Experimental investigation of ash deposits on convection heating surfaces of a circulating fluidized bed municipal solid waste incinerator

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Abstract
Incineration of municipal solid waste (MSW) is a waste treatment method which can be sustainable in terms of waste volume reduction, as well as a source of renewable energy. During MSW combustion, increased formation of deposits on convection heating exchanger surfaces can pose severe operational problems, such as fouling, slagging and corrosion. These problems can cause lower heat transfer efficiency from the hot flue gas to the working fluid inside the tubes. A study was performed where experiments were carried out to examine the ash deposition characteristics in a full-scale MSW circulating fluidized bed (CFB) incinerator, using a newly designed deposit probe that was fitted with six thermocouples and four removable half rings. The influence of probe exposure time and probe surface temperature (500, 560, and 700°C) on ash deposit formation rate was investigated. The results indicate that the deposition mass and collection efficiency achieve a minimum at the probe surface temperature of 560°C. Ash particles are deposited on both the windward and leeward sides of the probe by impacting and thermophoretic/condensation behavior. The major inorganic elements present in the ash deposits are Ca, Al and Si. Compared to ash deposits formed on the leeward side of the probe, windward-side ash deposits contain relatively higher Ca and S concentrations, but lower levels of Al and Si. Among all cases at different surface temperatures, the differences in elemental composition of the ash deposits from the leeward side are insignificant. However, as the surface temperature increases, the concentrations of Al, Si, K and Na in the windward-side ash deposits increase, but the Ca concentration is reduced. Finally, governing mechanisms are proposed on the basis of the experimental data, such as deposit morphology, elemental composition and thermodynamic calculations.

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Introduction

In modern industrialized societies, large quantities of waste are produced. The disposal of municipal solid waste (MSW) is one of the more serious and controversial urban issues facing local governments, globally. Compare to landfilling, incineration of MSW has many advantages including a significant reduction in volume (about 70–90%), recovery of energy and complete disinfection. Therefore, incineration of MSW has been adopted in many countries, such as China, Japan, the US and several European countries. Compared to more traditional incinerators such as grate furnaces and rotary kilns, fluidized bed combustion has shown to be a versatile technology, capable of burning practically any waste combination, with lower emissions (De Boom et al., 2011). The significant advantages of fluidized bed combustors over conventional combustors include their compact furnace, simple design, effective burning of wastes with low calorific value, relatively uniform temperature and the ability to reduce emissions of nitrogen oxide and sulfur dioxide gases (Van Caneghem et al., 2012). In China, circulating fluidized bed (CFB) boilers are playing an important role in MSW combustion and electrical power generation. However, MSW often contains large proportions of ash (25%), which can be deposited on the heat transfer surfaces, and ash-related problems like deposit formation, corrosion and erosion are usually responsible for the malfunctioning of combustion systems (Mu et al., 2015; O’Hagan et al., 2015; Phongphiphat et al., 2011; Wang et al., 2008). These problems may have implications for heat transfer rates and hence decrease the efficiency of the boilers or even render the incinerators unmanageable (Garba et al., 2012; Teixeira et al., 2012; Wieland et al., 2012; Zbogar et al., 2009).

Ash deposition phenomena can be influenced by many physical and chemical processes, such as ash chemical composition, distribution of mineral matter in ash, ash fusion temperatures, furnace temperature, ash particle temperature, surface temperature of heat-exchanger tubes, tube materials, the flow field in the furnace, and ash transport mechanisms (Phongphiphat et al., 2011; Wieland et al., 2012). A number of reviews relating to ash deposition characteristics have already been reported (Reichelt et al., 2013; Teixeira et al., 2012). The formation of deposits depends strongly on the boiler type, the fuel and the temperature in the system. Deposits in coal combustion plants are formed at high temperatures above 900°C and show a large amount of amorphous phases, anhydrite, hematite and silicates (Kostakis, 2011). In biomass-fired FBC boilers, the vaporization and condensation of alkali metal elements, in particular potassium, play an important role in the ash deposition process (Bashir et al., 2012; Garba et al., 2012). Potassium is dispersed in biomass in different forms, e.g., organometallics and salts, while silicon occurs primarily as hydrated silica grains (Li et al., 2013).

MSW differs from coal or pure biomass, such as wood and straw. MSW is a very complex and heterogeneous fuel, containing several individual material fractions (paper, plastics, food waste, metals, glass etc.) with different physical and chemical characteristics. MSW is a mixture of inhomogeneous materials which contains large concentrations of sulfur, chlorine, alkali and earth alkali metals and, in minor amounts, heavy metals like lead or zinc (Pfrang-Stotz et al., 2004). Currently, major research on MSW ash deposition has focused on the morphology or compositions of the collected ash deposit, especially in grate firing boilers. Ash deposits from MSW grate firing boilers are mainly composed of silicates and alumino-silicate minerals with low solubility, and the fly ash contains considerable amounts of soluble salts of alkali and alkaline earth metals. The major components of fly ash and bottom ash are SiO₂, CaO, Al₂O₃, Fe₂O₃, Na₂O, and MgO (Chou et al., 2009; Cobo et al., 2009; Thipse et al., 2002). Phongphiphat’s work includes the analysis of bottom ash, deposits from the superheater and the fly ash from the economizer and fabric filters in a large-scale MSW grate firing incinerator in terms of particle size, unburned carbon, elemental composition and surface morphology. According to this study, the main components of the deposits on the superheater are Ca–Si–Al and/or Si–K–Al, likely to be present as amorphous silicates (Phongphiphat et al., 2011). Based on the fouling behavior of three different grate incinerators, Reichelt’s study suggests that directly on the tube itself, a primary deposit is formed very rapidly due to mineralogical reactions. It contains sulfates and higher contents of chlorides, which both act due to their low melting points as glue for the secondary deposits (Reichelt et al., 2013).
In fluidized bed boilers, calcium-containing sorbents such as limestone are usually premixed with fuel and fed into the combustor to reduce emissions of nitrogen oxide and sulfur dioxide gases. Earlier studies showed that a typical mineralogical phase composition of a deposit from a CFB MSW incinerator power plant consists mainly of many different sulfates, rich in calcium, minor contents of silicates and oxides and small amounts of potassium and sodium. This mineralogical composition of deposits changes within the different parts of the boiler and in different operation conditions of boilers. Xu’s studies indicated that the main mineral phase in the ash deposits from different heating surfaces of a CFB MSW incinerator was CaSO₄. The structure of the sintering deposit can be divided into the root and growth part. Besides KCl and NaCl, low-melting point eutectics such as K₂O–CaO–SiO₂ were also found in the innermost layer of ash deposits. Vapor phase condensation and the thermophoresis of submicron granules are the leading mechanisms of the formation of inner layer of the deposits (Xu et al., 2007; Xu et al., 2006). However, these investigations mostly focused on the morphology or compositions of the collected ash deposits, rather than the dynamic deposition process at different tube temperatures.

The purpose of this study is to provide long-time, full-scale data on ash deposit formation in a CFB MSW incinerator. Furthermore, an analysis was carried out, giving quantitative information about deposit formation rates as functions of operating conditions. The influence of probe surface temperature (500, 560, and 700°C) on both the windward and leeward sides of the probe was investigated. Finally, governing mechanisms are proposed on the basis of the experimental data, such as deposit morphology, elemental composition, and thermodynamic results.

1. Experimental studies

1.1. CFB municipal solid waste incinerator

The probe measurements were conducted at one CFB MSW incinerator in Zhejiang Province, China, as shown in Fig. 1. The incinerator has a nominal capacity of 450 ton/day, supplying steam to a turbine at 485°C and 53 bar. The operation temperature of the furnace was between 850°C and 950°C. The excess air ratio in the furnace is around 1.3. An external heat exchanger is used in this boiler to adjust the furnace temperature and working material temperature. In the process of the boiler operation, MSW co-incinerated with coal is sent to the bed from two different feed ports and mixed with the hot bed materials to ensure the rapid combustion of fuel.

![Fig. 1 – Schematic overview of incinerator with identified probe measuring position.](image)
Fig. 2 shows a picture of ash deposits on the evaporating heat exchanger taken after the incinerator was shut down. The comb-like deposits were formed and grown mainly on the windward side of the tube. Most of the deposits were hard and brittle. The deposits that adhered to the shell of the tube were hard to remove after formation. In this study, one probe position was selected, as shown in Fig. 1. The probe measuring position was selected because of significant deposit build-up during straw firing in that boiler position. The selected probe measuring position was in the most contaminated area in the boiler.

The fuel properties, fuel ashes and limestone ash analysis results are presented in Tables 1 and 2. The coal and MSW contained 19.04% and 34.9% of ash, respectively, with SiO₂ and Al₂O₃ being the major components. MSW is a very complex heterogeneous fuel, containing several individual material fractions (paper, plastics, food waste, metals, glass etc.). Each element will thus have different concentrations and chemical associations in the different material fractions. Furthermore, the overall MSW composition varies with time, seasons, and geographic regions. Due to the high efficiency of the scavenging of recyclable materials, Chinese MSW has a calorific value of only 5.0 MJ/kg, half the EU or US value, and is usually mixed with 15% coal when incinerated (Steiner et al., 2015). In this boiler, to ensure proper combustion temperature and efficiency, the coal mass ratio is 20%.

Based on the analysis results, the major inorganic elements in the coal ash and mix fuel ash were silicon (Si), aluminum (Al), iron (Fe) and calcium (Ca). The limestone ash consisted mainly of Ca and small amounts of Si and Al. In fluidized bed boilers, sulfur capture is usually carried out with in situ injection of calcium-containing sorbents, such as limestone or dolomite. In air-fired atmospheric units, sulfur capture occurs via relatively rapid calcination and much slower sulfation reactions. The limestone was premixed with coal and fed into the CFB incinerator through the coal feeder.

1.2. Ash deposition probe

The deposit probe used during the measurements is shown schematically in Fig. 3. The probe is made of stainless steel, with a length of 1.5 m and an outer diameter of 38 mm. The probe is constructed as a double annular tube, which is cooled with cooling air. This cooling arrangement ensures a reasonably uniform surface temperature along the whole length of the probe. The probe surface temperature was set to 500, 560, 700°C in order to simulate typical evaporating heat exchanger tubes in a MSW incinerator. The probe surface temperature was maintained by regulating the cooling air flow. Six thermocouples were placed inside the outer probe metal tube, i.e., two thermocouples placed at 180° from each other in three horizontal positions (middle position and at the two ends of the half ring zone), as shown in Fig. 3, to ensure a reliable measurement of the metal surface temperatures. The deposit probe is equipped with four removable half rings. These half rings are located between the thermocouples, and can be removed, weighed and analyzed using Scanning Electron Microscope (SEM), X-ray Diffraction (XRD) and X-ray fluorescence (XRF).

1.3. Experiment procedures

A series of probe measurements were conducted in the evaporating heating region. The influence of probe surface temperature (500, 560, and 700°C) on both the windward and leeward sides of the probe was investigated. The deposition probe was exposed to flue gas temperatures from 600 to 850°C. Probe surface temperatures were varied between 500 and 700°C in order to investigate the ash deposit formation rate at different probe surface temperatures. Retractable steam soot blowers were used at regular intervals during boiler operation, typically at 4 hr intervals. The soot blower located nearest to the probe measuring position (approximately 1 m to the left) was shut down during the tests. In a typical experiment, at least 4 to 5 hr of stable operation was performed. When the test was finished, the ash deposition probe was carefully removed from the freeboard and the deposited ash rings were completely recovered for weighing to calculate the accumulated superficial ash deposition rate ($D_a$, g/hr) as defined below:

$$D_a = \frac{\text{Mass of collected ash deposit (g)}}{\text{Duration (hr)}}$$ (1)
The fly ash was sampled in the convection heating zone during the shutdown of the boiler. We collected the fly ash samples, which were formed by the condensation of flue gas, from the top of the heating exchanger surfaces.

Several analytical techniques were used to determine the elemental composition and surface morphology of each sample. The analysis of morphology and mineralogy was completed using an SEM and an Energy Dispersive X-ray Spectrometer (EDS). Ash elemental compositions were quantified using an XRF analyzer, with the model number of ARL9800XP+.

2. Results and discussion

2.1. Effect of probe surface temperature on ash deposition

In order to investigate the influence of the probe surface temperature on ash deposition, three different temperatures (500°C, 560°C and 700°C) were set by adjusting the cooling air flow rate. In these experiments, the sampling time was about 5 hr. The mass of each sampling half ring was measured before and after the experiment. See Fig. 4 for an illustration of the deposition morphology of the rings. Flue gas temperature, windward and leeward-side probe surface temperature measurement results during the test can be seen in Fig. 5. The flue gas temperatures measured by thermocouple were between 500 and 800°C.

Fig. 6 shows the deposited mass of ash for all the rings collected at different surface temperatures. It is found that, as the surface temperature increased from 500°C to 560°C, the ash deposit rate decreased for both windward and leeward sides. However, as the surface temperature further increased from 560°C to 700°C, the ash deposit rate conversely increased for both sides. It is seen that the deposition tendency at 560°C is lower than those for both 500°C and 700°C cases. This finding is consistent with a report in the literature (Li et al., 2013). The reasons for this phenomenon will be discussed in detail later in this paper.

Fig. 3 – Ash deposition probe. (a) Schematic of the applied deposit probe; (b) ash deposition probe.

Fig. 4 – Pictures of ash deposits. (a) Before sampling; (b) after sampling.
2.2. Morphology of the ash deposit

Fig. 7 shows the SEM images of the fly ash and ash deposition from the windward-side half rings under different surface temperature conditions. The deposited ash layer on the probe surface contains much finer ash particles (cube-like, elongated, needle-like and plate-like particles), with some spherical/polygonal particles that are evenly distributed across the whole probe, both upstream and downstream.

2.3. Elemental compositions of the ash deposit

Fig. 8 shows the energy dispersive X-ray spectrum results for the ash deposit at surface temperature 560°C. The EDX analysis revealed that in these ash particles, Ca and S are the two dominating elements, as shown, which is a typical elemental composition for combustion residues. Potassium, sodium, chlorine, sulfur, aluminum, iron, magnesium, zinc and phosphorus, which were typical ash-forming elements, were also found at all points, but the major elements varied between points.

A selected area in Fig. 8 was examined with EDX, and the results are shown in Fig. 9. According to EDX spot analyses, Ca–S were the main elements found at some points (spots 1 & 5), which was expected mainly to represent CaSO4. The spherical quartz grain (SiO2) at the center and calcium sulfate crystals (anhydrite CaSO4) as particle or as binder can be seen from Fig. 9. This means that calcium sulfate in the ash deposits of the convection heating zone can be formed from Ca minerals like CaO or CaCO3 as a binding material between the grains. Fig. 9 (spot 6) shows that besides CaSO4, KCl and/or K2SO4 could be part of the deposits as very small particles on the surface of the droplet, which can cause eutectic melting.

Fig. 10 illustrates the XRF analysis of mass fractions of several major elements in the fly ash and ash deposit under different surface temperature conditions. The main inorganic elements in the ash samples were Ca, Si, Al and sulfur (S), which is consistent with a report in the literature (Xu et al., 2007). Windward-side ash deposits contained a relatively higher Ca and S concentration, but lower amounts of Al and Si. As the windward-side probe surface temperature increased from 500°C to 700°C, the concentration of Al and Si increased. Further analysis of the ash deposits using an X-ray Diffractometer (XRD) found that for the ash deposits at 500 and 560°C, the main identified mineral phases are quartz (SiO2) and corundum (Al2O3). Quartz and corundum remained as crystalline phases at higher sintering temperatures, with gradually increased intensities. The Anorthite (CaAl2Si2O8) pattern was observed at 700°C, which may due to reactions of CaO with Al2O3 and SiO2 at that temperature. Corundum is an inert mineral phase with a melting temperature higher than 2000°C, which can enhance the sintering temperatures for both coal and biomass ash by the dilution effect (Van Dyk, 2006). Among all cases at different surface temperatures, the differences in elemental composition of the ash deposits from the leeward side were insignificant. However, as the surface temperature increased, the content of Al, Si, K and Na in the windward-side ash deposits increased, but the Ca contents were reduced.

It is known that there are five kinds of deposition mechanisms, e.g., inertial impaction, condensation, eddy impaction, thermophoresis, and chemical reaction (Baxter, 1993). For a general deposition system of a particle with a surface, a critical velocity is usually defined to decide whether this incident particle may deposit or rebound. Li discussed...
this process with a direct derivation based on the Johnson–Kendall–Roberts (JKR) theory. They found that the critical velocity is negatively correlated to the particle diameter, suggesting smaller particles would be more easily adhered to the surface (Liu et al., 2011). Considering a predeposited probe with a surface temperature below 700°C, which is usually lower than the melting temperature of ash particles, the adhesion energy between the incident particle and the probe surface is also in this range. This indicates the contribution of sub-micrometer particles (formed by easily vaporized minerals) by thermophoretic/condensation mechanisms during the initial deposition stage. As the deposit mass increases, the ash deposit surface temperature will increase due to the decrease of the ash heat-transfer coefficient, which will lead to the partial melting of the top layer of ash deposits. For instance, the melting point of silica decreases from 1700 to less than 750°C as potassium or sodium is introduced to form potassium silicates (Baxter, 1998). Low melting temperature Si–Al phases (like anorthite (CaAl2Si2O8)) can be formed via solid-state reaction of CaO with Al2O3 and SiO2 at temperatures ranging from 900°C to 1000°C (Unsworth et al., 1988). The partly melted phases make the deposits more “sticky”, thereby also accelerating the capture of impacting particles. That is why the ash deposit formed below 700°C contains the highest contents of Al, Si, Na and K, as can be seen from Fig. 10.

In the test with deposition temperature of 500°C, the temperature difference between the flue gas and the sampling probe is large. This large temperature gradient enhances thermophoretic/condensation mechanisms of fine particles. Then, more condensed elements and even the formed fine “sticky” particles will deposit on the probe surface to make the surface more adhesive, which results in a higher mass deposition rate compared to those at the deposition temperatures of 560 and 700°C. As stated in the literature (Xu et al., 2010), the ultrafine sub-micrometer particles act like “glue” during the ash deposition at lower temperatures. Meanwhile, at a higher surface temperature of 700°C, the deposited ash mass surface temperature is also higher compared to that of 560°C. The high temperature of the ash layer makes it easily sintered, and thus increases the sticking probability of ash particles. At high temperature, the sintering bulk ash particles are mainly deposited from inertial impaction. Generally speaking, the case of 560°C at the probe surface is just an intermediate state between these two kinds of distinct modes aforementioned, which causes the lowest collection efficiency to occur at this temperature, as shown in Fig. 6.

Earlier studies showed that the typical mineralogical phase composition of a deposit from a MSW incinerator power plant consists mainly of many different sulfates, rich in Ca, K and sodium (Na) or lead (Pb) (Pfrang-Stotz et al., 2007; Pfrang-Stotz et al., 2004). Sulfur was found to be specifically concentrated in the ash deposits, presumably due to the sorption of SO2 and the condensation of volatilized species, such as metal sulfates, during the prolonged exposure of the deposit to the combustion gas. Sulfates condense at relatively high temperatures compared to chlorides, and are predicted to become more thermodynamically favored as temperatures decrease, essentially delaying volatilization at lower temperatures. Current research indicated that the Ca-rich composition of

Fig. 7 – SEM image of fly ash and ash deposits from the windward side half rings under different surface temperature conditions. SEM: Scanning Electron Microscope.
the ash in CFB underwent significant sulfation reaction. These Ca-rich particles came from the fuel itself or the desulfurizer. It has been reported that the promotion of sintering by the desulfurizer process was manifested in the increased formation of the molten phase. For example, the reaction heat may cause a localized high temperature fusion region, or formation of a eutectic mixture with alkali metal (Bryers, 1986). The interaction between particles was strongly affected by the interfacial area between them. Fine CaO particles usually had large specific surface area, and thus there existed relatively large adhesion force among fine CaO particles, which resulted in a tendency for fine CaO particles to aggregate on heated surfaces, forming ash deposits (Kanaoka et al., 2001). The aggregation and precipitation of fine CaO particles were the critical factors that determined the formation of ash deposits on the heating surface of the CFB combustion system (Fig. 11).

2.4. Deposition mechanism discussion

Based on the morphology and composition of the collected ash deposits in this study, a primary deposit is formed on the two sides of the probe at different temperatures. SEM analysis indicates that ash deposits have a lot of crystals and fine particles inside. The chemical composition analysis indicates that the deposit, which has high content of Ca and S, is mainly composed of anhydrite (CaSO₄). In fluidized bed

Fig. 8 – Energy dispersive X-ray spectrum results for the ash deposits.

Fig. 9 – SEM-EDS analysis of droplet Ash deposits from windward side half rings under surface temperature 560°C. SEM-EDS: Scanning Electron Microscope-Energy Dispersive X-ray Spectrometer.
boilers, sulfur capture is usually carried out with in situ injection of calcium-containing sorbents, such as limestone or dolomite. Compared to grate-fired MSW systems, the content of Ca and S in fly ash and ash deposits are relatively higher due to the widespread use of calcium-containing sorbents. The Ca-rich particles of the ash come from the fuel itself or the desulfurizer by the sulfation reaction in the CFB, which will increase formation of the molten phase. The large temperature gradient between the flue gas and probe surface enhances thermophoretic/condensation mechanisms of fine particles, especially submicron and ultra-fine particles. More condensed elements and even the formed fine “sticky” particles will deposit on the probe surface to make the surface more adhesive, which results in a higher mass deposition rate. The calcium sulfate (anhydrite CaSO₄) in the ash deposits of the convection heating zone can be formed from Ca minerals like CaO or CaCO₃ as binding materials between the grains such as SiO₂. A low melting eutectic such as KCl and K₂SO₄ could be part of the deposits as very small particles on the surface of the droplet. These eutectics were also found in grate furnace and biomass boilers. At higher surface temperatures, more low-melting Ca–Si–Al phases (like anorthite (CaAl₂Si₂O₈)) can be formed via solid-state reaction of CaO with Al₂O₃ and SiO₂. The high temperature of the ash layer makes it easily sintered and, thus increases the sticking probability of ash particles. At high temperature, the sintering bulk ash particles are mainly deposited from inertial impaction.

3. Conclusions

A study was performed where experiments were carried out to examine the ash deposition characteristics in a full-scale MSW CFB incinerator. The influence of probe surface temperature (500, 560, and 700°C) on both the windward and leeward sides of the probe was investigated. The results indicate that the deposition mass and collection efficiency achieve a minimum at a probe surface temperature of 560°C. Ash particles are deposited on the probe by impacting and thermophoretic/condensation behavior. The major inorganic elements present in the ash deposits are Ca, Al and Si. Compared to ash deposits formed on the leeward side of the probe, windward-side ash deposits contained a relatively higher Ca and S content, but were lower in Al and Si. For all the tests at different probe surface temperatures, the differences in elemental composition of the ash deposits from the leeward side were insignificant. However, as the surface temperature increased, the content of Al, Si, K and Na in the windward-side ash deposits increased, but the Ca contents were reduced.

The information gathered by these investigations on the deposits will help to optimize the process conditions inside the boiler in order to improve heat transfer on heat exchangers and enhance the energy efficiency of power plants.

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