

Agglomeration in Fluidized Bed Combustion System

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Abstract— In fluidized bed, low-grade and waste materials are used for combustion. These fuels have high alkali, sulphur and toxic elements which on combustion produces deposition and corrosion in the system. The major problem associated with fluidized bed system is agglomeration. Fuel, ash and bed particles stick together to form bulk mass which reduces fluidization and finally shutdown the system. In this study discussion made on factors affects fluidization, combustion efficiency and emission. Identification and control techniques of agglomeration and difficulties involved in bed sulphur capture are also analyzed.

Key words: Agglomeration, Fluidised bed, Fouling, Sulphur capture

I. INTRODUCTION

Fluidisation is the art of making granular solids to behave like fluid, fluidised bed technique used for gasification, combustion and incineration. All type of coal, coal residue, biomass, petroleum products and municipal solid waste are used as fuel in fluidised bed. Fuels with high ash content, low bulk density, poor flow characteristics and low ash melting point are utilised in fluidised bed. The bed material used as thermal flywheel to store heat energy, maintains bed temperature and restart of the system without external heating. Simple design, compact combustion chamber, good heat and mass transfer, high reaction rate of gas solid mixture, high combustion efficiency, easy temperature control makes the system attractive [1, 2]. Fluidised bed promotes good mixing of air and fuel, uniform heat distribution, low operating temperature and short system start-up time makes it economical and quick response to varying load; no pre-treatment of fuel required and low ash related problems. Excellent recirculation of hot solids provides longer residence time and adequate temperature to fuel [3, 4]. Low NO and NO₂ emission from the fluidised bed system, compared to pulverised coal combustion system and sorbent injection absorbs SO₂ and heavy metals which reduces the post cleaning requirements [5]. Fluidized bed operates 1-2 % of fuel with bed material, sorbent and fuel ash, variation in the fuel property does not affect operation of the system and permits, wide range of low-grade fuel of non-uniform size and varying moisture content. Fluidized bed is used for drying process, power generation, catalytic cracking and production of synthetic gas [6].

A. Terminologies in fluidized bed combustion system:

Defluidization is any condition where a well fluidized bed losses its fluidity partial or total, the time elapsed from the start of operation till defluidization is called fluidisation time. The air velocity required to support the entire weight of the bed is known as minimum fluidisation velocity, increasing the velocity above minimum fluidisation velocity increases turbulence and mixing of bed material [1, 7]. Sintering point is the temperature at which the ash pellet starts to develop a measurable strength, fuels with sintering temperature lower

than the operating temperature shows agglomeration. Grate-heat release rate is the amount of heat released by the furnace per unit cross sectional area and used for sizing of combustion chamber. Heat release rate is directly proportional to the combustor pressure, gas velocity and inversely proportional to mass flow rate of air [8, 9]. Fuel ratio is the ratio of fixed carbon to volatile matter, burning rate of a char particle is the instantaneous rate of oxidation of char per unit time. The burning rate depends on particle size, reactivity of the char and oxygen concentration. Specific burning rate is rate of oxidation of char particle per unit external surface area of the particle. Burn out time is the time required for complete combustion and it depends on burning rate of the particle, combustion temperature and particle surface area. Oxygen enrichment decreases burnout time at low temperature, at high temperature the effect is less, for complete combustion, fuel residence time should be greater than burn out time. [2].

II. FACTORS AFFECT OPERATION OF FLUIDISED BED COMBUSTION

Sintering behaviour of ash depends on fuel iron content, sulphur and alkali/alkali earth metal oxides, fluidisation velocity and operating temperature, heating rate, bed material particle size, shape and distribution, combustion atmosphere, quantity of ash particles in bed inventory and reaction mechanism [10].

A. Role of minerals in agglomeration:

Fouling and high temperature corrosion directly linked with nature and occurrence of mineral matter. Fouling is sticky deposition of ash in boiler tubes, it reduce heat transfer, steam generation, steam temperature and increases the shell temperature, continuous run of certain fuel with high alkali content and sulphur causes adhesion of ash with the bed material, increase in bed material density and reduction in fluidisation. Sintering behaviour of ash under pulverised coal combustion cannot be applicable to fluidised bed combustion system [10]. Relative amount of clay (Al₂O₃) and anhydrite (CaSO₄) in the ash is responsible for formation of low temperature eutectics and maximum compressive strength of agglomerate is observed for clay to anhydrite ratio of one. The interaction between alkali and silica sand under high temperature lead to formation of low-melting point eutectics on the surface of the bed particle and it causes agglomeration. The agglomerates formed in the fluidised bed consist of amorphous and crystalline phase, Common crystalline phases were CaSO₄, CaCO₃, SiO₂ and Fe₂O₃ [6]. Agglomeration tendency depends on Na₂O, Al₂O₃ and basic oxide content in the ash, agglomeration increases with Na₂O content and decreases with Al₂O₃ content. K, Na, Si, Ca are sources of agglomeration and Mg, Fe, Al are agglomeration inhibitors [10].

B. Effect of temperature on agglomeration:

Operating the fluidised bed combustion system at temperature more than 750°C makes the ash to form viscous

liquid which spreads over the bed, flows readily and form bridge between bed materials, on cooling viscous liquid forms concrete like structure causes the expensive shutdown of the system. Soft and thick viscous flow at particle surface makes the particles more deformable and to have less momentum, favours agglomeration [5]. The operating temperature of fluidised bed selected based on optimum sulphur capture, ash melting point, NOX formation and alkali metals vaporisation temperature. High temperature combustion is beneficial for low volatile, less reactive fuel but operating at low temperature increases carbon in fly ash [2]. The agglomeration tendency in fluidised bed combustor decreases as characteristics temperature of ash increases, lignite ash can agglomerate at temperature level about initial deformation temperature [10]. Sintering temperature for reducing, neutral atmosphere are lower than oxidising atmosphere. Sintering temperature decreases with increase in pressure irrespective of combustion atmosphere [8].

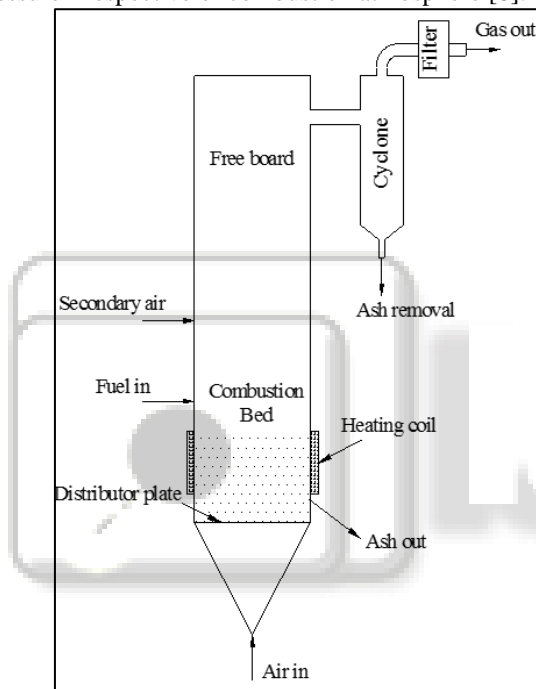


Fig. 1: Schematic representation of fluidised bed combustor.

C. Effect of velocity on agglomeration:

Fluidisation quality is controlled by changing superficial air velocity within permissible limit for chosen particle size. Poor mixing of bed material decrease the particle movement, which makes separating force smaller than adhering force causes bridge between bed materials. Probability of agglomeration is inversely proportional to particle momentum, increase in gas velocity increase the volatile elutriation, particle momentum, collision force and drag force [1].

D. Effect of bed particle size distribution:

Increase in particle size due to agglomeration is desirable in pellet making, compact granulation, sintering of ores baking and briquetting [7]. Wide particle size distribution enhances fluidisation but narrow particle size distribution reduces the segregation force, coarse particle led defluidisation more easily than fine particle. Flat, binary distribution has shorter defluidisation time, narrow and Gaussian distribution exhibits good mixing and uniform distribution with low-level

of agglomeration. Binary and flat distribution have greater tendency to segregation, Gaussian and narrow distribution tend towards complete mixing. The sand bed has superior stability when narrow particle distribution used. The fluidisation quality of binary and flat distribution is inferior to the Gaussian and narrow distribution [11, 12]. Geldart classified particles based on their size, group C represents fine particles, group A represents larger particles, group B particles were larger and heavier than group A, group D is the largest and heaviest. When agglomeration begins particles move from one group to another in the order of A-C-B [7]. Low ash fuel is not affected by size and composition of bed material. If the system does not use sorbent, the average size of bed material governs the hydrodynamics and heat transfer of the bed, size distribution of ash in fuel. Avoiding agglomeration problems by significantly increasing the refreshing rate of the sand in the bed is unattractive by economical and environmental point of view [13].

III. FACTORS AFFECT COMBUSTION EFFICIENCY

Combustion efficiency is the ratio of actual heat released to the chemical energy present in the fuel. Combustion efficiency depends on chemical property of the fuel and operating condition. Combustion efficiency decreases with increase in fluidisation velocity due to entrainment of unburned fuel with fly ash [1]. Fine particles have shorter burnout time, higher probability of entrainment and shorter residence time. The carbon content in bed ash is lesser than fly ash because coarse particle reside in combustion zone longer than fine particle. The extensive combustion of volatiles in the free board causes heat loss by outgoing gas, combustion in the free board decreases with increase in bed temperature, fluidisation velocity and bed depth. Ignition temperature of the fuel influences bed start-up condition, lower the ignition temperature shorter the start-up time. High value of fuel ratio leads to lower combustion efficiency, lignite and bituminous coal has higher combustion efficiency than anthracite [2]. Fly ash particles formed from original fine particles during devolatilization by fragmentation in fluidised bed [14]. Unburned carbon in fly ash decreases with increase in volatile content and heating value of the fuel. Recirculation of unburned material used to increase the combustion efficiency for less reactive fuels. Improvement in Efficiency of 8-9% takes place by recirculation [1, 2].

A. Effect of fuel feeding method and excess air addition on combustion:

Over bed feeding of fine particles has negative impact on combustion, particles entrain instead of reaching the bed and it is effective for high fuel ratio feedstock. Under bed feeding provides higher combustion efficiency, good mixing and adequate residence time but it is expensive and prone to plugging. The residence time of the fines are governed by internal circulation, height of furnace and cyclone performance [2]. Increase of excess air increases CO emission by low temperature formation but provides smooth temperature profile, NO emission increases gradually as excess air ratio increases. Excess air ratio indirectly affects SO₂ emission by changing combustor temperature, the optimum excess air ratio depends on the amount of fuel supplied to the combustor, NO, CO, SO₂ emission and it increases with increase in fuel feed rate [15].

IV. THEORY OF AGGLOMERATION

Agglomeration classified as homogeneous and heterogeneous agglomeration, homogeneous agglomeration is slight agglomeration occurring on the particle surface resulting in uniform particle size distribution of agglomerates. Mineral compounds of Sodium, potassium and calcium are present in ash and uniformly distributed over particle surface, continuous ash deposition with increase of Na and S compounds on bed particles surface during coal combustion leads to formation of eutectic points. Eutectic mixture of silicates melts around 875°C which makes particle surface sticky and generates local hot spot leading to agglomeration [2, 10]. The tendency of particle to stick together is directly proportional to their adhesion, area of contact and inversely proportional to their inertial momentum. The adhesive force in the process of agglomeration of coal ash particles depends upon plasticity of coal particle. Eutectics are transferred to bed particle surface via particle collision; collision between two particles may be completely elastic, plastic or intermediate between two states.

Particle sticking is promoted by presence of viscous liquid layer, kinetic energy of particle is dissipated by viscous liquid layer bridge and higher minimum fluidisation velocity is required to balance the increased pressure drop across the bed. The adhesive force of agglomeration includes Van der Waals force, cohesive force and capillary force of the liquid materials. Between colliding particles Van der Waals force promotes stickiness, but limited for fine particles [7]. The segregation force includes the gravitational force, collision force and drag force. If adhesive force is greater than segregation force agglomeration starts, adhesive force increases with increase in temperature and time. Channelling occurs in fluidised bed to decrease pressure drop under defluidisation condition. The adhesion tendency of a particle is determined by extent to which the melting and chemical reactions generates liquid phase material and extent of glassy material formation [16].

A. Agglomeration identifying methods:

Agglomeration propensity of coal ash is determined by measuring compressive strength of sintered ash pellet, over the fluidized bed operating temperature range. Ash fusibility test, differential thermal analysis (DTA), thermo gravimetric analysis (TGA), thermo-mechanical analysis (TMA) and compression strength test are used to find agglomeration tendency but these techniques are inadequate [7]. Agglomeration temperature indicated by measuring bed temperature and pressure drop across the bed, the combustion malfunction is indicated by violent fluctuation in the bed temperature and rapid decrease in the bed pressure drop [8, 10]. Pressure Vs Time profile and visual observation used to estimate the defluidization time and it decreases with increase in temperature, amount of bed material, Na concentration, increases with increase in gas velocity for all particle size. Physical strength of agglomerate influenced by characteristics inorganic matrix of fuel and degree of agglomeration, strength of agglomerate indicates cohesiveness of particles and frequency of surface collision [10].

B. Agglomeration control methods:

The general method to avoid agglomeration is reducing formation of low temperature eutectic. Common control Methods for agglomeration are leaching technique, additive and alternate bed material use, fuel blending. Operational changes to avoid agglomeration can create adverse impacts, decreasing the bed temperature decreases conversion efficiency [4, 7]. Leaching technique converts high sulphur and high ash coal into low sulphur and low ash coal and it does not reduce greenhouse gas emission but reduces particulate emission [2]. Sudden reduction of agglomeration is possible by increasing air velocity, reducing fuel supply and adding fresh bed material [10]. Substituting coal for biomass has positive effect on energy consumption also reduces unpleasant gaseous emissions, low nitrogen and sulphur content of biomass lowers NO_x and SO₂ emission, substituting coal by MSW would lead to sustainable development on energy supply and waste management [14].

Chlorine deposition in the form of alkali chloride is the major problem associated with biomass combustion, alkali chloride act as glue and makes deposit sticky and creates resistance to cleaning [4,17]. The properties of ash material formed during combustion of a fuel mix cannot be predicted from the known characteristics of the ash formed from each fuel. The correct way to investigate agglomeration behaviour of fuel mix is burning it in a fluidised bed combustor under operating condition [2]. Cl-rich biomass co-fired with coal without operational problems by proper selection of blending ratio. Sulphur and alumina silicates in coal are able to capture alkalis from alkali chlorides and release HCl, increased kaolinite and decreased alkali content in coal improves alkali capture [17]. Co-firing offers economical benefit, technical benefit along with environmental benefit by avoiding operational problems and seasonal supply difficulties. The operation can last 12-13 times longer with the coal blends compared to raw run. Successful operation of co-firing units depends on the content and composition of mineral matter in fuel. From the knowledge of blending, elimination of unwanted properties of final ash or even designing an ash material for certain application is possible. Co-firing may lead to reduced system efficiency, capacity, availability of facility and increasing the power cost [18]. Combustion of biomass produces fly ash rich in Ca, Si, Fe, K, Na minerals, blending of fuel reduces content of Ca, Fe, K, Na and increases Si, Al in fly ash [4]. The role of additive in controlling agglomeration is either chemical effect or physical dilution effect. Addition of bauxite enriches bed ash with calcium compounds and addition of CaO, Al₂O₃ prolongs defluidisation in incineration and air gasification process [6].

V. COMBUSTION PHENOMENA

Stages of combustion are heating and drying, devolatilisation, volatile combustion and combustion of char with attrition, Combustion/gasification of solid fuels is always associated with the occurrence of particle comminution. When coal is fed in to fluidised bed above 350°C, it under goes a rapid thermal decomposition during which 30-50% of coal by weight is released in the form of volatiles depending on volatile content of coal and volatile release time depends on amount of volatile in parent coal, particle size and bed temperature. Devolatilisation time varies 10-40 seconds

depends on nature of fuel and coalescence phenomena. The volatile release is responsible for stable fuel particle segregation at bed surface [19]. The released volatile undergo complex chemical reaction including cracking and reforming before final oxidation. Thermal decomposition not only alters the physical property of coal but also change the role of heat transfer [19, 20].

In devolatilisation, coal particles undergo many structural changes which continue up to residual char combustion. Wide ranges of gaseous products released through decomposition of fuel, above 100°C initial release of CO₂ takes place, above 400°C light hydrocarbons CH₄, C₃H₈ released and above 600°C CH₂, CO released. Tar release takes place between 250-600°C with major constituent of CH₄, CO, CO₂, H₂O, H₂, C₂H₆ and traces of higher hydrocarbon [2, 19, 20]. Enthalpy of devolatilisation or pyrolysis depends on fuel nature and particle heating rate, increasing heating rate and temperature leads to larger volatile yield and in turn higher enthalpy of pyrolysis [18]. At initial moment of combustion, stress created by thermal shock in particle structure and interior pressure rise due to volatile release leads to fragmentation. If size of fragment comparable to initial size is called as primary fragmentation. Primary fragmentation appears to influence both average particle size and its distribution, the secondary fragmentation takes place along combustion and it is due to structural fragility of particles by collision and breaking up of solid bridges connecting elements of devolatilised material [2, 21-23]. Primary and secondary fragmentation by percolation and attrition could occur in series or parallel, Percolation is due to loss of particle connectivity by pore enlargement and overlapping associated with internal burning. Primary fragment and char under goes attrition causes elutriation of fine material which reduces fuel residence time, efficiency and affects reliability [20, 23].

Change in fuel particle size distribution influence rate and mechanism of fuel particle conversion, solid emission, particle heat and mass transfer co-efficient and performance of combustor [21, 23]. Combustion rate is controlled by diffusion of volatile matter and oxygen concentration. Char is highly porous, which has large number of internal pores of varying size and tortuosity and surface area of pore wall is greater than external surface area of char. When char burns, internal pore of char increases which makes bridge weak to withstand hydrodynamic force. Char fines with fewer internal pores takes longer time for complete combustion. Char particle comprises micro porous grains surrounded by meso-pores and macro-pores, the gas-solid reactions takes place on micro-pore surface, macro-pore serve as channel for transportation of reactant and product gases. During combustion of char, oxygen transported to particle surface and undergoes oxidation reaction with carbon to produce CO and CO₂. Carbon in coal char oxidised to CO by OH radicals and CO oxidised to CO₂ at 900°C. Temperature at which char burn is partially controlled by amount of CO oxidised by OH radicals. Production ratio of CO/CO₂ depends on surface temperature of fuel; above 1000°C reaction product is CO [2, 20].

A. Regimes of combustion:

During starting of fluidised bed temperature is low, for fine porous particles mass-transfer is high and combustion is

kinetic controlled. Oxygen gets enough time to enter all pores of char particles and burns uniformly as a result density of particle decreases when combustion progress. Oxygen concentration is uniform throughout the char and sudden collapse of bridge occurs due to uniform density decrease in char. For medium size char particles and for some parts of fluidised bed, reaction and pore diffusion rates are comparable, allows limited penetration of oxygen into pore. For large particles mass-transfer rate is very low compared to kinetic rate or kinetic rate is so fast and combustion is diffusion controlled. As combustion progresses size of char reduces and mass transfer increases, when the combustion progresses controlling rate moves from diffusion to kinetic [2, 19, 20].

B. Sulphur dioxide retention:

Desulphurisation is solid-gas heterogeneous reaction; initial stage of reaction is first order and proportional to concentration of SO₂. Partial conversion of limestone into CaO and CO₂ is known as calcination. During capture of SO₂ a layer of CaSO₄ forms on the surface of limestone and remaining gases diffuses through this layer [2, 24]. Formed CO₂ creates pores on limestone to enhance the reaction. Fine pores provides large surface area for sorbent but entrances of pores are easily blocked, large pores gives access to the interior but has less reaction surface area. If partial pressure of CO₂ greater than equilibrium partial pressure of CO₂ stops the calcinations, dolomite used as alternate sorbent in pressurised fluidised bed. During SO₂ absorption pore volume of sorbent surrounded by the products of sulphation process, large amount of sorbent required for SO₂ capture. SO₂ capture rate increases with rise in temperature up to 840°C and then start to decrease because of decomposition of CaSO₄ at high temperature [2, 24]. High fluidisation velocity reduces residence time and increases sorbent entrainment, sulphur capture decreases along height of furnace. High volatile fuel has low sulphur capture by formation of SO₂ and H₂S; staging of air reduces NO_x but affects SO₂ capture [2].

C. Emission from fluidized bed combustion system:

N₂O is responsible for green house effect and NO_x is responsible for acid rain. NO_x and N₂O emission influenced by interaction between flue gas and fuel particle. Increase of coal particle size, temperature and limestone feed rate decreases N₂O emission but increases NO_x emission. Excess air results in increase of N₂O, NO_x emission but staged air addition reduces NO_x emission, in pressurised fluidised bed combustor increase in pressure decreases NO_x emission. Co-combustion is one of the solutions to reduce NO_x, N₂O emission. Fixed carbon content plays an important role in combustion of fuel bound nitrogen to N₂O. Control of temperature and residence time is crucial for NO_x formation [2, 17, 25].

VI. CONCLUSION

Fluidised bed combustion system has improved combustion and reduced emission characteristics than conventional systems but its operation is severely affected by agglomeration. Agglomeration occurs around fuel ash initial deformation temperature indicated by fluctuation in bed temperature, reduction in system pressure drop. Operating the system under low temperature reduces the agglomeration

formation but it decreases the thermal efficiency of the system, system operating temperature selected based on ash melting point, NOX formation temperature and optimum sulphur capture and it is in the order of 850°C-900°C. The agglomeration control methods based on limiting formation of low temperature eutectics, common methods to control are alternate bed materials and additives, leaching technique and co-firing. China clay, dolomite, silica, limestone, alumina and andalusite, sillimanite, gibbsite are common bed materials and additives, feldspar, dolomite, magnesite, alumina were capable of producing eutectic mixture with higher melting point. Leaching used to remove sulphur content from fuel; co-firing of coal with biomass reduces emission level and increases defluidisation time about 12 times but decreases system efficiency and capacity. Chlorine content of biomass causes deposition problem. Further understanding is required to reduce solid waste and CO₂ production from fluidised bed combustion system.

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