surfaces.[17] .Agglomeration is a major operational problem. Usually, the conversion of the solid fuel is carried out with silica sand and ash as bed material. Inorganic alkali components from the fuel, mainly potassium (K) and sodium (Na), can be a source for agglomeration by the formation of low-melting silicates with the silica from the sand. The content of this critical inorganic material can vary much between fuels; especially in the case of certain types of biomass as well as some low-rank coal types the content is often rather high. When both alkalis and silica are present in the bed they can form low-melting silicates, characterized by a lower melting point than the individual components. As a consequence, the sand particles become coated with an adhesive layer. Sand particles with a sticky surface then grow towards larger agglomerates due to the formation of permanent bonds upon collisions. If this process is not recognized, it eventually propagates to partial or total de-fluidization of the reactor, which in turn results in a lengthy and expensive unscheduled shutdown.[12] Fig.3. show ash development and ash agglomeration.

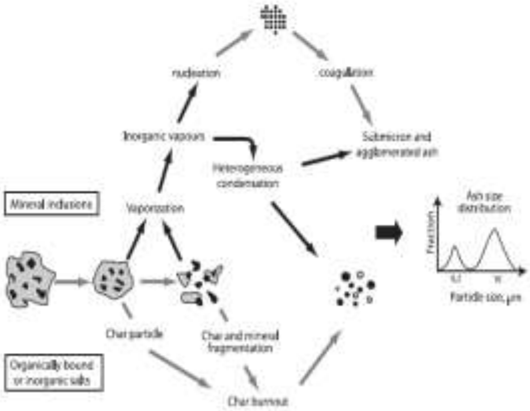

Fig. 3 Schematic illustration of ash developing, adapted from [12].

2. Objective of the review

Major objective of this literature review to find out the method used to predict ash agglomeration phenomenon in Fluidized Bed Combustion Boiler. In this review we studied different model which used by researcher to find out the ash agglomeration, ash deposition. After this we want to develop CFD base model to know combustion behaviour and location of ash deposition, ash sintering and ash agglomeration.

3. Literature

S. Chakravarty etal.[2] -The present study aims to evaluate the chemical and mineralogical compositions of coal samples collected from three different seams of a particular borehole of Samaleswari Block, Ib river coalfield, Odisha, India. Subsequently, different experimental and theoretical studies were conducted to predict and correlate the chemical and mineral composition of coal ash to AFTs. The experimental techniques used include proximate analysis, ultimate analysis, gross calorific value determination and chemical analysis of coal ash for quantification of major oxides such as $SiO2$, $Al2O3$, $Fe2O3$, CaO, MgO, $Na2O$, $K2O$, $SO3$ and $TiO2$. In addition, X-ray diffraction (XRD) and electron probe micro analysis (EPMA) techniques were used to identify the mineral phases present in coal and ash samples. Finally, FactSage Thermodynamics Model (FactSage 6.3) was used to understand the ash fusion behaviour and to predict the phase transformations that occur during the process of combustion.

Chiou-Liang Lin, etal [3] study focused on the effect of particle size distribution (PSD) on agglomeration and defluidization in a fluidized bed. The four PSDs studied were narrow, Gaussian, binary and flat. The experimental variables studied included the gas velocity, the operating temperature, the Na concentration and the addition of Ca. The defluidization time decreased with increasing operating temperature and Na concentration, and these effects were independent of the sand bed's PSD. In contrast, the defluidization time increased with increasing gas velocity for all PSDs. Comparing the four PSDs, the narrow and Gaussian distributions had higher defluidization times when using operating temperatures of 700 °C and 800 °C, gas velocities of 0.163 m/s and 0.187 m/s, and Na concentrations of 0.5% and 0.7%. However, the flat and binary distributions had lower defluidization times under these conditions because they had poor fluidized quality. Thus, the PSD apparently affects the agglomeration and defluidization properties of a sand bed.

Nevin Selcuk etal. [4] A comprehensive model, previously developed for a rectangular parallelepiped shaped 0.3 MWt circulating fluidized bed combustor (CFBC) fired with high calorific value coal burning in sand and validated against experimental data is adapted to cylindrical configuration and is extended to incorporate NOx formation and reduction reactions and pressure drops around cyclone, downcomer and loop seal. Its predictive accuracy is tested by applying it to the simulation of Middle East Technical University (METU) 150 kWt CFBC burning low calorific value indigenous lignite with high Volatile Matter/Fixed Carbon (VM/FC) ratio in its own ash and comparing its predictions with measurements. Favorable comparisons are obtained between the predicted and measured temperatures and pressure profiles and emissions of gaseous species. Results reveal that predictive accuracy in pressure profile strongly depends on the correlation utilized for entrainment in dilute zone and that accuracy in NO emission requires data on partitioning of coal nitrogen into char-N and volatile-N and is affected significantly by dilute zone oxygen content.

E.J. Anthony, etal [5] Fluidized bed combustor (FBC) ashes from high-sulfur, low-ash fuels, can agglomerate if subjected to sulfating conditions for long enough (days to weeks). The degree of sulphation increases with both temperature and time under these conditions, and at a conversion equivalent to the production of 50–60% or more of $CaSO4$ in the deposit the ashes agglomerate. Fly ash agglomerates less readily than does bed and loop seal ash and produces weaker deposits, although all of these materials will agglomerate if sufficient time is allowed. The potential for agglomeration increases if the temperature is increased from 850 to 950^0C. Agglomeration also occurs at lower temperatures (down to at least 750^0C), but the mechanism may be via carbonation and then sulphating of the ash.. Two bed materials with strong and weak agglomerating tendencies were studied. These were shown to have very similar particle shapes and only slightly different angles of repose, but quite different bulk densities. Residues with a greater bulk density appear to have a stronger tendency to agglomerate, and this may provide a method of ranking the agglomeration potential of different bed materials.

S. Datta etal.[6] A suitable pilot scale Fluidized Bed Gasifier was utilized in this study. Stabilized operating conditions in terms of coal feed rate, air feed rate, bed temperature, etc., already identified for maximum ossible carbon conversion, were maintained in all experiments and the steam flow rate was only varied. Though the ash fusion temperature of the coals were above 1200^OC, agglomerate was formed during gasification at 950 ^{O}C with ‘steam to coal ratio’ less than 0.15 (kg/kg). On increasing this ratio above 0.2 local heat-concentration and agglomeration could be avoided with certainty. Chemical composition alone was not sufficient to explain the relative strength of ash-agglomerates. Compositional variation and state of iron within the matrix were assessed through SEM-EDX and electron paramagnetic resonance (EPR) study, respectively. The probing also required the ash-loading and iron-loading factors to be freshly defined in the context of gasification.

V. MarinoyS etal. [7] Investigated Intensive ash agglomeration has hampered the fluidized bed gasification of lignites from the Elhovo deposit (Bulgaria) containing 5.9 wt% sulphur in the dry state. Samples of slag and agglomerates from the pilot plant have been examined by means of chemical, X-ray analysis, IR spectroscopy and scanning electron microscopy. Pyrrhotite (FeS) and wUstite (FeO) have been established in the agglomerates, where junctions between ash particles have been found to consist of magnetite, spinel and garnet grains. The chemical reactions leading to garnet formation have been studied. Centres of sintering and centres of melting during the ash agglomeration process have been distinguished. The pyrite product, an eutectic of FeS and FeO melting at 924 °C, is assumed to be responsible for the cessation of lignite gasification with steam and air under pressure at a bed temperature of 930°C.

C. Tangsathitkulchai etal.[18] Investigated the bed agglomeration tendency of coal ashes by following and mechanism of bed materials and additives. In this work, the compressive strength measurement was used to follow the extent of ash sintering under the operating temperatures of a fluidized their sintering behaviour as well as the role bed combustor. It has been reported that the bed agglomeration involves the association of amorphous sticky ash with bed materials. To enable a more precise study of bed agglomeration, this amorphous phase matrix was purposely created within the sintered ash particles by mixing the amorphous silica with the original ash and sintering experiments performed.

Huang et al., [15], described the ash deposition as a cumulative effect of the thermophoretic and inertial impaction. The inertial model is considered as a function of the total mass flux of the ash particle and the fraction captured once collision on the surface has occurred. The impact efficiency was calculated considering the balance between the inertial and drag forces via Stokes number. Once impacted, the colliding particle either really sticks or rebounds according to a sticking probability based on the particle viscosity. The particle viscosity is calculated according to the ash composition of the deposit and is compared with a critical viscosity.

A. Lawrence et al [19] Particle-to-particle sinter bonding, usually results in shrinkage. The present technique is based on measuring the area shrinkage continuously during heating of ash pellets over a temperature range of interest.

The area shrinkage measurement showed clear differences in the sintering profiles among the coal ashes tested.

Present work describes the sintering profiles of ashes for the temperature range of 800–1100^{O}C. The finger print of sintering behavior, over the temperature range is made easy using the area shrinkage measurement.

The probable mechanism behind the sintering behavior observed in some low rank coals in the temperature range 800–1000 _C is proposed. The advantages over the other conventional techniques used for prediction of sintering such as compression strength measurement, electrical conductance are brought out.

Robert C. Brown et al. [20] A survey of agglomeration and deposit formation in industrial fluidized bed combustors (FBCs) indicate that at least five boilers were experiencing some form of bed material agglomeration. Deposit formation was reported at nine sites with deposits most commonly at coal feed locations and in cyclones. Other deposit locations included side walls and return loops.

Three general types of mineralogic reactions were observed to occur in the agglomerates and deposits. Although alkalies may play a role with some “high alkali” lignites, we found agglomeration was initiated due to fluxing reactions between iron (11) from pyrites and alumino silicates from clays. This is indicated by the high amounts of iron, silica, and alumina in the agglomerates and the mineralogy of the agglomerates. Agglomeration likely originated in the dense phase of the FBC bed within the volatile plume which forms when coal is introduced to the boiler.

Jiangang Xu [21] proposed four scenarios represent possible mechanisms for the formation of coal ash and bed agglomerates in fluidized bed combustion.

3.1 Conclusion of literature

No	Type of boiler	Type of fuel	Author	Model	Result
1	Combustion	Indian coal	[2] S. Chakravarty etal. (2015)	FactSage Thermodynamics Model (FactSage 6.3)	to predict the phase transformations that occur during the process of coal combustion
2	fluidized-bed reactor	solid waste	[3]Chiou-Liang Lin etal. (2011)	particle size distribution	agglomeration and defluidization in a fluidized bed
3	Power plant boiler	coal	[17]Lourival J. Mendes N. etal (2012)	SEM image, EDX detection and X-ray diffraction	Detected in sample of ash
4	CFBC	indigenous lignite	[4]Nevin Selcuk etal. (2011)	comprehensive model,	pressure drops around cyclone, downcomer and loop seal
5	FBC Gasifier	high ash Indian coals	[6]S. Datta etal. (2015)	gasification pilot plant	reason of agglomerate formation
6	FBC Gasifier	Lignite	[7]V. MarinoyS, etal.(1992)	X-ray analysis, IR spectroscopy and scanning electron microscopy.	Two kinds of ash agglomeration centres can be distinguished
7	CFBC	coal, peat	[13]Bengt-Johan Skrifvarsa etal(1996)	On site sample measurement	Ash agglomeration behavior detected
8	FBC	Thai low-rank coal	[18]C. Tangsathitkulchai et al.(2000)	X-ray detection SEM-EDX. and X-ray diffractometry XRD.	Agglomeration propensity of Thai low-rank coal ashes

Ash formation and deposition process is not fully understood Traditional ASTM analyses do not always provide information that can be used to make predictive judgments at the confidence levels desired. The potential for agglomeration increases if the temperature is increased from 850 to 950^{O}C. Factors that enhance the formation of agglomerates includes local reducing condition in the bed ; high temperature, particularly on surface of coal particles which approach the melting temperature of various minerals phases. Increased pressure which speed reaction rate as a result of increased partial pressure of the oxygen and the pressure fluxing agent such as sodium or potassium. High temperature agglomerates form primarily during upset conditions. Although higher temperature tend to favor of formation of agglomerates, there exists a temperature window between 1550 and 1650^{O}F where the agglomeration is minimised. CFD modeling tool will be very useful to understant the ash deposition, ash sintering and ash agglomeration phenomenon.

4. Model description

Combustion and gasification of coals in circulating fluidized bed have been considered for a number of decades. An early comprehensive mathematical model produced that was starting with simplified chemical reactions to determine emission predictions. Mathematical modeling and simulations are helpful to understand combustion and gasification processes deeply and these are significant for fluidization industry since 1960. Several models are developed and improved in the last two decades. Focus was less on three-dimensional models due to more costly computational power. Due to advancement in computers the computational fluid dynamics is being applied on fluidization during the last decade.[30]

4.1 Governing equations

Continuity equations:

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\right) + \nabla.\left(\alpha_g\rho_g v_g\right) = 0, \qquad 4.1$$

$$\frac{\partial}{\partial t}\left(\alpha_s\rho_s\right) + \nabla.\left(\alpha_s\rho_s v_s\right) = 0, \qquad 4.2$$

Momentum equations:

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g v_g\right) + \nabla.\left(\alpha_g\rho_g v_g v_g\right) = -\alpha_g\nabla_p + \nabla.\tau_g + \alpha_g\rho_g g + \beta\left(v_s - v_g\right), \qquad 4.3$$

$$\frac{\partial}{\partial t}\left(\alpha_s\rho_s v_s\right) + \nabla.\left(\alpha_s\rho_s v_s v_s\right) = -\alpha_s\nabla_p + \nabla.\tau_s + \alpha_s\rho_s g + \beta\left(v_g - v_s\right) \qquad 4.4$$

4.2 Devolatilization submodel

The devolatilization process begins when the solid fuel reaches a particular level. Many devolatilization models have been developed in past. One-step global mechanisms and semi-global multi-step mechanisms can be basically distinguished. The simplified approaches define devolatization rates with single or two step Arrhenius reaction schemes.

The details of one-step devolatilization mechanism is shown below [30]

Coal → Volatiles + Char → Tar + Gases + Char 4.5

5. Result and discussion

The phenomenon of agglomeration is important in several applications that use fluidized bed echnologies. Prediction of agglomeration is crucial to avoid losses due to reduced efficiencies and reactor downtime.

Agglomeration may be used to improve material flow properties in applications such as granulation and pelletization. Good control over the agglomeration process is desired in such situations. Undesirable agglomeration occurs in applications such as combustion and gasification. Methods of accurate prediction of such undesired agglomeration which may begin locally in the reactor are lacking in the literature. [14]

CFD has played an active part in analysis of the distribution of products, heat flux, flow, temperature, ash deposits, CO, SOx and NOx emissions during combustion and gasification of fuels in fluidized bed. These parameters could affect the performance and Design. No evidence of E-E TFM CFD model influencing the design of industrial fluidized bed units when combustion and gasification issues involved. [15].

6. Conclusion

Aim & objective is to understand the cause of failure & serve the solution with technical aspects. This can be only achieved by using advance CAD/CAE/CFD tools available to demonstrate the actual boiler operation phenomenon virtually in to computers. This makes accurate prediction with mere experimentation difficult. Steps followed to achieve the simulation are

Prepare geometry of boiler with cyclone separator CAD software
Prepare the general arrangement of CFBC boiler
To simulate the combustion of lignite coal and flow of flue gas inside the loop of CFBC boiler by using CFD software to understand ash deposited area.

7. Proposed results

Proposed outcomes of the study by Simulation of the Mathematical Model of CFBC Boiler with Cyclone Separator using ANSYS (Fluent) Software tools are:

Full model analysis boiler with cyclone separator
Exact location of ash agglomeration by observing temperature and pressure.
Combustion flow pattern.
Ash concentration
Mass fraction of Agglomeration or precipitants

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