Review of models and tools for slagging and fouling prediction for biomass co-combustion

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1. Introduction

In addition to increasing the overall power plant cycle efficiency, there are two principal means of the reduction of the CO_2 emissions from coal fired power plants, viz:

- by co-firing biomass, i.e. the substitution of some or all of the coal fired in the plant with a carbon neutral fuel, and
- by the capture and long-term storage of the CO_2 emitted by the power plant.

Carbon dioxide capture and storage will involve substantial capital expenditure, will involve a significant power plant cycle efficiency penalty, and is not currently available on a fully commercial basis. Biomass co-firing has a number of attractions, viz:

- The technology is commercially available and reasonably well established, particularly in Northern Europe,
- The projects can be implemented fairly quickly, and
- The capital expenditure is modest, because maximum use is made of the existing equipment and infrastructure.

For these reasons, it is very likely that biomass co-firing will continue to play a significant role in the achievement of the CO_2 reduction goals in the European Union and elsewhere.

Principal types of biomass materials that are utilised in industry in significant quantities are listed in Table 1. The majority are waste and residue materials from agricultural, forestry and industrial activities. In most cases, these materials are traditionally left in situ or sent for disposal to landfill. There, they will be subject to microbial respiration and other processes, which release greenhouse gases into the atmosphere.

In recent years, the value of biomass as a renewable fuel has been increasingly recognised, and they are being collected, processed, if necessary, and delivered as fuel for utilisation in combustion and other thermal processing plants. An increasing number of dedicated biomass power plants are being built worldwide, and the level of biomass co-firing activity at the coal-fired power plants is also increasing. There is also an increasing international trade in biomass materials for use as fuel for the generation of power and heat.

To date, much of the biomass co-firing in large coal-fired utility boilers has been at relatively low co-firing ratios (in most cases up to 20% mass based), and the impact on boiler performance and integrity have, in general, been modest. With increased co-firing levels, the impacts on plant performance and integrity will become more significant, particularly with the lower grade biomass materials. Principal technical concerns are associated with the behaviour of the mixed coal-biomass ashes, and there are significant concerns about the potential impacts of ash deposition on surfaces in the boiler and associated equipment.

Agricultural products	**Forestry products**	**Wastes**	**Energy crops**
Harvesting residues	**Harvesting residues**	**Domestic/industrial**	**Wood**
Cereal straws Oil seed rape and linseed oil straws Flax straw Corn stalks	Forestry residues	Municipal solid waste (MSW) Refuse-derived fuels Construction and demolition wood wastes Scrap tyres Waste pallets	Willow Poplar Cottonwood
Processing residues	**Primary processing wastes**	**Urban green wastes**	**Grasses and other crops**
Rice husks Sugarcane bagasse Olive residues Palm oil residues Citrus fruit residues	Sawdusts Bark Offcuts	Leaves Grass and hedge cuttings	Switchgrass Reed canary grass Miscanthus
Animal wastes	**Secondary processing wastes**		
Poultry litter Tallow Meat/bone meal	Sawdusts Offcuts		

Table 1 **The major biomass materials of industrial interest on a worldwide basis**

Operational problems associated with the deposition and retention of ash materials can and do occur on all of the major gas-side components of combustors and boilers. The more important high temperature occurrences in the more common solid fuel combustion systems are associated with the following:

- The partial fusion and agglomeration of ash particles in the fuel beds of stoker-fired and fluidised bed-fired combustors can lead to poor combustion conditions and de-fluidisation of fluidised beds, and can cause problems with the ash removal system and with the downstream ash handling equipment.
- The deposition of fused or partly-fused ash materials on burner component and divergent quarl surfaces in large pulverised fuel furnaces can result in interference with burner light-up and other operational difficulties, and can affect combustion performance.
- The build up of large accumulations of fused and partially-fused ashes can interfere with the operation of stokers and fluidised bed combustors, and can block ash hopper throats in pulverised fuel-fired furnaces. This can result in a requirement for load reduction or can lead to significant unplanned outages for off-load cleaning.
- The deposition of fused or partially-fused slag deposits on furnace heat exchanger surfaces reduces furnace heat absorption, and leads to increased gas temperatures both within the furnace and at the furnace exit. This, in turn, can lead to increased ash deposition and high metal temperatures in the convective sections of boilers, and it may be necessary to reduce load or to come off load for manual cleaning.
- The accumulation and subsequent shedding of large ash deposits on upper furnace surfaces can lead to damage to grates and to furnace ash hoppers, and to the de-fluidisation of bubbling fluidised beds.

These are slag formation processes which generally occur at relatively high temperatures in excess of around 800-1000 ºC, on refractory or water wall surfaces in the furnace which are in direct receipt of radiation from the flame. They occur relatively rapidly, over a matter of minutes or hours, when conditions are favourable. They usually involve the sintering and (partial) fusion, of fuel ash particles within the furnace.

The accumulation of ash deposits in the convective sections of boilers also occurs. These ash accumulations are normally termed fouling deposits, and the more common occurrences include:

- The formation of ash deposits on the surfaces of superheater, reheater and evaporator banks occurs at flue gas temperatures less than around 1,000-1,100 ºC. This is generally a much slower process than slag formation, and the tendency is for significant ash deposits to grow over a period of a number of days. The process involves the formation of deposits in which the ash particles are bonded by specific low melting point constituents, principally the alkali metal species. The gas temperature is generally too low for significant sintering or fusion of the bulk of the ash particles to occur. As the gas temperature decreases in the boiler convective section, the deposits tend to be less extensive, and to be less well bonded and physically weaker. This is commonly reflected in the design of the boiler convective section, i.e. it is often possible to reduce the cross pitches of the tube banks progressively as the flue gas temperatures decrease.
- Convective section fouling is one of the most troublesome ash-related problems associated with the combustion and co-firing of biomass materials, because of the relatively high alkali metal contents, and hence high fouling potential, of many biomass materials. Fouling reduces the heat absorption in the convective banks, and results in increased flue gas temperatures. Fouling also increases the gas-side pressure drop across the banks, and can eventually lead to ash bridging between the tubes. This further increases the gas side pressure drop, and can result in the channelling of the flue gas. The increased flue gas velocity can result in local overheating of the heat exchange tubes, and in localised damage to boiler tubes and other components by particle impact erosion.
- The ash deposits on economiser surfaces form at low flue gas temperatures and tend to be relatively weakly bonded. They are commonly initiated by the physical accumulation of ash, often by the gravitational settling of ash material. This material has been dislodged from primary deposition sites upstream of the economiser by the action of sootblowers.
- Low temperature fouling and corrosion of airheater surfaces are also common occurrences. This is a complex process, that can involve both ash deposition and the condensation of acid gas species on cold surfaces, and they tend to be very specific to the design and operation of the airheater.

It is clear, therefore, that the ash deposition process occuring on furnace and boiler surfaces is a complex phenomena. The process occurs over a wide range of flue gas and surface temperatures, and is dependent both on the characteristics of the ash and on the design and operation conditions of the combustor or boiler plant.

The principal objective of this paper is to present a short overview of the existing models and tools, which have been developed largely for pulverised coal combustion systems, and to review their application for the description and prediction of the slagging and fouling behaviour of the biomass ash and the mixed coal-biomass ashes in biomass firing and co-firing applications.

An overview of the principal technical approaches that have been taken to the predictive modelling of the extent and location of ash deposition in furnaces and boilers is presented in Section 2 of this document. In Section 3, there is a discussion of a number of the more important on-line diagnostic methods that are available for the monitoring of ash deposition in boilers, and of the use of the results of these methods to provide predictions of the extent and distribution of ash deposits by means of neural networking. The application of these methods to the mixed ashes produced by the co-firing of biomass with coal is discussed in Section 4.

2. Predictive methods for ash deposition

In general terms, three approaches to the development of predictive models for ash deposition in furnaces and boilers are apparent, viz:

- The empirical approach by traditional methods based on the use of simple Slagging or Fouling Indices, using the data normally available on fuel specifications, i.e. the ash chemical composition and the ash fusion temperatures. These relatively simple, practical methods are used by designers and operators, particularly when no fuel sample for more detailed analysis is available, as input to their normal design or fuel assessment procedures.

- The mechanistic approach involves the use of relatively simple models of the combustion and other processes that may occur in combustors and boilers, in an attempt to provide a general assessment of the ash deposition tendency and the nature of the ash deposit in a specific application.
- In principle the more advanced models based on computational fluid dynamics (CFD) can provide detailed information about the combustion process and the fluid dynamics. For the simulation of ash deposition processes, the CFD models have sub-models of the ash transformation process, particle deposition and adhesion and the impacts on heat transfer.

The individual approaches are discussed in the next sections.

2.1 The empirical approach

2.1.1 Ash fusibility

The fusion behaviour of solid fuel ashes is an important factor in determining the propensities of the fuels to form fused or partly-fused slag deposits on the reactor surfaces in all thermal processors systems and, in some circumstances, may have an influence on the nature of the fouling deposits that can occur on the heat exchange and other surfaces. The fusion behaviour of most fuel ashes is a fairly complex phenomenon, which is best described in terms of a melting curve, where the percentage of the ash, by mass, which is fused is plotted against the temperature. On full ash melting curves, two key temperatures are commonly identified, and can be used to describe the physical behaviour of the ashes, viz:

- The T_{15} temperature is the temperature at which 15% of the ash material by mass is molten. This is considered to be the temperature at which the surfaces of the ash particles or slag deposits begin to become sticky and receptive to the adhesion of solid particles, and
- The T_{70} temperature is the temperature at which 70% of the ash material by mass is molten. This is the temperature at which the outer surface of an ash deposit on a vertical surface will begin to flow under the action of gravity.

The determination of full melting curves for ashes is a very time-consuming exercise. The standard Ash Fusion Test, which has been applied for the characterisation of the fusion behaviour of coal ashes for many decades, is much simpler and is based on the determination of three or four key temperatures on the melting curve. This procedure has been developed and applied specifically for alumino-silicate, coal ash systems, which have very complex melting behaviour. Coal ash systems commonly melt over a fairly wide range of temperatures from around 1000-1500 ºC, and tend to produce relatively viscous melts.

The results of the application of this test procedure to biomass ashes, most of which are not alumino-silicate systems, and many of which melt at temperatures less than 1000 ºC, are of technical interest, but should be treated with great caution. There have been several attempts to develop correlations between the ash fusion temperatures and the ash chemical composition for coal and biomass ashes. These can be of some technical value in a general sense, however they tend not to be reliable or accurate enough for predictive purposes.

2.1.2 Ash deposition indices

A number of Slagging and Fouling Indices are available for the assessment of the propensity of fuel ashes to form deposits, in combustors and in the convective sections of boilers. A detailed description of the technical basis and use of a number of these indices is presented in Raask (1985). These indices are based either on the fuel ash content and the ash chemical composition, or on the results of the Ash Fusion Test. In the main, these indices have been developed for the assessment of coal ashes, and have been applied, with appropriate modifications, to the ashes from other solid fuels, including wastes and biomass materials, and to the mixed ashes produced by the co-processing of biomass materials with coal.

The majority of the Slagging Indices are concerned with the prediction of the fusion behaviour of the ash, and are based either on the results of Ash Fusion Test or on the chemical composition of the ash, commonly the ratio of the acidic metal oxides, (SiO_2 and Al_2O_3) to the basic oxides (Fe_2O_3, CaO, MgO, Na_2O and K_2O). These indices provide a general assessment of the fusion behaviour of an ash, which is then employed to rank the ash in terms of its propensity to form fused or partially-fused agglomerates and slag deposits. Despite the recognised technical limitations of both of these approaches, they are still used widely within the industry for fuel specification, furnace, reactor and heat exchanger design and for plant operational purposes.

A number of more sophisticated approaches to the assessment of the slagging propensity, for instance based on the use of phase diagrams of the appropriate alumino-silicate systems, or on the use of mineralogical analysis data derived from the characterisation of the fuel using scanning electron microscopes and other advanced techniques, have been developed. These have, however, enjoyed only relatively limited use within the industry, principally because they are less familiar and more complicated than the traditional methods and some need access to specialised equipment. These methods are more often used for investigative purposes

Since the majority of the coal ash slagging indices are based on the assessment of the fusion behaviour of alumino-silicate coal ashes, the application to biomass ash systems, which are chemically very different, can be problematic, and great care should be applied when interpreting the conventional Slagging Index values for biomass ashes and to the ashes produced from the co-processing of biomass materials with coals.

When considering the potential slagging behaviour of the mixed ashes from the co-processing of biomass with coal, it is clear that, apart from SiO_2, all of the significant chemical constituents of most biomass ashes, and principally the alkali and alkaline earth metals, are powerful fluxes for alumino-silicate systems. It is expected, therefore, that the co-processing of biomass with coal will tend to result in a significant reduction in the fusion temperatures, and hence an increase in the slagging potential. This will, of course, depend on the level of fluxing agents already present in the coal ash and on the co-firing ratio. It has been found that the effect is much more dramatic when biomass is co-processed with coals with high fusion temperature ashes, since the effect of adding fluxing elements to a coal ash with low levels of the fluxing elements tends to be much greater than adding fluxes to a coal with lower ash fusion temperatures and hence higher levels of fluxing elements.

For the co-processing of biomass with coal at relatively low levels, say less than 10-20% or so on a mass basis, the mixed ash is still predominantly an alumino-silicate system, and the normal coal slagging assessment methods can generally be applied, with some confidence.

The most commonly applied Fouling Indices for coal ashes are, in the main, based on the sodium content of the fuel. The technical reason for this is that the deposition of the sodium compounds in the fuel by a volatilisation/condensation mechanism is considered to be the principal driving force for heat exchanger fouling in coal plants. The majority of the potassium in coal ashes is present as a constituent of the clay minerals, and is not considered to be available for release by volatilisation in the flame to the same extent.

For most biomass materials, potassium tends to be the dominant alkali metal, and this is generally in a form that is considered to be available for release by volatilisation. The fouling indices which have been developed specifically for the assessment of biomass materials tend, therefore, to be based on the total alkali metal content of the fuel (see, for instance, Miles *et al*. 1995).

For the co-firing of biomass with coal, some combination of the two methods should be applied, and this assessment should always be carried out with great care.

2.2 The mechanistic approach

2.2.1 Comprehensive prediction models

A number of reviews of the development of models for the prediction of ash deposition in coal boilers have been published (for instance, Wang and Harb 1997, and the references cited therein). The majority of the models are mechanistic in nature, and attempt to provide descriptions of some or all of the following processes:

- Fuel and mineral matter characteristics,
- Fuel combustion, ash formation processes and the ash particle characteristics,
- Fluid dynamics and particle transport,
- Particle impaction and adhesion,
- Deposit growth rate as a function of the ash characteristics, the conditions at the deposition site and time,
- Deposit properties and strength development,
- Heat transfer through the deposit,
- The effect of deposition on operating conditions (e.g. temperatures and heat fluxes), and
- The deposit structure and its effect on gas flow patterns.

A schematic diagram which describes the general approach that has been taken to the development of mechanistic models of the ash formation and the ash deposit formation processes, based on this general process scheme is presented in Figure 2, below.

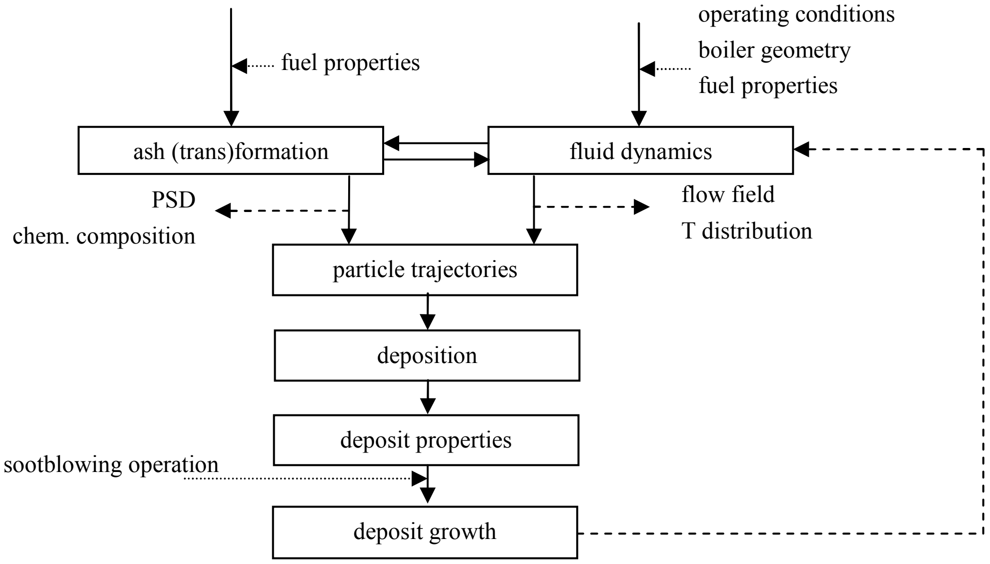

Figure 2 **Comprehensive modelling approach**

Fuel particle combustion and ash formation

An ash formation model which provides predictions of the chemical composition and particle size distribution of the fly ash particles is required. These models require detailed input on the physical and chemical properties of the fuel particles and the associated mineral material. This most commonly derived from the data available from computer-controlled scanning electron microscopic examination (CCSEM) of the pulverised fuel. They normally incorporate a model of the combustion of the coal particles and the fractionation and coalescence behaviour of the ash particles in the flame, which generates a description of the particle size distribution and the chemical compositions of the fly ash particles. The general scheme of these processes is illustrated schematically in Figure 3.

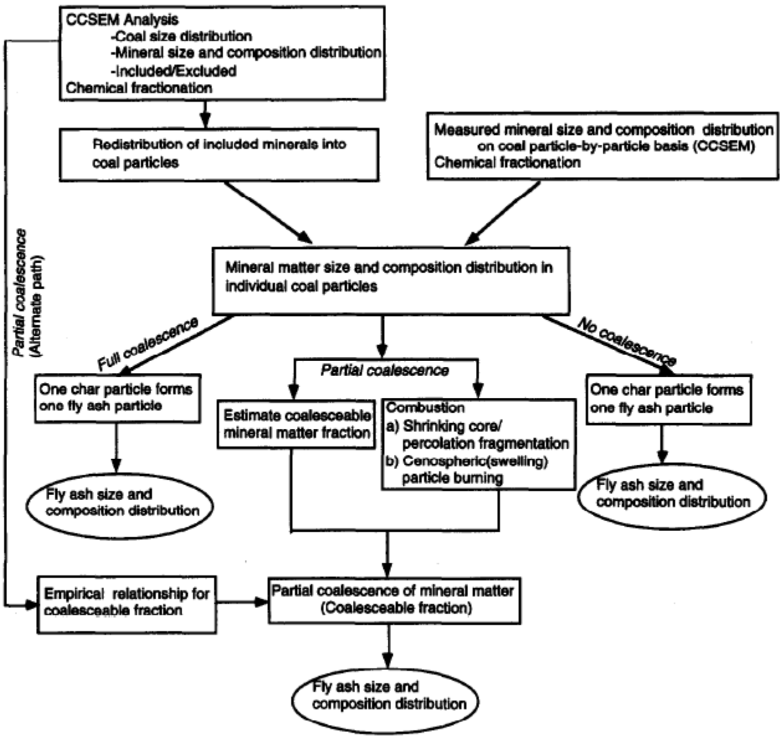

Figure 3 **General algorithm for ash transformations, using CCSEM as input source: [Wang and Harb, 1997]**

In an article by Yan *et al.* (2002), the ash particle fragmentation was simulated using a Poisson distribution method. The coalescence of the included mineral occurrences was treated similarly to char combustion, i.e. using a shrinking core model. Baxter *et al.* (1991) described the development of an alternative approach using standard ASTM analyses and chemical fractionation data rather that CCSEM data. Using this approach, the key chemical elements are allocated to one of thirteen different mineral groups whose behaviour as a function of the residence time and temperature is relatively well understood.

Computational Fluid Dynamics (CFD)

In recent years, a number of attempts have been made to utilise CFD methods to model the ash formation and transport processes in pulverised fuel and fluidised bed combustion systems (Huang *et al.*, (1996), Wang and Harb, (1997), Lee and Lockwood, (1999), Mueller *et al.*, (2001), Kær *et al.*, (2006), Ma *et al.*, (2007)). This type of modelling offers the prospect that it can take into account local conditions within the furnace and boiler, and that it may be possible to simulate the consequences of changes in the plant operating conditions. In the majority of these models, a number of key phenomena are considered, [Kær *et al.*, 2006], viz:

- turbulent fluid flow,
- gas and particle combustion,
- heat release and heat transfer, and
- ash particle transport.

When a converged steady-state solution is obtained, the ash particle fluxes to the boiler surfaces and the deposit growth rate is calculated as a "post-processing" calculation.

Deposition modelling

A number of particle transport or deposition mechanisms can be responsible for the build up of a deposit layer on the surfaces on the furnace walls or on a convective pass tube, depending on the concentration, size and chemistry of the fly ash particles, the nature of the surface and the local physical conditions, viz:

- Inertial impaction,
- Thermophoresis,
- Eddy and Brownian diffusion,
- Condensation, and
- Heterogeneous reactions of deposit constituents, generally with acid gas species in the flue gases.

One of the more common approaches to the modelling of the deposit build-up with time [Kær *et al.*, 2006] is illustrated in Figure 4.

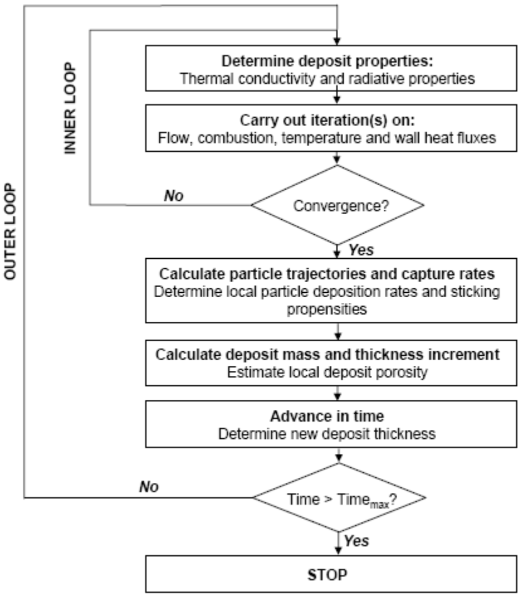

Figure 4 Flow chart of deposition model concept with advancement in time; source: [Kær *et al.*, 2006]

The inertial impaction of fly ash particles on the growing deposit surface is most often the dominant process for slag formation processes within the furnace, and this is relatively easily described [Baxter, 2007]. The impaction efficiency can be written, for instance as a function of the effective Stokes number. The efficiency of subsequent adhesion of the incoming particles is commonly described using the viscosities of the particles and of the surface of the growing deposit. Several models of the particle adhesion processes have been developed (Walsh *et al.* (1990)).

Thermophoresis is generally important only at very low deposition rates, e.g. for the initial ash deposit when the boiler tubes are clean and new. According to Baxter (2007), there is a lot of potentially useful theory available to describe thermophoresis processes, however the results have not so far been very satisfactory.

Condensation, particularly of alkali metal species, is a key process during the very early stages of slag deposit formation on clean furnace tubes, and in the formation of convective pass fouling deposits, where temperatures are too low for fusion of the bulk ash material. The theory of condensation is available, but is rather complex for practical applications.

The key chemical reactions involved in ash deposit growth are sulphation, alkali absorption and oxidation. They add to the mass of the deposit and may increase deposit strength due to recrystallisation. These are complex to describe in the condensed phase [Baxter, 2007].

It is clear from the above, therefore, that there are significant difficulties associated with the modelling of the deposit growth and strength development processes for processes primary deposition sites, i.e. where the deposit growth involves the addition of coal fly ash particles to the deposit. Deposition processes which involve the shedding or migration of the deposited ash material, and which may result in subsequent deposition of ash deposit material at a secondary site, can be very important in the development of mature ash deposit patterns in boilers. These processes, however, have not been extensively studied are not well understood. They are generally not covered by the current models.

Uncontrolled ash deposition, with no shedding or deposit removal would, in most plants firing solid fuels, very quickly result in significant operational problems. The majority of solid fuel furnaces and boilers are fitted with on-line cleaning systems of various types to permit a level of control over the extent of ash deposition in key areas of the plant. There are also natural ash deposit shedding mechanisms and other processes which are responsible for the reduction in the extent of deposition.

The key processes responsible for the shedding of ash deposits include the following:

- The principal means of the on-line control of ash deposit growth in most solid fuel-fired furnaces and boilers is the use of the installed sootblowers or lances. These devices direct a high velocity jet of steam, water or compressed air at the deposits, and employ a combination of mechanical impact and thermal shock to break up and remove the deposits. Sonic sootblowers can also be deployed, particularly for the dislodging of relatively weak deposits in the cooler parts of the boiler convective section. In extreme circumstances, where very tenacious and troublesome ash deposits have formed, small explosive charges and blasting cord have been employed to break up the deposit material.
- The deposit material removed in this way may be carried forward with the flue gases, but can also accumulate elsewhere in the furnace, or in the convective pass of the boiler, where the tube pitches may be narrower.
- The natural shedding or detachment of deposits also occurs. This can occur when deposits grow too large for the adhesive forces to support them, or due to the effect of thermal expansion differences between the ash deposit and the boiler tube, during shutdowns and boiler load changes. Rapid boiler/combustor load changes, or periods of firing low ash fuels such as oil or gas, can be deliberately used to encourage these processes, for deposition control.
- The detachment of large accumulations of slag in this way can, however, result in damage to components or in troublesome accumulations of ash lower in the furnace.
- Heavily fused deposits of low viscosity can drip on to surfaces lower down in the furnace or boiler.
- In extreme circumstances it may be necessary to reduce load or to come off load for manual cleaning of the boiler in order to get the extent of ash deposition under control.
- In the boiler convective section, fly ash particle impact erosion wear can result in the reduction of the thickness of fouling deposits, particularly on the sides of tubes.

Clearly, both secondary ash deposition and deposit shedding processes are of importance in the development of mature slagging and fouling deposits within boilers. This has been recognised only recently and it is clearly very difficult to model these processes in a practically meaningful way.

The first serious attempt to describe these processes in a systematic fashion is presented in a recent review by Zbogar et al. (2009). A number of deposit shedding mechanisms, both natural and artificial, were identified. The general conclusion was that the fundamental knowledge of the key shedding mechanisms and of the relevant properties of the ash deposits is limited, and apart from the specific issues associated with the operation of kraft recovery boilers, no serious attempt to model these processes has been made. This represents a major barrier to the development of practically useful predictive models for ash deposition in solid fuel-fired boilers.

2.2.2 Thermodynamic equilibrium modelling

In addition to the conventional ash chemical analysis and ash fusion tests, a number of other techniques are used to characterise the behaviour of fuels ashes. The use of chemical fractionation techniques, for instance, which were developed originally for the characterisation of the inorganic components of coals, has also been applied to the characterisation of biomass materials. The procedure normally involves the treatment of a small sample of the fuel by a standardised leaching process, with a series of progressively more severe chemical reagents. The leaching reagents employed for this purpose are commonly:

Water → ammonium acetate solution → hydrochloric acid solution

Four fractions are obtained, as described in Figure 5, viz:

- The water-leachable components which, in most cases, are principally the alkali metal salts, sulphur and chlorine compounds,
- The acetate-leachable components, which are generally associated with the organic fraction of the fuel, i.e. are present as in the fuel in the form of cations and chelates,
- The acid-leachable components, i.e. generally the carbonates and sulphates, and
- The solid residue, principally silica, silicates and other mineral species insoluble in mineral acids.

It is generally considered that the water and acetate-leachable elements are those that are likely to be more readily released into the vapour phase, and which may tend to form the very finest aerosol fraction of the ash generated from the biomass at elevated temperatures. The acid soluble and solid residue fractions are not considered to be available for release into the vapour phase during most thermal processes, and tend to report to the coarser fractions of the ashes.

In general, the general results of chemical fractionation tests on solid fuels can be summarised as follows:

- For bituminous coals, very little of the inorganic material in the fuel, and generally only the sodium chloride, is found in the water and acetate soluble fractions.
- For lignites and peat, a higher level of water and acetate soluble material, with some of the calcium in the acetate soluble category, is commonly found.
- The biomass materials, in general, have significantly higher levels of water and acetate soluble material, with the majority of the potassium and chloride, and some of the calcium and magnesium, being in this category.

Clearly, the chemical fractionation techniques can provide some useful, general information about the nature and potential behaviour of mineral material and ashes in combustion and other thermal processing plants. It is also clear, however, that the procedure has a number of important limitations and the results should be interpreted very carefully. These techniques are also relatively time-consuming and expensive to perform, and are employed principally for research and investigative purposes.

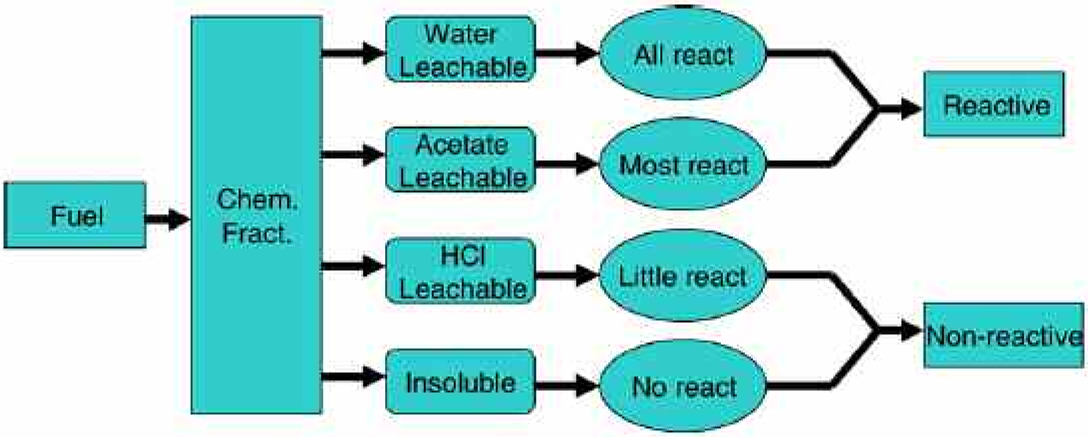

Figure 5 **Definition of reactive and non reactive fractions from Chemical Fractionation analysis, Nutalapati *et al.*, 2007]**

In thermodynamic equilibrium modelling of ash behaviour, the reactive fraction from the chemical fractionation test is used as input for the thermodynamic equilibrium calculations of the deposit formation processes, whereas the non-reactive fraction is considered as being relatively inert.

This approach was adapted by Nutalapati *et al.* (2007) to allow for interactions between the gas phase alkali metals and silica particles at elevated temperatures. They investigated the effect of regarding the HCl leachable fraction and the non-leachable fraction as partly reactive, and considered that the outer layer of the quartz particles after reaction with the alkali metals, to produce a surface layer of alkali metal silicates of lower melting temperatures, could be regarded as being reactive

This concept is illustrated in Figure 6. Assuming spherical particles with a diameter of 10 μm, an active surface layer of 1-5 μm in thickness would result in 5-25% of the acid/non leachable fraction by weight being in the reactive category.

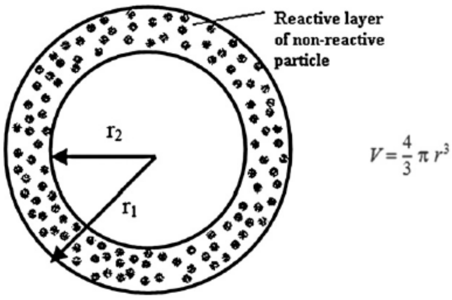

Figure 6 Spherical ash (silica) particle with outer (molten) reactive layer; source: [Nutalapati *et al.*, 2007]

There is experimental evidence, for instance, that significant reaction between the alkali metals in the vapour phase and the silica particles, during the combustion of wheat straw, occurs at temperatures in excess of 1300°C, according to measurements made by .Lindner and Wall (1990).

For ash deposition processes in biomass firing and co-firing situations, the models have to describe the non-ideal behaviour of alumino-silicate slags, alkali metal silicates and molten alkali salts. The key modelling approach makes use of the FactSage code. For liquid phases with strong interactions among the atoms, which is the case in silicate slags, strong short-range ordering occurs, so there is no random distribution of the atoms. The modified quasi-chemical model is applied to take this in account. Molten salts are described in FactSage using sub-lattice models. For details of the results of this type of modelling work, reference should be made to the work published by Pelton and Blander, (1986); Pelton, (1988); Pelton *et al*,. (2000); Pelton and Chartrand, (2001); Chartrand and Pelton, (2001); Pelton *et al*., (2001).

It is clear from the published work to date that the thermodynamic equilibrium modelling of the complex ash generation and deposition processes taking place in the combustion systems and boilers is very difficult. It is also clear that some processes will be kinetically controlled. The incorporation of reaction kinetics into the models will require exhaustive knowledge of the reactions, and this is not available for all of the relevant processes. The use of equilibrium calculations is considered to provide an “educated guess” and this is current common practice.

It should be noted in this context that the heating rates in the flame zones of pulverised fuel boilers are of the order of 10^3-10^5 Ks^{-1}, and that the particles and flue gases have residence times of a second or two in the flame, a few seconds within the furnace, and tens of seconds in the boiler. It is recognised that the equilibrium state is not completely reached in boiler processes, especially for CO_2/CO, SO_2/SO_3, and for a number of the trace elements like Hg. Equilibrium calculations can provide, at best, an alternative means of studying the key ash formation and deposition processes, and this can be of some benefit in certain circumstances.

3. The on-line measurement and prediction of ash deposition

The control of ash deposition in solid fuel-fired combustors and boilers is a fairly complex issue, involving fuel diet, boiler design and operational factors. The key factors are:

- The careful design of the furnace and boiler convective section, which recognises properly the characteristics and behaviour of the fuel ashes, is of prime importance, and the equipment supplier obviously has the key role in this regard. The incorporation of specific furnace and boiler design features, where appropriate, to minimise ash deposition, to aid the removal of ash, and to avoid ash accumulation within the system, is obviously of key importance.
- The correct design, operation and maintenance of the combustion equipment and of the on-line cleaning systems are important issues. It is usually preferable to minimise the risks of excessive deposition by maintaining the furnace and boiler surfaces at a relatively low level of deposition, rather than deploying the on-line cleaning systems only when there is evidence of significant ash deposition. The intensive cleaning of the furnace and boiler surfaces during boiler outages can be very effective in increasing the operating times between forced outages for manual cleaning, particularly in situations where the control of the ash deposition is a significant operational issue.

There are specialised on-line deposition monitoring and sootblowing control systems, that are commercially available, and that can assist with the optimisation of the sootblower operations and the control of ash deposition. These systems are designed principally for the control of deposition in the larger industrial and utility fossil fuel-fired boilers. Systems are available for the control of ash deposition in both the furnace and the convective sections, and for optimisation of the boiler performance. These systems are generally based on the on-line measurement of the temperatures or heat fluxes at the furnace walls, or on measurement of the heat transfer performance of individual convective banks.

There have been relatively few detailed reports of the systematic testing of the performance of these on-line sootblower optimisation systems. Recently, some comments on the shortcomings of the commercially available systems for the on-line monitoring of ash deposition and the use of the intelligent sootblowing systems, were published by Teruel *et al.* (2005). The comments included:

- The vendors of the on-line systems, in some cases, claim exaggerated benefits for their products, often on the basis of the results of plant trials, however very little impartial and authoritative technical information on the effectiveness of these systems has been published in the open literature,
- Most of the on-line systems provide only very simple estimates of the fouling factors, and apply only a very crude approach to the optimisation of the sootblower operation,
- The interpretation of the outputs of the on-line monitoring with reasonable repeatability is somewhat difficult, bearing in mind the uncertainty in the measurement of plant data, and the variability of the feedstock;
- The optimization of on-line cleaning systems requires effective monitoring of deposit growth and the prediction of the future evolution of the deposits. This is particularly important for slag formation on furnaces surfaces, since the deposit growth rate is distinctly non-linear. This exceeds the abilities of the current systems.

The authors were clearly sceptical about the effectiveness of the commercial systems currently available for the on-line measurement and prediction of ash deposition. They argued that the preferred option would involve the analysis of the appropriate on-line plant data using neural network methods. Their view was that the conventional statistical tools, such as simple curve fitting, would not be able to cope with the highly dynamic character of ash deposition and the uncertainties associated with the effectiveness of sootblower use.

In this context, there has been growing interest in modern modelling methods. Neural networks, for instance, can provide a more generalised approach to regression analysis that can be particularly useful in situations where the complexity of the problem presents difficulties in terms of the number of relevant factors, and where the use of simplifying assumptions may not be appropriate. The general approach can be described using an example presented by Bhadeshia (1999), as follows.

The solution to a linear regression can be described by the following equation:

$$y = \sum_i w_i x_i + c$$

where x_i represents the major input variables (concentrations, temperatures, etc.) and w_i is the associated weighting coefficients. Normally, the solution is obtained by systematically adjusting the values of w_i and c until the best fit to the data is found.

The correlation can be made both more general and non-linear by defining a hidden node as follows:

$$h = f(\sum_j w_j^{(1)} x_j + c), \text{ and}$$

$$y = w^{(2)} h + c^{(2)}$$

where f is a non-linear function, and $w^{(2)}$ and $c^{(2)}$ are a new weight and constant, respectively.

The output y is, therefore, a non-linear function of x_j. The function employed within the hidden node is most commonly the hyperbolic tangent, because of its inherent flexibility in this context. Further degrees of non-linearity can be introduced by the combination of more than one hidden node into a more complex network. The resulting quantitative models can be interrogated, and the model parameters can be examined allowing the significance of particular variables to be investigated.

In the current context, input values, i.e. data such as the plant operating conditions, the fuel analysis, etc., are related to output data through a combination of linear and non-linear functions. A data set, commonly called the training set, is used to minimize the error between the calculated and known outputs, prior to the application of the model to the real systems.

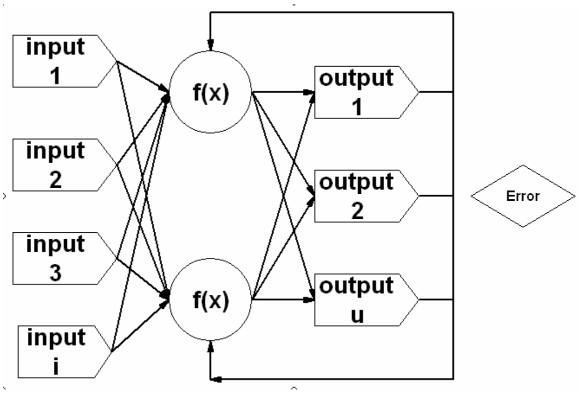

Figure 7 Overview of a neural network; source: [Schulze and Salverda, 1999]

As the processes involved in the build up of ash deposits are very complex and highly dynamic, it is probably unreasonable to expect that a network based on simple boiler load, fuel quality parameters, can adequately describe the evolution of deposit build-up. Teruel et al. considered, therefore, that it is more appropriate to use the neural network approach to describe simpler sub-systems.

The sub-systems used in this case were:

- The sootblower effectiveness,
- The increase in heat exchanger surface cleanliness after a deposit shedding occurrence, and
- The increase in the heat flux after a deposit shedding occurrence.

These sub-models are relatively simple and are similar in nature, and this helps to simplify the modelling work. The results of this approach, as reported by Teruel et al. were encouraging, as illustrated in Figure 8.

It was demonstrated that, by the detailed analysis of the data collected from an array of thirty heat flux meters arranged across the side and rear walls of the furnace, it was possible to provide a reasonable simulation of the effectiveness of the furnace wall sootblowers and the furnace heat absorption under realistic ash deposition conditions. They considered that this approach may be suitable for the optimisation of the operation of the on-line cleaning systems.

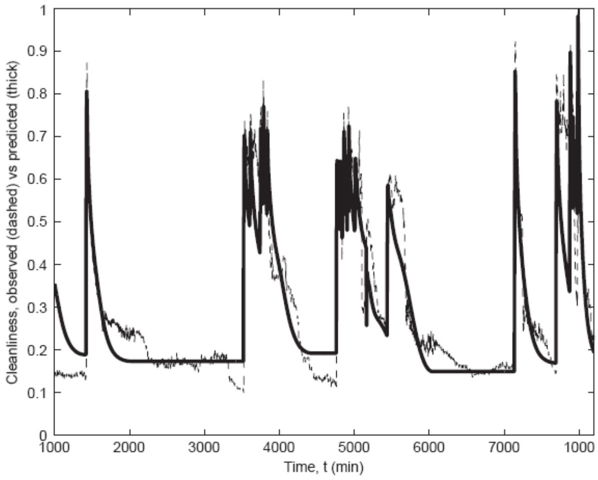

Figure 8 Predicted (bold line) versus measured (dotted line) cleanliness, (afterTeruel et al., 2005)

4 The application of ash deposition models and assessment methods to biomass co-combustion

As stated above, the majority of the models and tools have been developed for, and have principally been applied to, the description of ash deposition from pulverised coal combustion. More recently, there has been increasing interest in the co-firing of a wide range of biomass materials with coals, at co-firing ratios generally up to around 20% by heat input. In a limited number of cases, co-firing at higher ratios, or the full conversion of coal-fired boilers to 100% biomass, have been successfully achieved.

For coal and biomass firing, and co-firing, there has clearly been significant progress on the development, and the testing and validation, of the methods for the description of the chemical, physical and microstructural characteristics of the parent pulverised fuel particles, and of the evolution of the fly ash particles in the flame, particularly in terms of their size distribution and chemical composition. These developments have been supported substantially by the development and the application of computer-controlled Scanning Electron Microscopes with selected area chemical analysis facilities, and the associated data analysis software, over the past 20 years or so.

There have also been significant developments of the methods available for the computer simulation of the mass transfer processes which may influence the ash particle flux at the primary deposition sites, and, to a lesser extent, of the processes responsible for the adhesion of the on-coming ash particle to the surface of the growing deposit. Despite these developments, the capabilities of the existing models to predict the deposition rates at primary sites are limited, and the current technical approaches to the modelling of the deposit shedding and secondary deposition processes, are poorly developed. These are key processes in the development of mature deposits on boiler surfaces. These concerns apply both to the slag deposition in the furnace and the fouling deposits in the convective section of the boiler. Although the basic mechanisms responsible for slagging and fouling are significantly different, both types of deposit are subject to natural shedding processes and sootblowers are applied to control deposit growth in both cases. In both cases, there is a tendency for ash material, detached from the original deposit site, to accumulate at secondary sites.

The development of the predictive models has also been hindered significantly by the practical difficulties in obtaining reliable plant data for model development and validation from operating coal and biomass boilers. These systems are notoriously difficult to study because of the very hostile environment in which the key processes take place.

Overall, the result has been that the attempts to date to develop quantitative predictive models of ash deposition processes in the furnace and convective sections of industrial scale boilers, which can be of value to plant designers and operators, have not met with great success. The models are of significant academic interest, however their use by the industry has been principally for development and investigative purposes.

In the main, therefore, the industry has not made much in the way of practical use of the existing ash deposition models for fuel characterisation, boiler design or operational purposes, and continues to rely predominantly on the more traditional ash ranking methods for the routine characterization of the deposition propensities of coal and biomass ashes, and the mixed ashes generated by biomass co-firing.

As stated above, the measured ash fusion characteristics of a coal, carried out by the standard method, are widely used and are often quoted in coal analyses and specifications. This method has also been employed routinely within the industry to assess the slagging behaviour of biomass materials and biomass-coal mixtures, principally because it is familiar and simple to perform. There have been, however, some technical issues with the application of the procedure to some biomass ashes, and there have been difficulties with the reliability and repeatability of results in some cases.

The tendency towards slag formation is controlled largely by the fusion behaviour of the ash, and this can be assessed using the normal coal ash slagging indices, which are based on the ash chemical composition, or can be measured in the laboratory. For the mixed ashes produced when co-firing, the same technical principles apply. It is generally considered to be legitimate to apply these methods for mixed ashes in the same way as is done for coal ashes, although this should always be done with care.

For convective pass fouling, the main driving mechanism is the release of alkali metal species in the flame by volatilisation, and the subsequent condensation of the inorganic vapours on cooled boiler surfaces. Again, it is legitimate, with care, to apply the fouling indices available for coals, albeit in a modified form, to take into account the differences in chemistry between coal and biomass materials, or to apply the specific fouling indices for biomass materials, which are based on the total alkali metal content of the fuel per unit mass or per unit of heat content.

It is generally considered to be legitimate, therefore, to apply current boiler design methods, with appropriate modification where necessary, to provide an assessment of the slagging and fouling behaviour of the mixed ashes from co-firing, although it has to be recognised that the risks of obtaining misleading results will increase with increasing co-firing ratio.

5 Summary and conclusions

To date, much of the biomass co-firing in coal-fired utility boilers has been at relatively low co-firing ratios, less than 20% on a mass basis, and generally less than that on an ash basis. The impact on the combustion process, boiler performance, and boiler integrity, has been modest. The current empirical methods for the assessment of the fuel characteristics have proven to be adequate in most instances. With increased co-firing levels, it is anticipated that the fuel-related impacts on plant performance increase. The principal technical concerns are with the behaviour of the mixed ashes and the potential impacts on ash deposition on surfaces in the furnace, the boiler and the associated equipment.

The ash deposition process that occurs when biomass is co-fired with coal, is a complex phenomena, which occurs over a wide range of flue gas and surface temperatures. The process is dependent on the characteristics of the ash, and on the design and operation of the combustor or boiler plant. The prediction of the growth rate and the nature of the ash deposits for plant design or operational purposes is therefore a complex task.

Traditionally, for routine fuel specification, equipment design and operational purposes, relatively simple empirical methods have been applied. Alternatively, more complex technical approaches to the modelling of these processes have been attempted over several decades. It is fair to say that the deposition models have not been widely adopted for these applications. The use, within the industry, of the predictive models and the associated descriptions of the ash generation and deposition processes, has largely been for development and investigative purposes. The principal reason for this is that the quantitative, predictive capabilities of even the best of the analytical models are limited. It has proven very difficult to provide practically useful simulations of the development of mature ash deposits within the furnace and in the convective sections of a boiler, without proper consideration of natural ash shedding and sootblowing, and of the secondary deposition processes. This has been recognised recently by some of the research groups involved in the development of the mechanistic ash deposition models, but, as also described by Zbogar *et al.* in a recent review paper, serious work on the description of the key features of these processes has only just begun.

On a more practical level, there has been significant improvement over the past few years in the techniques available for the monitoring of ash deposition in operating plant and for the optimisation of the use of the on-line cleaning systems. Some of the recent work on the use of on-line plant monitoring with advanced data analysis techniques to predict the effectiveness of the on-line cleaning systems may be of some interest to plant operators, initially to provide additional information to the operating staff, and in time it may be possible to introduce systems for the automatic optimisation of the on-line cleaning equipment.

It is concluded that various relatively simple empirical deposition models have been developed for coal firing applications. More complex models for coal and biomass co-firing applications have been developed or are under development. The deposition models have not been widely adopted for these applications today. In addition, improvement has been made in the techniques available for the monitoring of ash deposition and on-line cleaning systems for the radiative and convective section of a pulverized fuel fired boiler.

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