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Ash particle sticking and rebound behavior: A mechanistic explanation and modeling approach

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Abstract

In this work, a mechanistic ash particle sticking and rebound criterion is developed and validated against experimental data. The model is able to predict the threshold of particle sticking and rebound as a function of the particle kinetic energy. Furthermore, it explains the selective deposition of large iron-rich and small aluminum silicate particles, which were found in deposits on a cooled probe taken in a pulverized solid fuel fired power plant. Large particles stick to the deposition probe due to their low viscosity caused by the formation of a low melting eutectic. Small aluminum silicate particles completely dissipate their kinetic energy during the impact due to viscous deformation. There is no excess energy left for them to rebound. It is shown, that the particle kinetic energy and viscosity are key parameters for the sticking propensity. The model is extended for deposit properties, enabling the capture of solid or solidified particles on a sticky surface. Since all input parameters can be calculated, it is suitable for the application in CFD codes. The required data are the particle and deposit composition, their temperatures in combination with the particle kinetic energy just before the impact.

Keywords: Ash deposition; Particle adhesion; Droplet impaction; Slagging and fouling; Critical viscosity

1. Introduction

Ash deposition on heat exchanging surfaces is causing a series of problems associated with the operation of pulverized fuel (PF) boilers. The steam production is decreased as a consequence of reduced heat transfer rates, and due to the steam required for cleaning purposes inside the boiler.

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In addition, power plant shutdowns are frequently caused by deposits and their uncontrolled growth. One crucial aspect of ash deposition is the particle sticking or rebound behavior. Several studies proposed a series of sticking criteria, however their accuracy differs and no single model was successfully applied among different studies or validated in depth. Furthermore, no criterion considers all important parameters affecting the sticking probability. Three main types are found in the literature using different approaches, which are the particle melt-fraction [1–4], the particle viscosity [5,6] and energy conservation methods [7–9]. The majority of criteria use a so-called critical value, below which the particle starts to stick to the surface. A very popular sticking criterion is the model of Walsh et al. [5], which compares the particle viscosity to a reference viscosity at which sticking starts. In addition, the model accounts for the stickiness of the deposit itself. However, it is often used in combination with the bulk ash composition and particle to particle variations in chemical composition are not included or considered. Furthermore, the effect of particle kinetic energy and the angle of impaction on the rebound behavior are missing.

Therefore, the aim of this study is the development of a comprehensive sticking criterion, considering all parameters affecting the particle sticking and rebound behavior. The sticking probability is dependent on a number of characteristics, such as: the particle temperature, viscosity, surface tension, wettability with the substrate, and density. Furthermore, the particle diameter, velocity and the angle of impaction are known to change the particle sticking [7,10]. Another aim of this study is to explain deposits and their composition which were found in a power plant. In the first section power plant measurements and literature findings are evaluated and compared. In the next step, a theoretical model, based on energy conservation is used to explain observations. In the end, a global model suitable for Computational Fluid Dynamic (CFD) codes is proposed. It is a simple and reliable set of equations considering all important parameters.

2. Experiments and observations

Measurements in a 730 MW_{th} PF boiler located in Altbach, Germany are conducted in order to gain insight in the deposition process. The focus is on the initial layer built-up. A cooled deposition probe is placed upstream of the first superheater tube bank. The probe is maintained at 690 °C and composed of Nickel alloy 740. The flue gas temperature at this location was measured to $T_{FG} \approx 1050 \pm 50\,°C$ using a suction pyrometer. The flue gas velocity is estimated to $v_{FG} \approx 7 \pm 1$ m/s [11]. The bituminous coal Pittsburgh #8 is fired in a staged combustion system with an under-stoichiometric furnace and over-firing air. Figure 1 shows a back-scattered electron image taken from the windward side of the deposit. The deposit is mainly composed of two types of particles. The first group are large, iron-rich (Fe-rich) particles; the second are small, aluminum silicate (Al–Si) particles. The majority of large particles were found in the size range of 20–50 μm. Large Al–Si particles, which are frequently found in the fly ash, are missing in the deposit. Babat et al. [12] originally differentiates large particles into bright and darker ones. However, chemical analysis reveals that all large particles (with two exceptions) have an iron content exceeding 30 wt% on an oxygen-free basis. Therefore, only two major groups are discussed in this study. There are some particles directly in contact with the substrate showing a high wetting and deformation. Small particles are mainly found in the size range of 5 μm or below. Small particles are spherical, indicating that they have been molten in the flame and solidified upon cooling either in the gas flow or the boundary layer of the deposition probe. A previous investigation by Babat et al. could explain the low melting temperature of Fe-rich particles due to reducing conditions in the furnace [12]. A further study used CFD and found that thermophoresis is the driving force for the small particle impaction on the probe [11]. However, the reason why small Al–Si particles with relatively high melting temperatures stick, remained unclear. This is even more surprising when considering the rapid cooling of small particles inside the boundary layer. Small particles travel with the fluid velocity which strongly decreases at the front stagnation point of the cylindrical probe. Thus, a suitable sticking criterion should be able to describe both, the stickiness of large iron-rich, low-viscosity particles and the adherence of small Al–Si particles with a relatively high viscosity. The chemical composition of inorganic elements in the fuel and the deposit is given in Table 1. The fuel inorganics were quantified using an ICP-OES analysis. The deposit chemistry was investigated semi-quantitatively using wavelength dispersive X-ray spectroscopy (SEM/WDX). Individual particle chemistry and the cross-section they cover are used to calculate the deposit composition given in Table 1. Obtained results agree with cross-sectional analysis conducted by Babat et al. [12]. The fuel minerals are dominated by aluminum silicates, whereas the deposit shows large quantities of iron-bearing particles. A small decrease in sodium (Na), potassium (K), and sulfur (S) might indicate the vaporization of these elements during fuel conversion. However, this has to be verified by additional tests. Babat et al. [12] explained the increased presence of iron by the formation of low melting eutectic in the reducing furnace. These particles show a relatively high melt-fraction even at temperatures around 1000 °C and thus a high stickiness. Large Al–Si particles on the other hand are not found in the deposit, which implies rebound upon impaction.