Overview of Actual Methods for Characterization of Ash Depostion

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ABSTRACT

Utility operation with frequent fuel switching is a common practice, forced by cheaper coal availability in the international market. Additionally, a substitution of coal by cheaper local secondary fuels, ranging from forest wood to sewage sludge and industrial or domestic residues, is gaining importance. Switching between different fuels, even if these do not differ much from the design coal, enhances operational problems arising from ash deposition. In order to prevent operational problems, through comprehension of the phenomena taking place within the furnace, appropriate sampling and characterization of the deposits are necessary.

Methods commonly used for analysis of ash deposits and their characterization are summarized in this paper. The goals of the experimental work at the Institute of Process Engineering and Power Plant Technology (IVD) are then summarized. Finally, work on modeling the slagging and fouling phenomena or their characterization is presented.

INTRODUCTION

Slagging and Fouling (S&F) phenomena are one of the main reasons for unscheduled plant shut-down[1] due to the loss of efficiency in the heat transfer. Furthermore, ash deposition is also related to corrosion processes[2] and thus to material life reduction.

A reduction of the problems related to ash deposition is therefore one of the main concerns during boiler design and all along power production down to utility operation. The difficulties in the past involved in predicting ash behavior and the changes in patterns of fuel use, highlight the need to understand the mechanisms involved in ash deposition, so the problems can be assessed accurately[3].

The deposition of ash particles on the heat exchange surfaces and refractory walls of power plants and the formation of molten phases depend on ash composition and local thermal, physical and chemical parameters. In spite of the large amount of local variables, the complexity of the S&F problem starts at the beginning of the power generation concept. The different fuel qualities and techniques for fuel preparation, have a determinant influence on the combustion process. Together with the various firing systems, different fuel compositions result in different release mechanisms and thus in different gas, liquid and solid phases of combustion products. The reactions among these streams, influenced by geometrical design and a large number of operational parameters determine which particles arrive at the surfaces and fulfill the requirements to remain there and form a deposit.

The path from the fuel to a mature deposit is complex, and includes a great number of variables which influence ash deposition. The characterization of the slagging and fouling processes and their assessment through prediction tools requires thus extensive investigation in many related fields. A scheme of this thematic breakdown can be found in Figure 1.
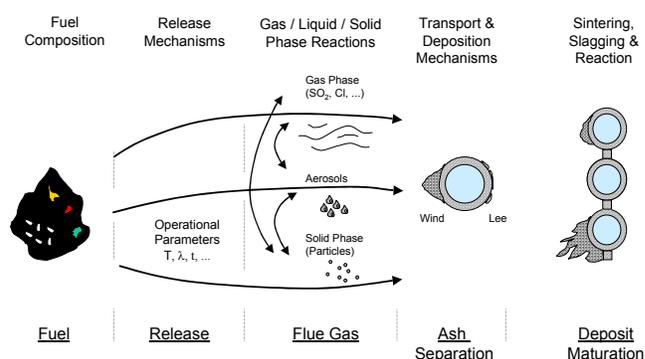
Fig. 1: Topics in the investigation of ash formation and deposition phenomena.

ASH RELATED PROBLEMS

Several problems related to ash and ash deposition can be defined[3] as follows:

Slagging: "refers to deposition taking place in the boiler sections where radiative heat transfer is dominant".

Fouling: "takes place in the cooler convective heat transfer sections of the boiler and results from the behavior of components as the gases cool down".

Corrosion: "takes place when metal from the tube wall reacts with a component from an ash deposit or flue gas".

Erosion: " is due to the impact of hard particles on tube surfaces and tends to occur in the high velocity sections of the convective part of the boiler, and is exacerbated by partial blockage due to fouling deposits".

Table 1. Boiler zones or regions and associated ash deposit characteristics and boiler symptoms that indicate a potential ash deposition problem[4].

Boiler Zone or Region	Temperature Range	Specific Boiler Components	Boiler Symptoms
Lower Furnace / Radiant Zone	1400-1600°C	Burners, slag hoppers, sloping walls	Slag tap plugging, hopper clogs, tube leaks, low steam temperature
Upper Furnace / Radiant Zone	1250-1400°C	Nose region, suspended surface pendants	Low steam temperatures, increased attemperation
High Temp. Convect. Zone	1000-1250°C	Superheater and reheat regions	Lowered steam temp., pressure drops
Low Temp. Convect. Zone	600-1000°C	Backend reheat, primary reheat and economizer	Lowered steam temp., press. drops
Air Heater and SCR* Regions	300-600°C	Air heater, SCR regions	Corrosion, press. drops, blinding of SCR

* Selective Catalytic Reduction

CHARACTERIZATION

It is not the intention of the authors to establish hereby guidelines for deposit characterization. The methods presented hereunder are known to the authors either due to their application at the Institute of Process Engineering and Power Plant Technology (IVD) laboratory and test facilities, through common investigation work with other researchers or through the literature. Newer, more accurate or even more appropriate methods for deposit characterization may be available.

Common, widely used methods for the characterization of ash deposits are presented below. The properties have been divided into three groups that are described separately: mechanical, thermal and chemical properties of the deposits.

A. Mechanical properties

Total Deposition Rate (TDR)

The efficiency reduction in a utility boiler is directly related to the amount of ash deposited on its heat exchange surfaces. This amount can be quite easily determined online by means of gravimetric probes, for no sophisticated analytical device is required. Thus, sootblower operation relies conventionally on one of the most simple, but at the time inaccurately defined variables of ash deposition, the deposition rate. This parameter characterizes the mass of ash that settles on a surface, and is thus usually measured in [g/h·cm²]. TDR includes information on the amount of ash deposited only and not on its further characteristics. The

fusion state, for example, influences directly the thermal properties of the deposit, and therefore the heat transfer from the furnace into the steam cycle. A thin but porous layer can reduce heat transfer to a greater extent than a thicker but molten ash layer. Thus, the deposition rate alone can not be used for characterization of a deposit.

Porosity

Investigation results in the past years have shown that the thermal properties of ash deposits depend more on their structure, particularly on their porosity, rather than on their composition, as shown in Figure 2.
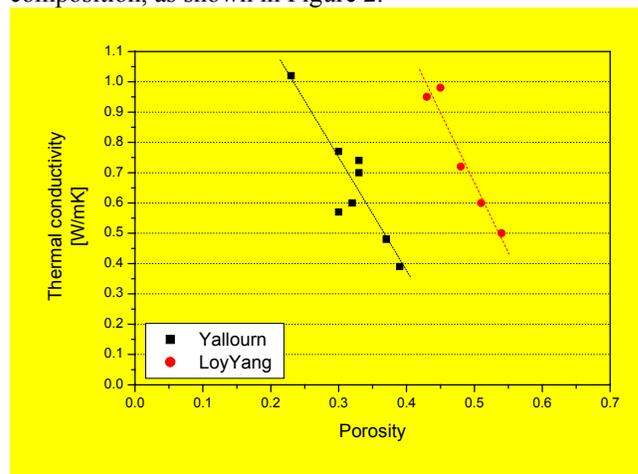
Fig. 2: Relation between the porosity and the thermal conductivity of bonded ash deposits from the Yallourn and Loy Yang power stations[5].

The determination of the mass of a deposit is straightforward, but its volume determination is not, due to its irregular shape. As an example, the volume of displaced water can therefore be measured after sealing the surface with paraffin wax to avoid water absorption. The bulk density (ρ_B) can be determined. The porosity (ψ) is then calculated using the true density (ρ_T) and the bulk density according to the following formula[5]:

$$\psi = 1 - \rho_B / \rho_T \qquad (1)$$

The specific surface of a deposit can be determined by measuring the volume of an inert gas (commonly nitrogen) going through the sample. After that, the bulk volume and thus the porosity can be calculated.

Strength and degree of fusion

The efficiency of sootblower operation to remove ash deposits on furnace surfaces depends mainly on the strength with which the ashes are bonded both together and to the surface itself. The nature of collected deposits is therefore often assessed on scales of deposit types, including a visual description of the sample and the measured compressive strength. An example of this approach is the system first

introduced in the UK by the CEGB[6]. Table 2 presents the deposit description as well as the approximate compressive strength.

Table 2. Classification of ash deposits according to their approximate compressive strength with their description[7].

Type	Description	Ultimate Compressive Strength kN/m²
0	Dust	0
1	Mostly dusty, some very light sintering	< 50
2	Mostly lightly sintered, some dust	50-100
3	Coherent light sintering	100-150
4	Light / medium sintering	150-400
5	Coherent medium sintering	400-750
6	Medium / strong sintering	750-1000
7	Strongly sintered	1000-1500
8	Strongly sintered, some fusion	1500-2500
9	Mostly fused	2500->3000
10	Hard slag	>> 3000

However, experience has shown that a simple visual assessment of the deposits is at least as reliable as the more difficult strength measurement[7].

Viscosity (ν)

One of the most common approaches for the assessment of operational problems related to ash deposition is based on determining the fusion behavior of ash by measurement of its viscosity. The determination of the temperature of critical viscosity (250 poise under oxidizing conditions and 1000 poise under reducing condition) is here decisive. But researchers find themselves confronted several problems while attempting rheological measurements. The high temperature ranges of interest (700-1800°C) imply special highly resistant equipment. Contamination of the sample by the construction materials is not always excluded, specially by the use of cheaper materials. And finally, the presence in the ash samples of heavy metals results often in an attack of the equipment material, e.g. in the case of iron-rich ash and platinum cups[8]. The difficulty and high cost of measuring the viscosity of slags derived from coal with varied ash analysis has led to many predictive models based on chemical composition[9]. The attempt to describe the adhesion of ash particles to superheater tubes as a function of the viscosity has proven successful[10] in several cases. However, the prediction of the critical viscosity temperature for slags with any accuracy is today still difficult.
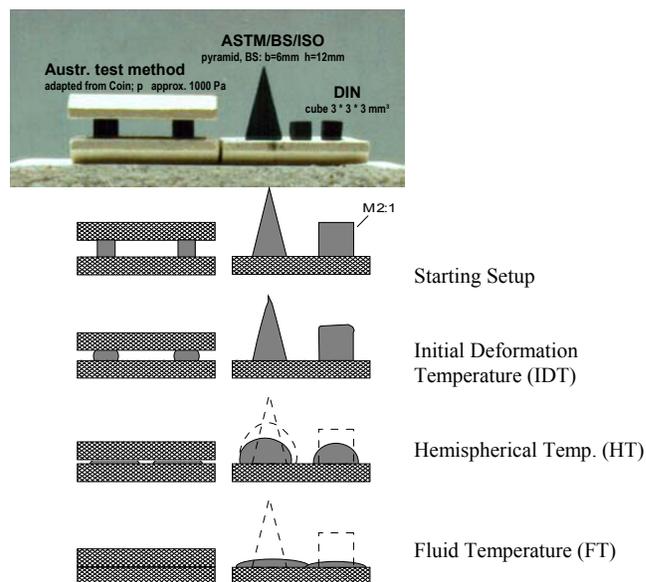
Fusion behavior

In order to avoid deposition problems, the ash resulting from combustion must remain dry and powdery[11]. The thorough characterization of ash fusion behavior is therefore crucial. There are several different approaches in the study of fusion behavior, and various procedures to carry out an ash fusion test (AFT).

One approach is based on the determination of the sintering temperature. Techniques used for coal ash include: compressive strength, thermal conductivity, thermomechanical analysis and pressure drop measurement. The use of a Thermo-Mechanical Analyser (TMA) seems to have proven itself as the most precise method to determine the sintering temperature of an ash sample[11]. The sintering temperature is here determined very accurately by the change in the physical height of a load of ash while heated at a constant rate. This approach is fast, simple and not expensive, but it can not provide a complete description of the fusion behavior.

A second and very common approach is to classify ash fusion behavior by measuring three characteristic temperatures, viz.: initial deformation temperature (IDT), at which the sample begins to loose its original shape; hemispherical temperature (HT), at which the sample reaches the shape of half a sphere; fluid temperature (FT). For this purpose, the ash is first formed into a standard shape. This shape varies among the different world standards, being most commonly either a pyramid or a cube. The principle of these methods is shown in Figure 3.

The determination of these temperatures, in spite of the well defined standards, in many cases does not exclude subjective assessment. This method provides more information on the fusion behavior, but is not accurate enough to distinguish similar samples.

Figure 3: Scheme of methods for the determination of the fusion behavior of ashes.

A final approach is based on monitoring the shrinkage of a sample of defined geometry while being heated at a constant rate. Here the fusion behavior is recorded from beginning to end, and the actual height related to the initial one. The complete data of the fusion process allows a better distinction of similar samples. This has proven to be the most complete and accurate method to describe fusion behavior.

A Differential Thermal Analysis / Thermogravimetric Analysis (DTA/TGA) is also used simultaneously during ash fusion investigations. The DTA/TGA technique is unique in providing the means to discriminate between endothermic reactions caused by melting or decomposition reactions during ash fusion testing and slag deposit formation. DTA/TGA provides an experimental technique that measures when phase changes and reactions occur by measurement of associated endothermic and exothermic heat. Thus, it supplies additional information to the other techniques for measurement of ash fusion characteristics.

Nevertheless, none of the three approaches can eliminate the uncertainties related to ash fusion temperature measurements for the prediction of ash deposition in utility boilers. The major source of uncertainty within the methods is the origin of the samples itself. Ash samples can still not be generated in laboratory equipment under the same conditions as found in utility boilers. Major deviations are found here regarding heating rates and heat flux values. Thus, the results obtained by this method are not directly comparable to real ash. To minimize the deviations, AFT measurements are run on ash samples collected during pilot scale testing. Thus extensive experience in the correlation of pilot and full scale results is still necessary.

Ash particle size

The determination of the particle size and particle size distribution of ash samples depends strongly on the region of interest for the subsequent studies. Due to irregularities in form, no universal method is available for the determination of particle size distribution. Commonly, the particles are grouped for their general study in three so called modes. These are listed with the different principles used for their detection in Table 3.

Simple techniques provide quick information for the coarser fractions (down to approx. 1µm). Typical is the use of dry and wet sieving with different screening layers or the optical determination by laser diffraction. However, for the determination of the small size fractions, more sophisticated methods are required. Developing accurate procedures appropriate for online measurement of all ash fractions is a world wide challenge. Problems to be solved here are mainly representative sampling and material requirements, particularly for in-furnace measurements.

Table 3. Particle size modes and the principles used for their detection[12].

Mode	Particle Size [nm]	Determination principle	Measurement of the
Ultrafine	>3-100	elect. mobility (SMPS, OPC, APS, Impactor, ELPI)	number of particles
Accumulative	100-1000	elect. mobility / optical	number of particles / mass
Coarse	>1000	optical	mass

The information on ash fractions, not only regarding their size distribution but mainly their composition is a key determinant in the identification of ash formation and deposition mechanisms.

B. Thermal properties

The efficiency of a utility boiler depends mainly on the heat exchanged from the fuel into the steam. The deposition of ash on the heat exchanger surfaces creates an additional, undesired resistance.
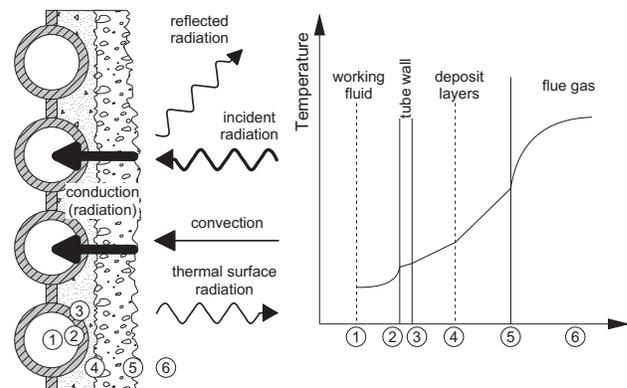
Fig. 4: Heat transfer across furnace walls (left) and heat transfer resistance for several deposit layers (right)[13].

Furthermore, the reduction in the heat exchange not only affects boiler efficiency, but it also implies higher temperatures all along the utility and resulting increased problems. The determination of deposit thermal properties is therefore crucial, specially for the quantification of the related operational problems. All three types of heat exchange are present in a utility boiler: radiation, conduction and convection, as shown in Figure 4. Thus, several thermal properties of the deposits need to be taken into account. Thermal conductivity (k), and the radiative variables emissivity (ε), absorptivity (α) and reflectivity (ρ) are commonly studied parameters.

Conductivity (k)

The resistance offered by an ash deposit to the heat exchange via conduction (through the tube together with the deposit) is quantified by the thermal conductivity. This value can vary considerably for ash deposits, depending on their structure (powdery, sintered or molten), physical properties such as the porosity, and the phase (cooling down or heating up).

Radiative properties

The primary effect of ash deposition is a reduction of the fraction of incident radiation which is absorbed by the surface where the ash remains. Thus the radiative properties ε, λ and ρ are of major importance in the characterization of deposits. Effective radiative properties depend on spectral distributions and surface temperatures. They are related by the equation:

$$\varepsilon_\lambda = \alpha_\lambda = 1 - \rho_\lambda \qquad (2)$$

The experimental techniques used by researchers to estimate the radiative properties of coal ash fall into four groups according to the method used for the measurement[12]. The methods, with their application ranges and limitations are presented in Table 4.

Table 4. Methods for the estimation of radiative properties of coal ashes[14].

Reflection method		
For surface temperature of 600-650K, ε 0.85-0.90. Anthracite fines. Spectral ρ for wavelength range 0.4-0.75, source temp. 1100-1350K, ε 0.30-0.55		
Absorption method		
Absorption of black body radiation, surface temp. 300K, source temp. 1000-2500K, ε 0.70-0.85. Range of Russian coals. Absorption of black body radiation, surface temp. 810K, source temp. 970-1140K, ε 0.20-0.65. Victorian and S.A. ashes		
Emission method	Emissivity levels at temperatures	
	600K	1200K
comparison of emission with standard. Anthracite fines (a) and ash from four Russian coals (b)	(a) 0.90-0.95 (b) 0.80-0.90	0.75-0.85 0.65-0.75
Spectral radiation from an ash surface	0.90 0.90	(4.5μm) 0.60 (3.5μm) 0.41
Specular emission measured by pyrometer and integrated. Russian coal ash.	0.75-0.90	0.60-0.85
Hemispherical pyrometer method		
LAND SP pyrometer wit sample heated from below, and thick layers (3.5mm)	0.55-0.70	0.50-0.65
LAND SP pyrometer with samples heated in a muffle, layers of 0.75-2.55 mm thickness	0.55-0.70 (at 1000K)	

The disadvantage of the emission method, when applied to powders, is the accuracy of measuring the temperature of the powder surface. The hemispherical pyrometer method, when used on thick layers, involves an uncertain extrapolation of the pyrometer reading. Of the methods for determining the emissivity of coal ash and deposits, the reflectivity technique is least prone to experimental error[14].

C. Chemical properties

Composition

Determining the chemical composition of an ash sample, be it loose or as a deposit, begins commonly by a number of standard analysis, viz.:

-   proximate analysis, for determination of the moisture content, fraction of volatile matter, ash and fixed carbon remaining. This is usually carried by menas of a thermogravimetric (TGA) device.
-   ultimate analysis, for determination of the content in C/H/N, often combined with sulfur (S) measurement. Combustion of the sample in an oxygen atmosphere with subsequent analysis of the gas phase by gas chromatography is usually applied for this purpose.

However the information provided by these standard analyses has become insufficient. Particularly the need of developing modeling tools for the prediction of the deposition problems highlighted the need for extended and thorough analysis of the ash and the deposits. Most of these tools are based today on the chemical composition of the ash, requiring at least its main inorganic components. Several techniques are available for this purpose, providing different types of information.

The ashing process affects the structure of the fuels, so that its mineral matter is converted to silicates, aluminosilicates, and other new phases. Ash composition is commonly expressed on the basis of oxides: SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, TiO_2, MnO, P_2O_5 and SO_3. These are commonly determined by several different analytical methods, e.g. inductively coupled plasma (ICP) with optical emission spectroscopy (OES) or with mass spectroscopy (MS), X-ray fluorescence (XRF), ion chromatography (IC), atomic absorption spectroscopy (AAS). Each of these analytical techniques presents errors for the determination of certain species. Thus often one single analysis is not representative for a sample.

The preferred method for characterization of deposit samples is the Scanning Electron Microscope (SEM) with an EDX analysis, specially when combined with computational calculations (CCSEM-EDX). The application of SEM-EDX provides valuable information on the deposits regarding two topics:

-   the texture of the samples (Figure 5), through the SEM images of two types of energetic signals, secondary

electrons (SE image) and back scattered electrons (BSE image).
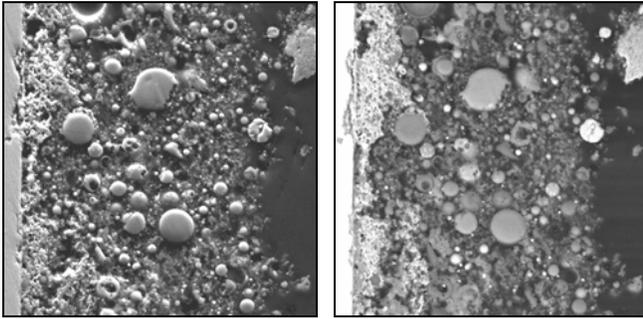
Fig 5a: Secondary electron (SE) image from a deposit sample collected during coal combustion on a tempered metallic probe (left).

Fig 5b: Back scattered electron (BSE) image from a deposit sample collected during coal combustion on a tempered metallic probe.

- the qualitative chemical composition of the sample, through the X-ray emissions captured by an energy dispersive detection system (EDS).

The major restriction of this method is clearly the lack of quantitative information on the sample. Therefore, a great effort has been concentrated on developing quantitative tools based on computational treatment of the analytical results. The resulting chemical spectra of a sample are compared to those of standards of known composition. The main remaining difficulty is to obtain reliable standards for the samples. These not only have to present a well defined chemical composition. The angle of incidence of the X-ray on the sample surface determines the amount of energy reflected/emitted and its angle towards the detector. The structure of the surface is therefore determinant for the analysis. Thus, standards have to account as well for surface properties as similar as possible to those of the samples to be measured. The great heterogeneity of ash and deposit samples turns this into a highly complicated and time consuming task. Even if samples are embedded and perfectly polished, errors are not excluded. CCSEM-EDX analysis provides, in spite of its limitations, highly valuable information, particularly for the identification and validation of deposition mechanisms.

Mineralogical phases

Quantitative X-ray Diffraction (XRD) can be applied to both ash and deposits for the determination of mineral phases. This enables to identify the mineral species which can give rise to slagging problems in utility boilers. Figure 3 presents the results of XRD analysis of filter ash collected during co-combustion of coal and straw. The presence of low melting potassium salts Sylvite [KCl] and Aphthitalite

$[K_3Na(SO_4)_2]$ is clearly due to the introduction of the biomass.
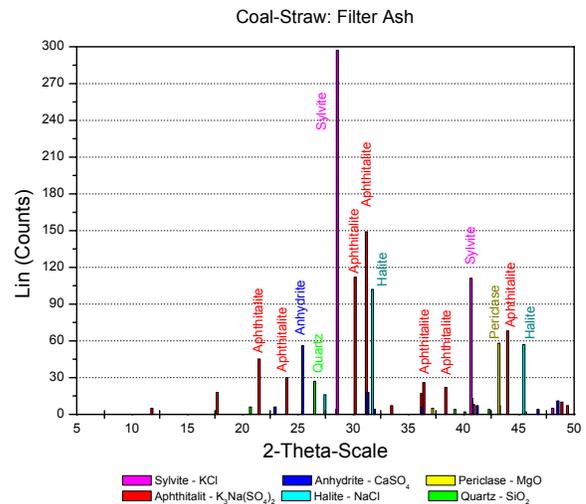
Fig. 6: Spectrum obtained from the XRD analysis of a filter ash obtained during co-combustion of bituminous coal and straw[15].

The results of XRD analysis constitute a very valuable tool for identification and/or validation of deposition mechanisms. However, not only the high analytical costs represent serious restrictions to its application. XRD analysis is limited only to crystal phases. The determination of amorphous phases within the ash or deposits is herewith not possible. This implies the major restriction of the method, for often these amorphous phases are precisely the responsible for S&F phenomena.

EXPERIMENTAL METHODS

The open questions in slagging and fouling are investigated in the experimental work at IVD under the following topics:

Release mechanisms

- analysis of the gas phase, through conventional and advanced measurement techniques. Examples of these are the determination of sulfur, chlorine as well as hydrocarbons through Fourier Transform Infrared Spectroscopy (FTIR), or the determination of alkali concentration in the gas phase through Excimer Laser Induced Fluorescence (ELIF).
- characterization of the solid phase and the release of aerosols through sampling and further analysis. The different stages in the ash formation are considered and therefore samples are taken at different locations: from samples within the

flames, by means of impactor or plane filters, down to the different ash separation devices.
- determination of gas and particle temperatures by means of suction and color pyrometry

Deposit formation mechanisms
- investigation of the primary layer formation, both on wind and lee sides of the heat exchanger surfaces. For this purpose, probes are usually inserted at different levels within the furnace for collection of ash deposits on temperature controlled steel surfaces[16]
- investigation of the reaction of the deposits with the metallic surface regarding corrosion effects[17]
- slagging investigations on ceramic probes that simulate mature deposits
- determination of deposition rates and height growth through video monitoring
- determination of surface temperatures and thermal emissivity values through color pyrometry

Deposit characterization
- analytical studies for the characterization of sintering and melting phases
- determination of mechanical resistance of the deposits for classification

MODELLING AND PREDICTION

One of the major constraints of the above methods for characterization of ash deposits is the impossibility of simulating real conditions. Neither generation conditions nor some of the most relevant operational parameters, e.g. flow patterns, can be emulated in laboratory equipment, and can only be partially recreated in pilot scale facilities.

Therefore, many different approaches are tested to provide valuable simulation tools that enable an accurate prediction of the S&F processes.

As a first step, empirical models are adjusted with the help of experimental data. These models provide good results, but are limited to the facility, and in some cases even to the specific operation conditions under which they are established. An extrapolation to other cases, specially other similar facilities is only in certain cases possible.

The determination of theoretical mechanisms for ash transport, ash deposition on the surfaces and chemical reactions enable the development of more sophisticated tools, based on theoretical models. Experimental data is here used only for validation purposes, and no dependency to the facility is necessary. These are therefore more powerful tools, as much as they allow a prediction for future cases. The development of this sort of tools requires, however, many years of basic investigation and vast experience.

The last step is brought by Computer Fluid Dynamic (CFD) codes. In these, the differential equations of Fluid Dynamics are solved by numerical methods with the help of computers. Thus the codes can by applied to any case study. Boundary and initial conditions are required, and validation of the computational results is achieved by comparison with experimental measurements. These codes provide the most powerful tool for prediction but are based on theoretical models developed individually and then implemented to the basic model.

Due to the large number of all methods and models existing for the prediction of slagging and fouling and under development, only an example is given in the following for each of the different properties characterizing a deposit.

A. Mechanical properties

ν = f (chemical composition)

The viscosity of fuel ash and its relation to operational parameters provides valuable information for the assessment of slagging potential. However, equipment for viscosity measurements is not common in industrial utilities and the measurement itself is difficult and time consuming. Therefore, models for calculating the viscosity upon more easily obtained data have become increasingly popular. These are commonly based on information on the chemical composition of ashes created in laboratory equipment.

The variety of viscosity models available, and the conflicting results occasionally obtained from viscosity models, has led researchers to develop a master program which incorporates six of the major viscosity models. The model calculates the viscosity of a given liquid by all six models: Hoy, Watt-Fereday, modified Watt-Fereday, Urban, IRSID, and modified Urban[18]. The input data for the calculations is the composition of lab ash determined by X-ray fluorescence.

These models provide acceptably good results in the prediction of ash viscosity, specially in the Newtonian-regions. However, often these powerful tools are largely derived from empirical fitting of data.

B. Thermal properties

k = f (temperature, porosity)

There are many parameters that affect the thermal properties of ash and deposits such as the physical characteristics (porosity and particle size), sintering time and temperature[19]. Chemical composition has a determinant influence on radiative properties. It has not shown though to have a relevant effect in heat transfer via conduction. From all parameters, temperature and porosity appear to have the major influence on the conductivity coefficient. Thus these are the main parameters for the prediction of this thermal property. Commonly the deposits are considered as a combination of two different materials of known thermal

conductivity as a function of temperature, air and ash. An overview of some models available for the prediction of the conductivity coefficient is given in Table 5.

Table 5. Models for prediction of the conductivity coefficient (k) for ashes[19, 20].

Model	Remarks
Rayleig	
Deissler & Eian	Porosity less than 0.52
Woodside	
Russell	Porosity 0 -- 1
CSP	Underestimates k
CPS	Overestimates k
Brailsford & Major	Evaluates k for any continuant phase
Baxter	Sets upper and lower limit to k based on the tortuosity of the particles

C. Chemical properties

Indexes = f (chemical composition)

It is very common practice to classify coals and their behavior upon combustion by the use of indices. These take into account the species in the fuel which have been identified as responsible for the S&F phenomena. Very often, they are relatively simple ratios of the concentration of several species in the fuel matrix. With time, indices have become more and more sophisticated, including aspects of the fuel nature such as the presence of a certain element in different compounds within the fuel matrix. In several cases, indices compare results from other of the presented tests for characterization of the ashes or deposits. An example of indices for iron-based slagging during coal combustion is given in Table 6.

Table 6. Summary of slagging indices[21].

Index	slagging potential			
	low	medium	high	severe
ash fusibility[(a)]	>1343°C	1232-1343°C	1149-1232°C	<1149°C
viscosity[(b)]	< 0.5	0.5-0.99	1.0-1.99	> 2.0
ash chemistry[(c)]	< 0.6	0.6-2.0	2.0-2.6	> 2.6

(a) $(4IDT + HT)/5$
where IDT = initial deformation temperature
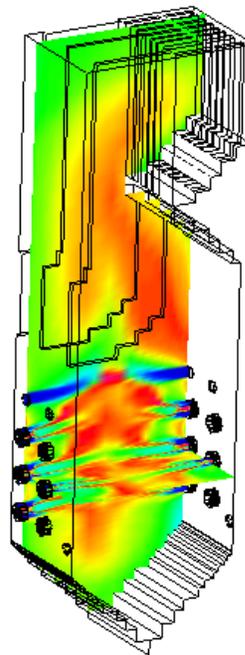HT = hemispherical temperature

(b) $(T_{250ox} - T_{1000red})/ 950 F_s$ where
T_{250ox} = 250 poise temp for oxidizing conditions
$T_{1000red}$ = 1000 poise temp for reducing conditions
F_s = correlating factor

(c) $[(Fe_2O_3 + CaO + MgO + K_2O + Na_2O) \times S]/ (SiO_2 + Al_2O_3 + TiO_2)$
where S = % sulfur in dry coal

Although these indices often provide valuable tools for operators, most of them can only be applied to a specific facility type. Results in other facility types are neither accurate nor reliable. Furthermore, most of the indices have been developed for coal or coal blends. Blending with opportunity fuels such as biomass or industrial refuses has not yet been considered.

CFD Codes

Complex computer fluid dynamic (CFD) codes are based on single modeling tools developed individually and compiled into one single program. In the case of the 3D CFD code AIOLOS developed at IVD, complete calculations can be made of the furnace and the following passes, as well as coupled simulations of fire side and water-steam cycle.

Fig. 7: Visualization of numerical results for an utility boiler regarding slagging potential in the furnace

Simulation of slagging and fouling behavior in utility boilers with the use of IVD's CFD-Code AIOLOS:
1. Calculation of flow patterns:
- monophase (Euler)
- multiphase ((Euler / Lagrange)
2. Calculation of ash deposition (Post-processing)
- small particles (Euler) < 10-20 µm
- large particles (Lagrange) > 10-20 µm
3. Effect of ash deposition on the heat exchange
- deposit thickness and structure (thermal conductivity)
- deposit emissivity (radiative properties)

Deposition Mechanisms considered in the model:

	Walls		Tubes	
	small particles	large particles	small particles	large particles
Inertial depostion		X		X
Turbulent depostion	X	X		
Thermo-phoresis	X		X	

CONCLUSIONS

This paper tries to summarize investigations carried out in the past years to describe the slagging and fouling phenomena taking place in utility boilers. The available knowledge is reviewed, methods developed are classified and their efficiency to characterize ash deposits assessed. Finally some suggestions are made to optimize work on S&F.

Not all methods available for characterization of ash deposition are presented in this work. The methods presented were chosen as relevant based on the authors experience in the IVD laboratories and experimental facilities or through collaboration with other researchers. The authors are well aware that newer, more accurate and possibly even more appropriate methods exist or are under development.

The slagging and fouling phenomena comprise a large number of variables that affect ash deposition in different ways. This results in a broad field of investigation, with several possible approaches. Thus many researchers are concentrating their effort on explaining the phenomena, identifying mechanisms and developing tools for an accurate prediction, with different points of view. The general topics under investigation can be summarize as follows:
- Study of the **mechanical properties** of the deposits, particularly characterizing mechanical resistance in order to assess sootblower operation, and characterizing ash fusion behavior to assess fuel choice and operational parameters.
- Study of the **thermal properties** of the deposits. The determination of thermal conductivity and emissivity values for ash is necessary to quantify the impact of ash deposition on heat transfer and thus on the efficiency of an utility boiler.
- Characterization of the **chemical composition** of fuel, ash and their deposits. The relation between fuel composition and the ash resulting from combustion allows to identify release mechanisms. In a further step including the analysis of ash deposits, mechanisms for ash deposition are identified. The results from chemical analysis are then commonly used as the base for predictive tools for slagging and fouling processes.

During the preparation of this publication, the authors found that:
- many valuable and accurate tools have been developed for coal combustion that predict ash deposition with high reliability. For instance, indices based on chemical composition enable a fairly good deposit prediction upon combustion of the specific fuel.

- However, such reliable tools are still missing for secondary fuels such as biomass fuels and industrial or domestic refuse. Work in this field has been started and investigations are ongoing, so that good results can be expected in the coming years.
- In order to best profit from the recent investigations, the knowledge achieved by different researchers could be thoroughly compiled into a master work on ash deposition, including all relevant aspects affecting this operational problem. An in-depth overview would identify gaps in the field, and work could be thus optimized.
- Finally, a tendency to individual development of theoretical models can be noticed. These models serve to establish pseudo codes that can be implemented on commercial 3D-CFD codes, such as e.g. in the case of AIOLOS. The individual development implies though the need for a continuos survey, to avoid duplicate models. A thorough exchange of information among the investigation community is crucial for this purpose.

NOMENCLATURE

α thermal absorptivity
AIOLOS 3D-CFD Code developed at IVD for simulation of utility boilers, fireside and steam cycle.
APS   Aerodynamic Particle Sizer® Spectrometer
AFT   Ash Fusion Test
ASTM   American Society for Testing and Materials
CCSEM Computer Controlled SEM
CEGB   Central Electricity Generating Board
CFD   Computational Fluid Dynamics
DIN   German Industrial Guidelines
ε thermal emissivity
EDS   Energy-Dispersive System
EDX   Energy-Dispersive X-ray
ELIF   Excimer Laser Induced Fluorescence
ELPI   Electric Low Pressure Impactor
FT   Fluid Temperature during an ATF
FTIR   Fourier Transform Infrared Spectroscopy
HT   Hemispherical Temperature during an AFT
IDT   Initial Deformation Temperature during an AFT
IVD   Institute of Process Engineering and Power Plant Technology of the University of Stuttgart
k   thermal conductivity coefficient
OPC   Optical Particle Counter
ρ thermal reflectivity
ρ_B bulk density
ρ_T true density
SCR   Selective Catalytic Reduction
SEM   Scanning Electron Microscope
SMPS   Scanning Mobility Particle Sizer
S&F   Slagging and Fouling
T_{cv} Temperature of critical viscosity

XRD   X-ray Diffraction
XRF   X-ray Fluorescence
ψ   porosity

Subscript

B   bulk (density)
λ   wavelength (spectral variable of radiative parameters)
ox   under oxidizing conditions
red   under reducing conditions
T   true (density)

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