MONITORING AND MODELLING OF GAS-SIDE BOILER FOULING

R. Korbee[1], **M. Losurdo**[2], **J. Lensselink**[1], **M.K. Cieplik**[1], **F. Verhoeff**[1]

[1] Energy research Centre of the Netherlands (ECN), P.O. Box 1, 1755 ZG Petten, The Netherlands; korbee@ecn.nl
[2] Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands; m.losurdo@3me.tudelft.nl

ABSTRACT

Co-firing high shares of biomass with coal in pulverized fuel-fired furnaces may give rise to increased deposition of ash in the convective area (fouling). This paper describes first results of work aiming to develop a mathematical model as well as a system for the on-line monitoring of ash deposition in full-scale plants. Ash deposition experiments have been performed using a new type of deposition probe featuring on-line heat flux measurement. Ash deposits from straw, coal and a 20/80 %/% mixture are compared. An initial increase of the derived fouling factor is attributed to the radiative properties of the first ash depositing on the probe. The subsequent decrease of the heat transfer is caused by the insulating effect of the growing ash deposit. A mathematical model is formulated to describe the processes of ash deposition in relation to local gas flow patterns; the model is a post-processor which uses the results of CFD calculations for input.

INTRODUCTION

It is expected that fouling in furnaces co-firing high percentages of biomass with coal will increase as a result of a reduction of the ash solidification temperature or the presence of aerosol particles which consist of, or are covered by low melting alkali salts. Efficient and effective methods are needed to control fouling to an acceptable level and prevent increased costs due to reduced heat transfer, increased maintenance or even unscheduled outages.

Recently, a project was initiated to monitor and control fouling in furnaces co-firing biomass with coal. The project consortium includes a utility company, a biomass R&D institute, an enterprise developing heat flux sensors and a university. In this project, portable sensors will be developed to determine ash deposition rates and deposit characteristics from full-scale tests as well as small-scale experiments. Besides data from these measurements, fluid dynamics data will be used to develop a validated Ash Deposition Post-processor model (ADP) in conjunction with a CFD combustion model. The ADP model predicts the location and characteristics of fouling for a given combination of fuel and operating conditions, and can be used for process optimization. In addition, an on-line monitoring system of stationary sensors will be developed as a basis to improve fouling control by means of the boiler cleaning system.

The paper presents first results of the project. First, results are presented on a new type of ash deposition probe featuring on-line heat flux measurement. The second part of the paper presents the initial structure and development of the ADP model. The present state of the art of the ADP model does not allow to correctly predict deposition rates and deposit thermal properties. Further developments are in due course for both experimental and numerical modelling.

EXPERIMENTAL

Ash deposit probe

Ranking fuels according to their fouling propensity has long been a matter of trying to establish a relation between fuels properties and ash deposition rate, measured as the mass or volume of ash deposited per unit of time and surface area. The chemistry and structure of deposits has been studied in detail to establish the major ash deposition mechanisms.

In this work heat fluxes are measured while deposits are building on a simulated steam tube. The calculation of a fouling factor from the measured heat flux and temperature difference between hot and cold tube side gives the possibility to rank fuels according to the thermal resistance which results from ash depositing on the tube. Not only does this create the possibility to rank fuels or fuel blends a priori, it also gives quantitative information about the heat transfer reduction which can occur due to ash deposition. When similar measurements would be applied in full-scale boilers, such information can be used as a basis to optimize soot blowing cycles.

Figure 1 shows the principles of the deposit probe which was designed for this work. In-line with the tubing of the probe sits a custom-built metal ring with four integrated sensors which measure the heat flux from the tube exterior to the air-cooled interior, in perpendicular directions. Each heat flux sensor simultaneously measures the metal ring exterior surface temperature. Next to the heat flux sensors sits a 4 cm tube piece which, after sampling an ash deposit, can be dismounted and prepared for detailed visual, chemical and structural analysis. The probe is installed within the ECN Lab-scale Combustion Simulator (LCS), which is used to investigate the behavior of solid fuels under conditions which are typical for pulverized fuel fired furnaces. A full description of the LCS can be found elsewhere (Korbee et al., 2003).

The probe simulates a steam pipe of a typical superheater in the early part of the convective section of a pulverised coal-fired furnace. The gas approach temperature of the probe is around 1200 °C, whereas the surface of the probe which is facing the particle-laden gas flow is controlled by the air cooling system at 500 °C. Other conditions can of course be implemented as well. The four heat fluxes, tube surface temperatures, cooling air flow rate and temperature are all logged. The heat flux sensors were calibrated using an electrically heated wire.

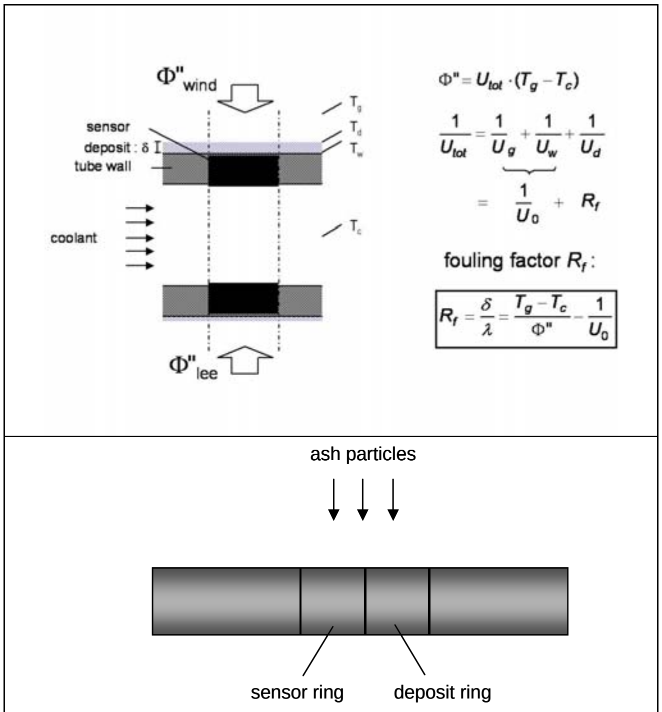

Fig. 1 Principles of the ash deposition probe with integrated heat flux measurement.
Left: cross section of the sensor ring showing two (top and bottom) of the four heat flux sensors, all sitting at 90° angles from each other.
Right: the sensor ring for heat flux measurement and the deposit ring for sampling, in line with the rest of the probe.

Ash deposition test

Three fuels were tested with the deposition probe. Their main characteristics are shown in Table 1. The duration of these tests was limited by the amount of fuel which can be stored in one small fuel container. The fuel feed rate was only 1-2 gram per hour. In the first test (coal), two containers of fuel were fed consecutively. The deposits obtained at the end of each test were photographed and are displayed in Figure 2.

The most obvious difference that can be observed between the deposits is in their color. The coal ash deposit has a light brown color, whereas the deposit from straw has two distinct colors.

	Coal	Straw
Calorific value [MJ/kg]	26.1	18.0
Moisture content [% a.r.]	2.1	5.0
Volatile matter content [% d.b.]	26.5	74.4
Ash content @ 550 °C [% d.b.]	18.8	7.1
Si [mg/kg d.b.]	42401	17838
Al [mg/kg d.b.]	20587	113
Fe [mg/kg d.b.]	9842	123
Ca [mg/kg d.b.]	7857	3297
Mg [mg/kg d.b.]	4433	376
Na [mg/kg d.b.]	1420	50
K [mg/kg d.b.]	3800	14075
Ti [mg/kg d.b.]	1039	12
P [mg/kg d.b.]	323	551
S [mg/kg d.b.]	5631	1329
Cl [mg/kg d.b.]	2702	9423

Table 1 Properties of fuels tested.

Fig. 2 Deposit of coal, straw and straw-coal.

A white film is observed surrounding the whole circumference of the tube. By the eye no particles can be distinguished. A second layer of coarse particles with a dark grey to black colors covers the white layer on the top side of the tube where particles first approach the deposit probe. The ash deposit formed from the straw-coal blend is greyer than the pure coal ash deposit, but completely lacks the white film as seen with the pure straw. All three deposits can be characterized as powdery, with little or no bonding to the tube surface.

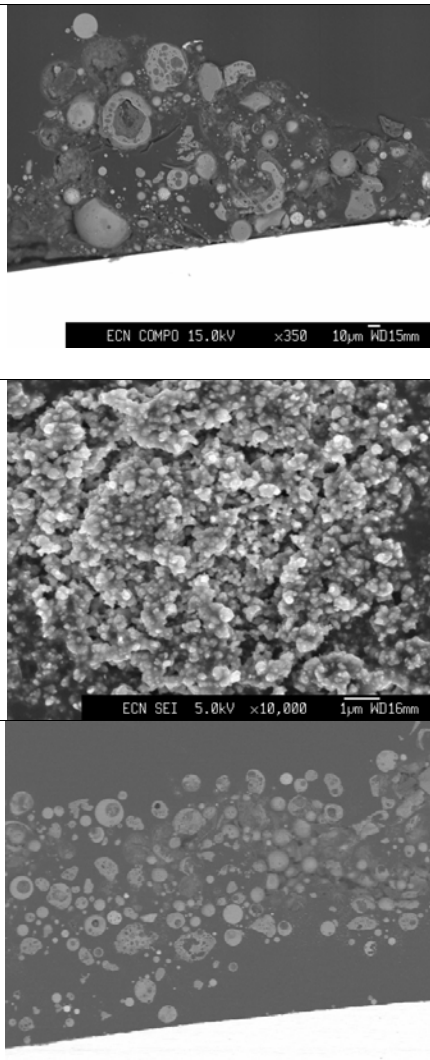

Fig. 3 Microscopic images of ash deposits.
Top and bottom: loosely bonded particles from coal and straw-coal, respectively. Middle: surface view of KCl rich white layer in straw deposit.

Figure 3 shows selected microscopic images of the ash deposits obtained after cross-sectioning, embedding in resin and polishing. The samples were inspected using a JEOL 6330F Scanning Electron Microscope. A coupled EDX analysis system was used to establish the composition of selected areas of the deposits. The fact that the ash particles as seen in the microscopic images do not touch one another, confirms the loose powdery nature of the coarse particle fraction of the deposits. The white film in the straw ash deposit was confirmed to exist mainly of KCl and some Si. In contrast to this, although no film was visually observed in the straw-coal ash deposit, a very thin layer containing K, S and O was found close to the metal surface. Both observations confirm previous findings that KCl may condense homogeneously or heterogeneously onto cold surfaces when straw is combusted, while sulphur from coal may prevent this by the formation of K_2SO_4, thus keeping chlorine in the gas phase as gaseous HCl (Korbee et al., 2001):

$$2\ KCl + SO_2 + H_2O + \tfrac{1}{2}\ O_2 \leftrightarrow 2\ HCl + K_2SO_4$$

Heat flux measurement

The heat fluxes measured during the deposition experiments are given in Figure 4 and 5. Next to these, the calculated fouling factors are presented and expressed as a function of the mass of ash fed into the system in order to correct for the fuels' different ash contents. The fouling factor R_f was obtained according to:

$$R_f(t) = 1/U_{tot}(t) - 1/U_{tot}(0),$$

where U denotes the overall heat transfer coefficient.

The point at which fuel feeding started was taken as the beginning of the heat flux measurement. Care was taken to establish stable conditions prior to that. In all cases the heat fluxes, surface temperatures, cooling air flow rate and temperature were found to be constant until the start of the deposition measurement. The heat fluxes at the start of the three deposition tests were found to be different, which may be attributed to e.g. a slight sensor displacement, even though the settings for the experiment are in principle the same.

As can be seen from the figures, nearly all heat flux trends show an initial increase, which means that heat transfer is actually improving. This effect is attributed to a change of the radiation properties of the deposit probe surface by the formation of an initial ash layer which enhances its radiation properties: since the probe is irradiated from the above high temperature zone, a change in the absorptivity and emissivity of the surface will affect the heat flux through the probe wall. As a result of this an initially negative fouling factor is found.

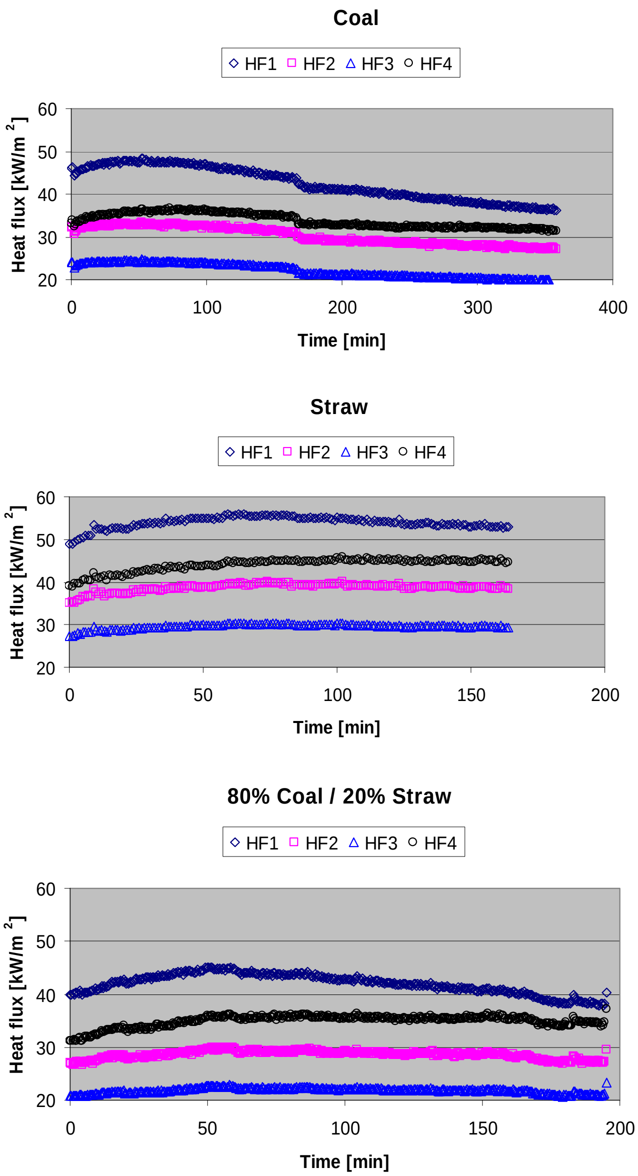

Fig. 4 Measured heat fluxes at 90° angles in deposit probe, as a function of time. HF1 denotes the top sensor, HF2/4 the side sensors and HF3 the bottom sensor.

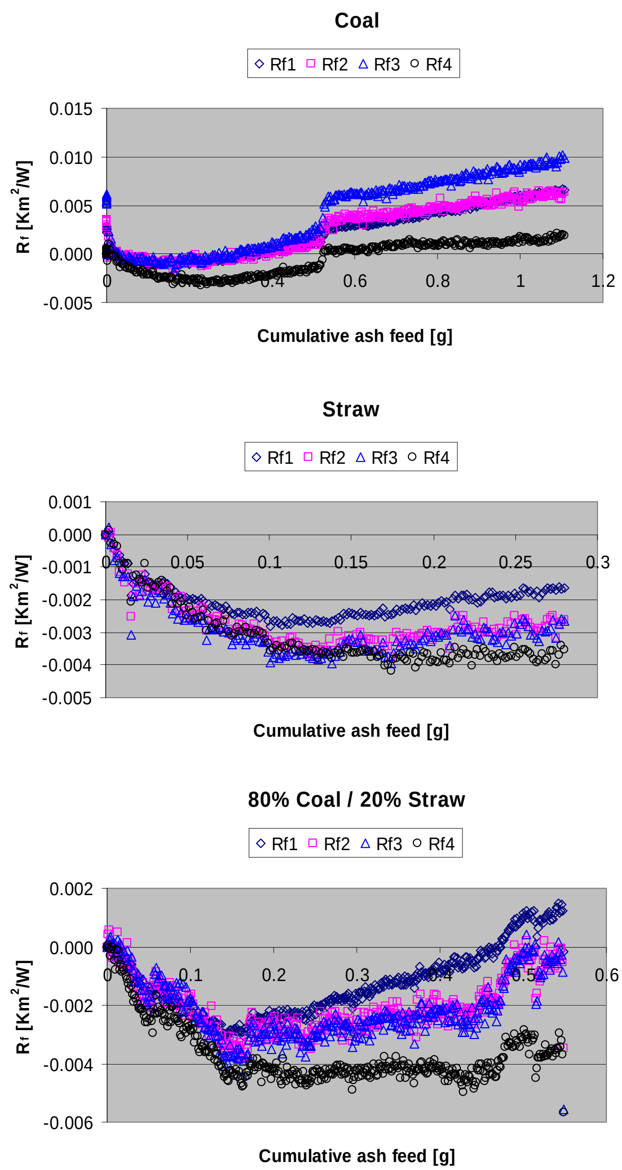

Fig. 5 Fouling factor R_f calculated from measured heat

fluxes. R_f has been plotted against the mass of ash fed to the combustor with the fuel.

As the deposition of ash continues, the increase of the heat flux is counteracted by the thermal insulation caused by the increasing ash layer, and the heat flux starts to decrease. Then, positive values for R_f are found, which compare well with values found for industrial applications (Van Beek, 2001).

In all cases, the heat flux measured at the probe leeside is smaller than the one measured at the windside, which is expected due to the reduced radiation downstream the probe. Both sensors at the sides of the probe measure fluxes in between the windside and leeside values, which also seems logical. However, a further evaluation including a correlation between the four sensors is desired to fully appreciate the results.

A comparison between fuels is best made from the calculated fouling factors. The initially negative value of R_f somewhat complicates the interpretation, therefore in future experiments the starting point (where U_{tot}=U_{tot} (0))

may be selected elsewhere. However, the information about radiation properties of the ash could have a practical value. Concentrating on the part of the graph where R_f increases due to the growing deposit, it seems reasonable to look at the slope of the curves, which would be a measure for the effectiveness with which the ash reduces heat transfer. A first estimate pointed out that for the straw case, the highest specific R_f was found and for the coal case, the lowest. For the straw-coal case, an intermediate value was found. The suggested methodology will be further developed in the near future to rank fuels according to expected full-scale fouling propensity.

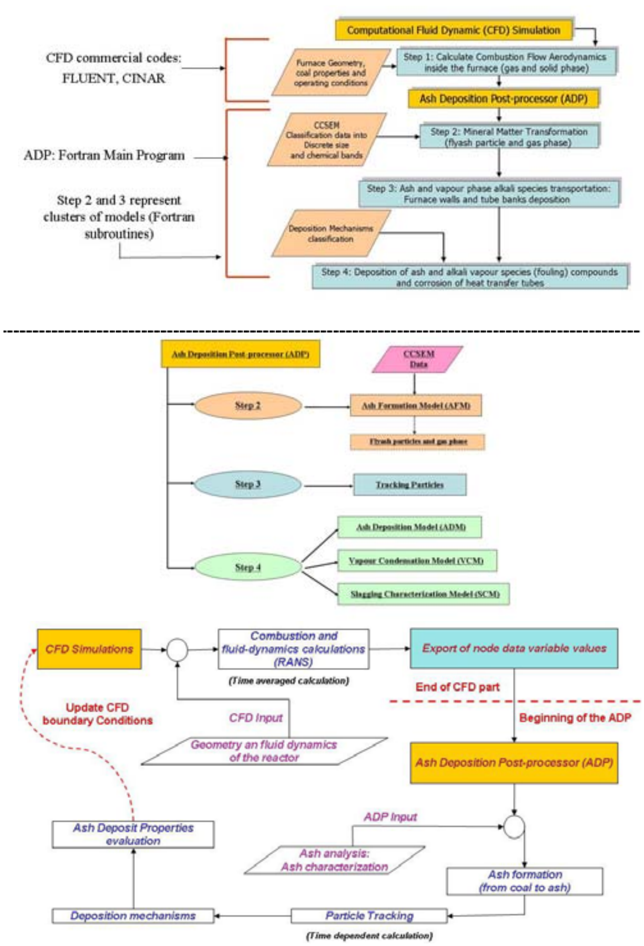

Fig. 6 Structure of Ash Deposition Post-processor (ADP)

ASH DEPOSITION MODELLING

Modelling approach

The numerical prediction of ash deposition in large scale furnaces is considered an important tool which can help to optimize plant economics by means of improving the management of operational problems. Given the complexity of ash formation and deposition processes in a multi-fuel application such as biomass co-firing, computer modelling is considered a more appropriate tool than empirical indices which are based on bulk fuel properties and do not consider fuel interactions.

In a pulverized coal-fired furnace, the gas phase residence time is several orders of magnitude lower than the time required to form an ash deposit layer on heat exchanging surfaces. The different time-scales allow that the ash deposition process is described separately from the combustion process. This approach is often referred to as post-processing. The aim of this work is to develop a post-processor tool which elaborates CFD combustion data and uses ash formation and deposition models to predict, primarily, local ash deposition rates and heat transfer performance. The results can be used for process optimization.

The development of an Ash Deposition Post-processor (ADP) was started by developing a CFD independent particle tracking tool which calculates particle trajectories within the computational domain (discretized furnace) and numerically predicts deposit growth. In the initial phase of the ADP development only the transportation and deposition of ash particles is considered. Depending on the particle properties, either the Lagrangian or Eulerian approach can be used to track particles. Here, only the Lagrangian approach was implemented in the ADP model.

Theoretical studies and experimental data have addressed the following main ash deposition processes: inertial impaction, Thermophoresis, condensation and heterogeneous reaction between inorganic species in the gas phase and the deposit surface. Since these phenomena can all occur along the flue gas path in the furnace, they must be considered and evaluated simultaneously during the computational time period. In a 3D beta version of the ADP model, particle-particle interaction is considered but so far only the inertial impaction has been implemented.

Structure of the ADP

The computational structure of the present version of the ADP model can be summarized as follows:

(1) gas phase fluid dynamics and coal/biomass combustion process are calculated by a commercial CFD code,

(2) results from the CFD calculation are loaded into the ADP model, data stored in the grid nodes are interpolated using a finite elements approach,

(3) particle groups are randomly injected through the inlet surfaces of the domain and tracked along the flue gas path.

The present version of the ADP model provides integration schemes for 2D and 3D grid domains. 2D grids can use both triangular and square elements to mesh the computational domain, while for a 3D grid only tetrahedral elements can be used for meshing. In due course, also cubic elements will be allowed, as well as hybrid meshes. The modelling approach and overall structure of the ADP model are schematically presented in Figure 6.

Mathematical Model

In order to simulate the two-phase flow a Lagrangian frame reference is used. Injected particles are represented by spheres with an aerodynamic diameter of 100 µm, and densities of 100, 500 and 1000 kg/m^3. Drag and gravity are the main forces acting on these particles. Heat exchange between particles and the surrounding environment is enabled. When a particle approaches a surface, two parameters describe whether it will develop a deposit: the impaction efficiency η_i and the sticking probability η_s. The impaction efficiency is evaluated by means of, among others, the particles' Stokes number (Baxter and Mitchell, 1992). The sticking probability depends on particle and deposit properties. Often, the sticking probability of impacting particles is evaluated as a function of its viscosity only, whereas in fact, a more rigorous approach would be concerning factors like temperature, viscous-elastic properties, angle of impaction kinetic energy, as well as surface roughness and stickiness. These will be considered in a later phase of model development. For now, the sticking probability is assumed to be unity, meaning that all impacting particles will stick.

Numerical Results

3D CFD simulations have been performed of the LCS (see Figure 7). In order to test the particle tracking subroutines and the computational frame of the ADP model, only the cylindrical lower part of the combustion chamber which holds the ash deposition probe (Figure 8) was studied. The initial calculations were carried out for room temperature conditions.

Simulation with the medium density (500 kg/m^3) particles (Figure 9) showed that, depending on the particle Stokes number, smaller particles, whose Stokes number is below 0.15) follow the main stream without impacting the probe, while injecting particles with a density of 1000 kg/m^3, all particles of which the trajectory was directed towards the probe deposited on the obstacle. Preliminary results are in good agreement with Baxter (the Stokes number of the particle impacted on the probe is greater than 0.15).

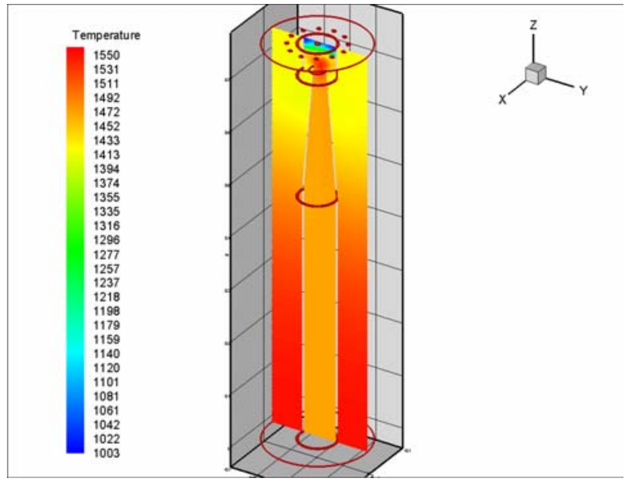

Fig. 7 CFD calculation of the Lab-scale Combustion Simulator (LCS) as input for the ADP model.

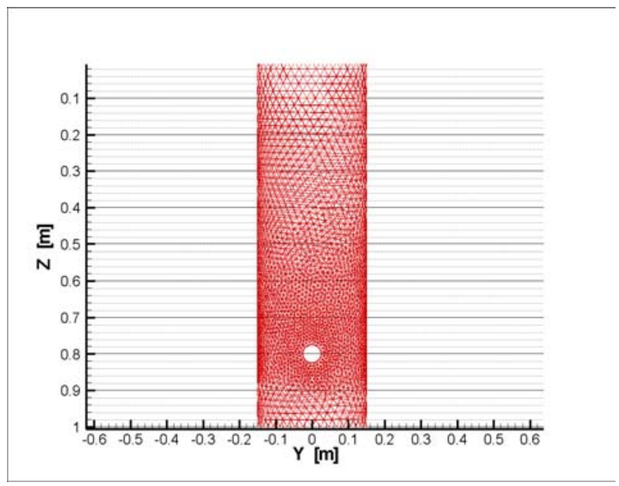

Fig. 8 Mesh used for the ADP calculations. Only the lower part of the LCS with the deposition probe is needed.

Calculations of the type reported here reflect the initial stage of development of the ADP model. Contrary to the development of many non-validated models, the approach pursued here aims to develop an ADP model, of which sub-models will be continuously validated against detailed small-scale ash deposition data. One of the first comparisons made between ADP model results and experimental data will involve the overall ash deposition rate (mass). Then, also more detailed comparisons will be made, involving the deposition efficiency as a function of various ash particle properties.

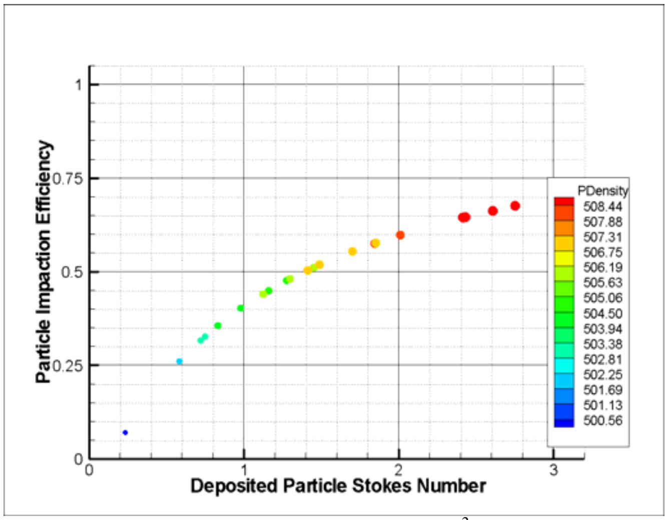

Fig. 9 ADP simulation with 500 kg/m^3 ash particles. Particle impaction efficiency vs particle Stokes number.

In addition to lab-scale data, deposits and operational information from full-scale boilers will serve to evaluate local phenomena which may result in specific deposition or deposit behavior

CONCLUSIONS

1. Ash deposition experiments have been performed using a new type of deposition probe featuring on-line heat flux measurement. Combusting a typical coal in a lab-scale facility showed that the heat transfer to a clean simulated steam pipe was reduced by approximately 20% after forming an ash deposit of 1-2 mm thick.
2. The probe yields heat flux values and fouling factors which compare well to those found for industrial systems. Different heat fluxes are measured at the probe's wind and lee side. The changes observed in the heat flux are clearly related to the ash deposition process. Initially, the heat transfer increases, which is believed to be caused by the irradiative properties of the depositing ash. Subsequently, the heat transfer decreases as a result of the insulating effect of the growing ash deposit.
3. In future work extended fouling periods will be considered to study the important effect of increasing deposit surface temperatures which may lead to sintering and subsequent strengthening of the deposit. A practical way to simulate this process using the same probe is to do deposition tests at a number of increasing probe surface temperatures.
4. The principles of the lab-scale ash deposition probe will be transferred to a portable probe for measurement and sampling in a full-scale furnace to address as well local ash deposition processes.
5. The Ash Deposition Post-processor model which is being developed can and will be validated using the results obtained from the lab-scale deposition tests and full-scale trials.

NOMENCLATURE

U_{tot}	overall heat transfer coefficient	[W m^{-2} K^{-1}]
U_g	gas phase heat transfer coefficient	[W m^{-2} K^{-1}]
U_w	wall heat transfer coefficient	[W m^{-2} K^{-1}]
U_d	deposit heat transfer coefficient	[W m^{-2} K^{-1}]
R_f	fouling factor	[m^2 K W^{-1}]
η_S	particle sticking efficiency	
η_I	particle impaction efficiency	
μ_g	dynamic gas viscosity	[Pa s]
δ	deposit thickness	[m]
λ	deposit thermal conductivity	[W m^{-1} K^{-1}]

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