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On predicting the ash behaviour using Computational Fluid Dynamics

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ABSTRACT

The objective of this paper is to examine several approaches for predicting the ash behaviour using Computational Fluid Dynamics (CFD). The emphasis is placed on details of the sub-models used. In models that aim at predicting the temperature–time history of fuel particles, from the injection position to the deposit surface, the information about the char combustion rate is essential. Of particular importance is determination (through measurements) of the rate of char oxidation for the last 20% of burnout. Predictions of the size distribution of fly-ash particles near the deposition surface seem to be unreliable and measured data are needed for deriving appropriate corrections. Fragmentation of fuel particles is perhaps one of the unresolved issues which require an urgent attention.

The current CFD-predictions of slagging and fouling in industrial boilers are indicative, at their best. This is certainly the case when numerous parameters, including these describing the particle sticking propensity, are taken from the literature. It is relatively easy to tune the model predictions to the expected (measured) results by changing a few key parameters. There is, however, a much more reliable way to proceed. By combining CFD-predictions with an advanced fuel characterization, with the latter being application dependent and fuel dependent, the deposition problems at hand can be tackled. What is to be determined experimentally and under what conditions, requires a consensus of an experienced fuel engineer/mineralogist and a CFD-expert.

1. Introduction and objectives

Ash related problems are for boiler operators of vital importance. Ash deposition through slagging or fouling is often the main reason for boiler unscheduled shut downs. Fig. 1 shows the regions of the ash related problems in typical boilers. The deposits collected in the boiler areas which are directly exposed to flame radiation, such as furnace walls and pendant superheaters, are identified as slagging. Fouling refers to deposits in the boiler areas which are not directly exposed to flame radiation where convection is the dominant heat transfer process. Generally, slagging takes place in the hottest parts whilst fouling occurs as the flue gases and ash particles cool down. Slagging deposits are chemically active at high temperatures being partially or completely molten and they are often hard and difficult to clean by soot blowing. The original chemical and physical structures of ash particles undergo substantial changes during slagging. Fouling deposits are formed at lower temperatures and typically the impacted particles keep their original physical and chemical structures.

Photographs of ash deposits from different boiler regions are shown in Fig. 2. Ash deposition problems manifest themselves in a variety of ways [1–3]:

(a) reduction of heat transfer rate due to deposited ash acting as an insulation layer. This results in an increase of the furnace exit temperature and an excessive heat transfer rate to superheated steam,
(b) build up of large clinkers on the furnace walls or on the radiant superheaters tubes. Shedding of such a massive deposit may damage boiler ash hopper,
(c) partial blockage of heat transfer tube banks which increases gas velocity and may lead to enhanced corrosion,
(d) impendence to gas flow as a result of excessive fouling in the convective banks,
(e) burner "eyebrows" deposits distort the burner aerodynamics which may cause problems with flame stability and ignition.

Nowadays more and more often Computational Fluid Dynamics (CFD) calculations are used to predict performance of boilers. Above all, multiphase flow simulations become a common practise in boiler design. Detailed review of the works on CFD-predictions of industrial boilers is beyond the scope of this paper, however publications related to the development of CFD-based ash deposition models are relevant. There exist not too many publications where CFD-

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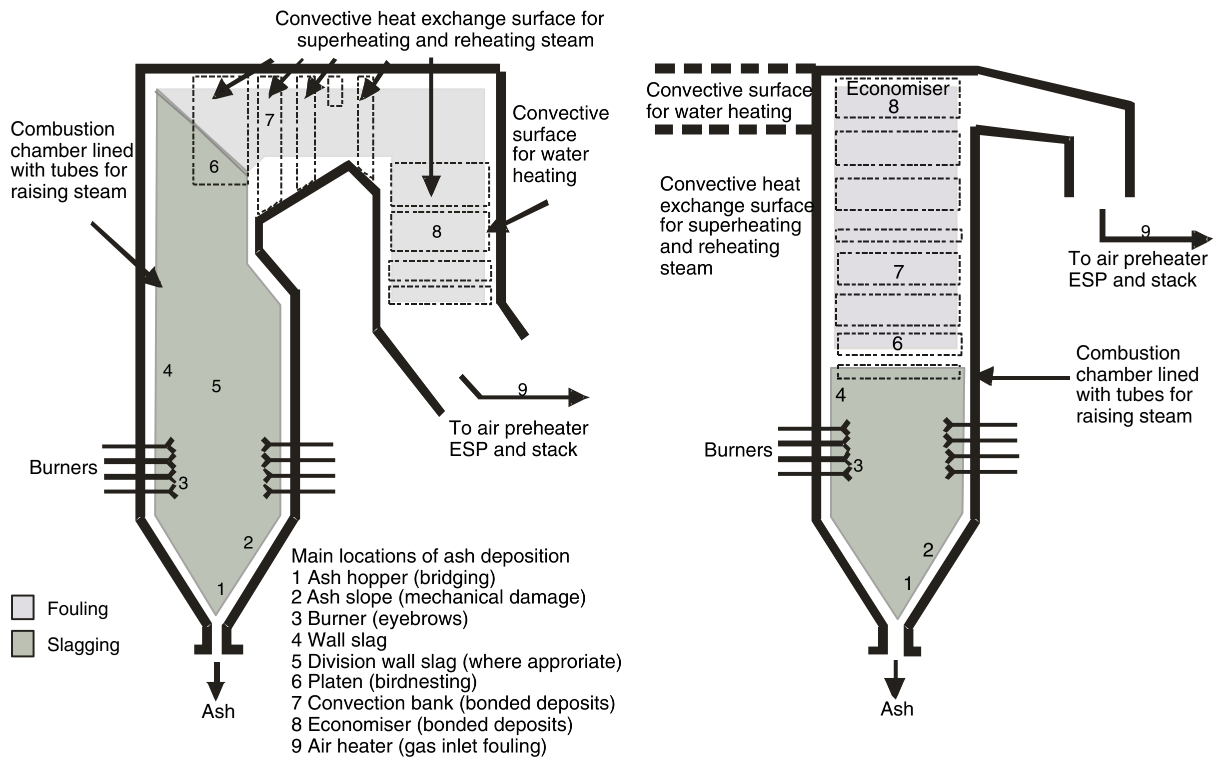

Fig. 1. Regions of ash related problems in boilers: left — conventional pulverised fuel fired boiler configuration; right — tower boiler configuration. Compiled from Ref. [1,2].

computations have been used to predict slagging and fouling propensity in industrial boilers, see Table 1. This is not too surprising; although the vision of possessing CFD-based ash deposition models is in our opinion realisable, a significant body of the development work is needed to achieve this goal. In short, the currently published papers just initiate the forthcoming proliferation of scientific articles in this field.

Recently a CFD-based model for straw-fired grate stocker was presented [5]. The model described combustion on the grate as well as in the boiler volume above the grate. The emphasis was placed on deposit build up on both platen superheaters and tube banks. The submodel handling the ash transport accounted for inertial impaction, turbulent transport and thermophoresis. An ash sticking sub-model specific to straw ash was developed and the deposit mass flux was calculated. Although reasonable predictions of the deposition rate were achieved, the model is used to identify “the areas of potential deposit formation problems” [5]. It was again observed that the inertial impaction was the dominant mechanism of particle transport and its rate was around an order of magnitude larger than the turbulent particle transport rate through the boundary layer. It was postulated that the initial deposit layer was formed mainly through the alkali vapour condensation which was then followed by a much faster ash particles deposition phase.

In a similar publication, Forstner et al. [6] performed CFD-computations of a pilot scale 440 kW_{th} biomass-fired grate furnace to predict the growth rate as well as physical and chemical structures of deposits. Inertial impaction and condensation of ash forming vapours were considered as mechanisms of matter transport to boiler surfaces. The concentrations of the vapour species were computed using chemical equilibrium calculations whilst the inertial impaction using the discrete phase model (see Section 2.2 below) of the CFD Fluent 6.1 code. It was observed that in the primary combustion zone, deposits were basically formed by impaction of coarse particles. In the cooled fire tube zone, the wall temperature was low enough to enable condensation of alkali vapour, however the inertial impaction was still the dominating mechanism of solid matter transport towards the walls.

Epple et al. [8] used a CFD-based mathematical model to predict combustion of lignites in a 330 MW boiler. A part of the work was dedicated to identification of the boiler areas that might be exposed to excessive slagging. Here also a Lagrangian particle tracking, presumably similar to the one described in Section 2.2 below, was used and the assumption was that the CFD code itself took care of the particle impaction efficiency. In other words, the CFD-computed flow pattern in the vicinity of the deposition surface and the Lagrangian particle tracking determined whether a particle hit a surface or not.

Mueller et al. [9] used a combination of CFD and advanced fuel analysis to predict the ash deposition behaviour in a 105 MW biomass fired bubbling fluidized bed boiler. The ash particle trajectories were computed using the Lagrangian model (see Section 2.2 below) and the impaction efficiency was assumed to be 1 since the worst case scenario was considered. The model correctly identified the location of the boiler areas where intensified slagging occurred.

Eddings et al. [11] presented a case study illustrating how knowledge of the transformation of pyrites coupled with CFD models could be used to explain problems of corrosion that were encountered in utility boilers as a result of modifications to reduce emissions of nitrogen oxides. Schell et al. [12] computed a 450 MW_{el} boiler fired with a brown coal using AIOLOS CDF-code of TU Stuttgart. Transport of ash particles towards the deposition surfaces was computed assuming that particles smaller than 20 μm followed the gas flow without any slip, whilst for larger particles a Lagrangian approach was used. Thus, turbulent eddy transport and thermophoresis were the transport mechanisms for particles smaller than 20 μm whilst particles larger than 20 μm were transported by inertial impaction and turbulent eddy transport. The adhesion behaviour was approximated by a linear dependence of the sticking probability with particle temperature; from zero at 970 °C to one at 1230 °C. Their considerations on the effect of deposit formation on heat transfer rate make the publication of Schell et al. [12] very informative.

Bernstein et al. [13] presented CFD-simulations of 800 MW brown coal fired boiler (Schwarze Pumpe, Germany) of which the slag