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Optimisation of water-cannon cleaning for deposit removal on water walls inside waste incinerators

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Abstract

Deposits in municipal waste incinerators are very inhomogeneous in structure and constitution. They cause corrosion and reduce the efficiency, so they need to be removed frequently. Among other systems, operators use water cannons for the deposit removal. Two different removal mechanisms of water-cannon cleaning are suggested: A direct shattering of the deposit by the impact of the water jet, as well as the cracking caused by thermal stresses where droplets cool the deposits. As the contribution of each of the aforementioned mechanisms to the overall cleaning efficiency is unknown, we performed empirical investigations to determine the dominating effect. In a first experimental setup focusing on thermal stress, cold droplets were applied onto hot deposits taken from a waste incinerator. Results showed that the cleaning effect strongly depends on the deposit thickness and structure, so that the deposits could be categorised in three different groups. A second measurement campaign focused on the influence of deposit material, deposit temperature and water jet momentum. It could be shown that both deposit material and temperature have a significant effect on the cleaning efficiency, whereas an increase in water jet momentum only led to modest improvements. The combination of these two parameter studies implies that the influence of the thermal stress outweighs that of the momentum. This knowledge is applicable to the cleaning setup by increasing the temperature gradient.

Keywords

Waste incinerator, deposit removal, water-cannon cleaning, water jet, thermal stress, momentum, water walls

Introduction

Waste incineration releases a variety of extremely different compounds containing, for example, chlorine, sulphur and heavy metals (Mueller et al., 2010). During combustion most of these components are released as vapour, liquid droplets or small solid particles and form deposits on the water walls, which negatively affects the combustors in two ways: First, deposits reduce the heat transfer (Gupta et al., 1999) and second, they are corrosive, which may lead to a damage of the water walls (Bryers, 1996). To avoid these two problems, the deposits have to be removed during the plant operation (Mueller et al., 2010). Material properties of the deposits, e.g. strength, porosity, thermal conductivity and others, are inhomogeneous and highly dependent on the original fuel composition and on the process control. The exact properties of deposits are unknown during operation. Different deposit structures need different cleaning adjustments (Zbogar et al., 2009). As a result, a general optimisation of cleaning mechanisms for the present types of deposits is not possible, yet. To improve the cleaning efficiency, empiric investigations concerning the influence of impact time and impact pressure, aimed at identifying the principle cleaning mechanisms, were performed by the authors. One focus of this work was to classify the deposits and to analyse the optimal cleaning parameters for every classification group. The investigations were carried out in two steps. At first, different deposits were collected from a waste incinerator and grouped by their material structure. Additionally, the effect of thermal stress was tested with these sample deposits. Further investigations were carried out at a test rig of the Technische Universität Dresden: Model deposits with defined properties were investigated to determine the influence of single parameters on the cleaning results; here the material porosity, the deposit temperature and the momentum of the water jet. This article contains investigation results of both measurement campaigns.

Deposits and deposit cleaning systems

Current investigations very often focus on the ash properties, but they do not investigate the most suitable cleaning setup for the specific type of deposit. A detailed description of ash in biomass-fired

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boilers can be found in Sandberg (2011). The deposit formed by the ash is usually classified into two groups – slagging and fouling. Between these two, there is a more or less gradual transition (Żelkowski, 2004). Slagging occurs primarily in the radiation section, while fouling can be found on the walls of the superheater packages and water walls in convection passes. In Erickson et al. (1995), the fouling and slagging within coal-fired boilers were described, and a slagging growth model as well as a fouling model, were developed. Baxter et al. (1996) analysed the deposits in biomass-fired boilers and focused on the alkalis within them. The deposit formation in biomass-fired boilers is described by Obernberger et al. (1997) and Obernberger and Biedermann (1997), with the focus on the influence of heavy metals. Skrifvars et al. (2004) investigated the deposit formation in a pulverised wood-fired boiler through deposit sampling and the collection of fly ash.

The mechanism of deposit formation in general, with focus on coal-fired boilers, is pictured (Bryers, 1996; Gumz et al., 1958; Raask, 1985; Żelkowski, 2004) giving detailed descriptions on the deposit formation process and the deposit composition of coal ash. Transferring these findings to waste incinerators is partially possible, because biomass, and waste in particular, have a very inhomogeneous constitution. Fewer sources analyse the ash of waste incinerators. Viklund (2013) describes the corrosion in biomass and waste-fired boilers in the superheater section, while Frandsen et al. (2001) investigated both fly ash and the deposit formation process inside a waste incinerator. A good summary of the state of knowledge regarding the physical properties of biomass deposits is presented by Zbogar et al. (2009). The scope of that review is especially the comparison of deposit strength and occurring stresses. The article gives an overview of typical cleaning mechanisms and classifies the deposits into four main groups, namely: powdery, lightly sintered, heavily sintered and liquid slag. They propose a cleaning effect through mechanically and thermally induced stresses. The result of these stresses could be a break-up owing to high internal force or a removal of the deposits from water walls. This knowledge shall be adapted to the deposits from waste incinerators.

Several cleaning systems exist on the market, which use different methods to remove the deposits during plant operation. The basic principles of these methods are either mechanically or thermally induced stresses that are created inside the deposits. The following online cleaning systems are based on a mechanical cleaning method.

1. Explosion: The cleaning is caused by pressure waves that are generated via a targeted explosion of a gas mixture. The explosion is initialised from an explosion generator. The tubes and walls oscillate and thereby the deposits loosen from the water walls (Luedi, 2011; Zilka et al., 1998).
2. Pneumatic knocking: A knocking system sets the heat exchanging surfaces also into oscillation. This results in a loss of bonds and therefore a removal of the deposits. The system is preferably used to clean superheater coils (Gehlen and Mergler, 2000; von Paczkowksi, 1995).
3. Sonic and infrasonic: The deposits are impinged with sonic or infrasonic waves. This cracks the deposit structures and loosens them from the water walls (Norris, 1996; Saikia et al., 2014).
4. Water-cannon: A high-pressure water jet blows off the deposits. The water jet follows a cleaning path. Therefore this cleaning system allows a very precise adjustment to the local deposit condition. The pressure of the cleaning medium can be adjusted to the deposit type to improve the cleaning result (Mueller et al., 2010; Scharton and Taylor, 1990).
5. Soot-blower: Process steam is blown with the aid of a soot blower under low pressure onto the water walls. The typical operating location is within the superheater package. Through the rotation of the blower, an adjusted cleaning is possible, but operating costs are high owing to the loss of process steam. The supersonic jet drills into the deposit and cracks it immediately during the exposure (Pophali et al., 2013).

The following online cleaning systems are based on a thermal cleaning method.

1. Water-cannon: The water jet temperature is beneath 100 °C. Hence, the water jet induces a very high temperature gradient and therefore causes thermal stresses. The smart cleaning is important to avoid thermal fatigue of the water walls (Coleman, 2007; Jameel, 1999).
2. Shower-cleaning: The shower-cleaning system consists of a shower head that is moved through the incinerator while it sprays water onto the water walls. The water washes the deposits and induces high thermal stresses comparable with those from a water jet. This method is only applicable to combustion chambers with empty passes and a small cross section (Mueller et al., 2010).

Materials and methods – Study 1

Study design

The thermal stress within deposits depends on many different factors, e.g. the Young's modulus or the heat transfer coefficient. That is why some deposits are suitable for cleaning methods based on thermal stress while others show no effect. To approach the decision of whether or not a deposit type is suitable for thermal cleaning methods, they have to be classified into main groups according to their composition. To do so, the experiments presented in the following were carried out.

The major problem of most cleaning mechanisms is the lack of information about the deposits and the correlation to the operating principle. Therefore, a systematic collection of several deposits and an analysis of their properties were necessary to provide an overview over the existing sorts of deposits. In the past, several possible cleaning mechanisms were determined (Kaliazine et al., 2010; Zbogar et al., 2009). One of the major mechanisms is thermal stress. The present investigation aimed at separating mechanical influences from thermally induced stresses. An experimental

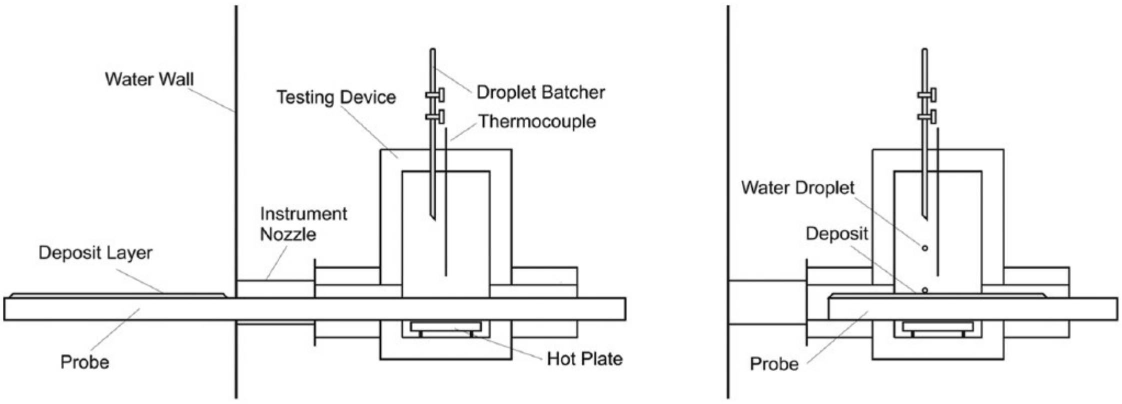

Figure 1. Setup and functionality of the experimental system with (a) the probe inside the combustion chamber and (b) the probe inside the heated chamber.

setup was developed that avoids mechanical cleaning and allows the occurrence of thermal stresses and evaporation.

The focus of the first experiment was the investigation on the influence of water on deposit removal under operational conditions. The avoidance of any cooling by the surrounding area during the measurement was critical, as this would result in a change of the deposit structure and, thus, its strength. That is why the investigations were carried out on-site at the combustion chamber of the municipal waste incinerator in Kassel, Germany. Figure 1 depicts the setup. The apparatus consisted of a heated chamber that was connected to a drop batcher. A thermocouple measured the gas temperature inside the chamber. A valve allowed access to the combustion chamber of the incinerator. A probe was slid into the combustion chamber and stayed there for several hours depending on the desired layer thickness of the deposit on the probe. Afterwards, the probe was pulled out of the combustion chamber and then was held inside the heated chamber of the testing device directly below the drop batcher. The water was dosed in droplets onto the hot deposits.

The probe itself consisted of a long outer metal pipe that was closed at the end facing the combustion chamber, and an inner pipe that served for cooling through compressed air. The compressed air exited the inner pipe at the probe tip, flew backwards between the outer and inner pipe, and left at the cold end of the pipe. Several thermocouples at the inner side of the outer pipe measured the probe temperature and served as an input signal for the flow control. The flow control realised a constant surface temperature. The experiments were carried out at different locations inside the line 4 incinerator in Kassel. The steam generator had a steam mass flow of 36.3 tonnes per hour, with a live steam temperature of 420 °C and a live steam pressure of 4.2 MPa. As depicted in Figure 2, the experiments were carried out at two different locations.

To retrieve comparable results, all experiments were carried out using the following parameters.

- The water droplets were applied at three locations onto the probe, located at 60 mm, 160 mm and 260 mm from the tip.

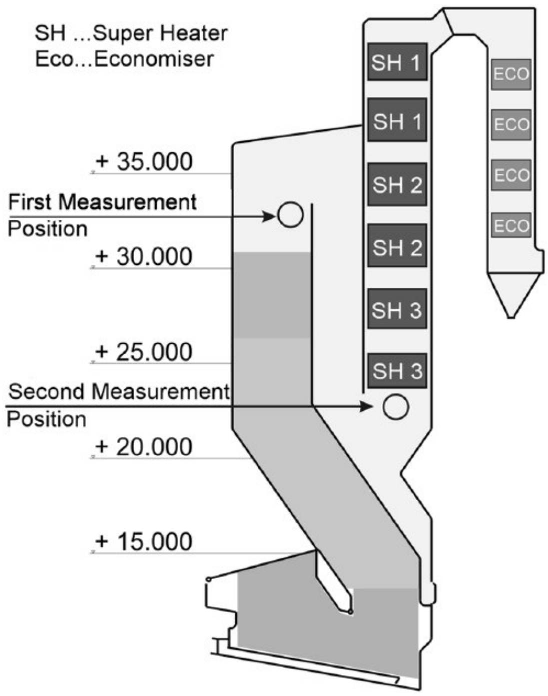

Figure 2. Measurement location inside the boiler.

- The probe temperature measured at a distance of 30 mm from the tip remained constant at 260 °C.
- The amount of water droplets was 20, with a frequency of 1 droplet per second.
- The flue gas temperature was measured at both locations as 790 °C at the first measurement position and 690 °C at the second one.

Altogether, six measurement series were carried out.

- Three experiments at the first measurement location with a duration of 16 hours inside the combustion chamber.
- One experiment at the first measurement location with a duration of 40 hours.
- Two experiments at the second measurement location with a duration of 16 hours respectively.

Table 1. Effect of water droplets on different deposit types.

Deposit type and effect of water droplets		Deposits on the probe	Layer	Lasting time
Thin salt layer: Water dissolves deposits			1 mm	16 hours
Crusty layer splits off			2–4 mm	16 hours
Thick layer of fine-grained particles remains without effect			10–18 mm	40 hours

Measurement execution

All probes were treated in the same way: After applying the water, all probes were compared regarding their layer thickness and the effect of the water droplets. The probes that remained inside the incinerator for 16 hours had a layer thickness of 1 mm to 4 mm. At the locations of the droplets, a removal of the deposits was visible. Obviously, some parts were split off. Here, the occurrence of thermal stress was very likely. Other parts were dissolved. These deposits consisted of salt layers, which were soluble in water.

Probe 4 lasted 40 hours at the same location as the first three probes. The deposit layer was much thicker (11 mm to 18 mm). Upstream side and downstream side were clearly distinguished. There was almost no visible effect of the water droplets. Hence, neither the thermal stress had an effect on the deposit nor was it dissolved or washed.

The two probes collected at the second location had clearly visible upstream and downstream sides from the flow inside the incinerator. The layer thickness lay within 9 mm to 14 mm. The impact point of the droplets was visible by eye, but no removal of the deposits occurred.

The comparison of all six probes showed a connection between the layer thickness and the thermal stress; the thicker the layer, the lower was the effect of thermal stress. We assume that the deposit structure is responsible for that. The very thin layer on the pipe was either sintered and very compact or consisted of salt while the material structure of the thick layer was more porous and not as vulnerable for thermal gradients. That connotes that not the layer thickness itself but the constitution of the deposit was responsible for the cleaning effect through thermal stress. To draw a conclusion about that, the material properties have to be similar for two experiments with different layer thicknesses. The results of the first measurement campaign are summarised in Table 1.

The results of the investigations showed that the cleaning effect of thermal stresses differs depending on the deposit type. To determine the influence of specific parameters, it is necessary to avoid unknown parameter constellations. The deposit properties have to be well-known to draw inferences about their reaction to stresses during the cleaning cycle. This is why a second measurement campaign used model deposits with known material properties. The following section describes the procedure and study design of these measurements.

Parameter study – Study 2

Study design

In a second measurement series, a test rig was used to analyse the cleaning efficiency of water jets on different deposits with known material structures. Following the experimental setup, the procedure and the obtained data are described.

The experimental setup consisted of a natural gas burner, a combustion chamber, a middle chamber to even flow and temperature distribution and the actual water jet. Inside the water jet chamber was a water jet cannon opposed to a superheater wall segment. Air flew through this segment to control the temperature. A model deposit was attached to the water wall. The air that streamed through the wall segment was preheated to model a steam temperature as in practical water walls. The exhaust gas streamed from the combustion chamber through the homogenisation chamber into the water jet chamber where it heated the deposit. Afterwards, the exhaust gas exited through the exhaust duct. The whole setup is shown in Figure 3.

Thermocouples were located within the deposit, which record the temperature profile of the model deposit. Figure 4 depicts the size and shape of the model deposit, including the position of three thermocouples that were installed in several distances from the heat exchanging surface of the superheater wall.

First, the probes were prepared in moulds to guarantee the same shape for all of them, afterwards they hardened for several days. Finally, the model deposits were fixed to the wall segment with gypsum. When the deposit reached a constant temperature

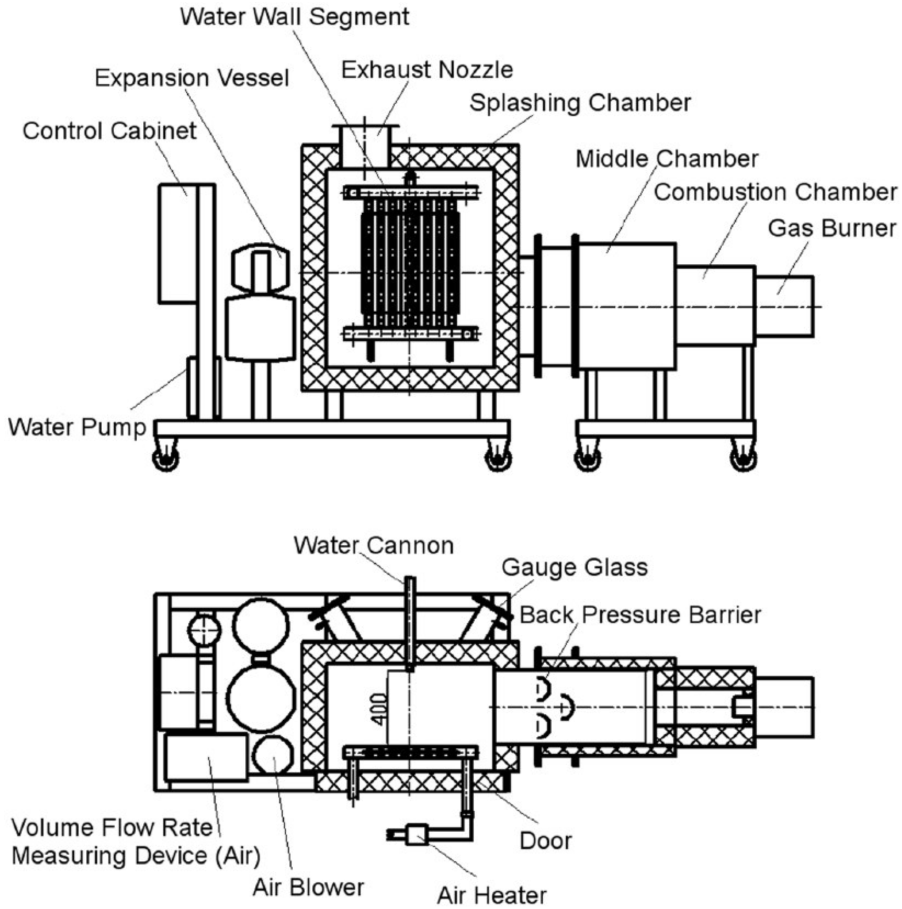

Figure 3. Measurement setup of the testing field.

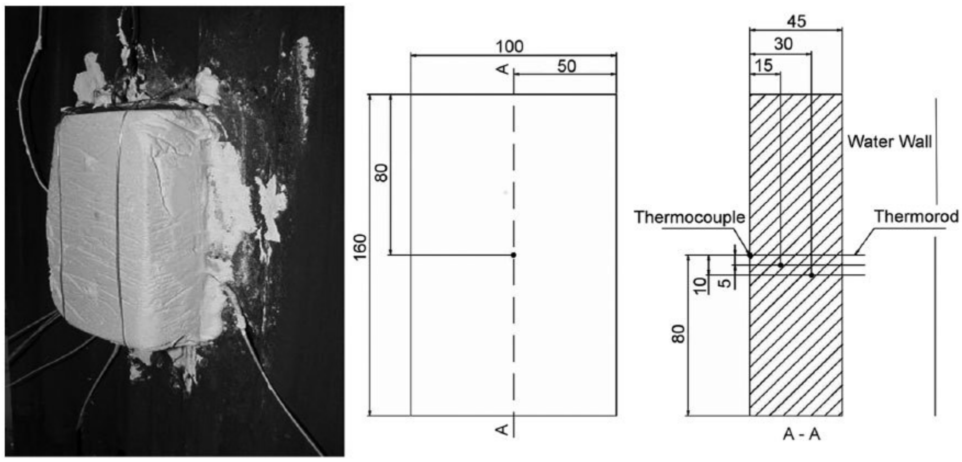

Figure 4. Shape and measure of the model deposit.

state, a water jet was imposed onto the deposit and the immediate cooling of the deposit was recorded by the thermocouples. All jets were applied to the deposits with water at a pressure of 0.45 MPa. The water nozzles were solid cone nozzles. The impact time was set to 3 seconds. An optical port allowed a visual monitoring of the process.

The aim of the measurement series was to gain information about the influence of the material properties, deposit temperature, and momentum on the material removal and the crack growth. It should be mentioned that the following presented results are not a systematic investigation. In the first step, the main influencing parameters shall be determined that form a basis for future experiments.

Measurement execution

The first study showed that the interaction of porosity and material strength plays a significant role for the cleaning, especially

for the use of thermal stress. This strongly influenced the choice of the model deposit. Three different types of model deposits were created to analyse the influence of the material properties. All three deposits contained gypsum as a basis material. The idea was, to create a compact and a porous material with similar strength and a third compact material with less strength. Therefore, the first model deposit was made of compact, hard and fine-grained gypsum only. To increase the porosity, the second deposit was a mixture of gypsum and styrofoam (50 vol%, respectively). During the heating of the deposit, the styrofoam burned and left large pores inside the material. Hence, the deposit was porous, but still hard and fine-grained. The third type was a mixture of sand and gypsum (80 vol% sand and 20 vol% gypsum), which made the deposit relatively loose. It consisted of gritty sand grains that were loosely connected and the material was brittle. All three deposits were treated in the same way.

- The surface was preheated to approximately 540 °C to 570 °C.
- The jet spray duration was 3 s.
- The flowrate was 0.36 L s^{-1} of cleaning water.
- The water pressure was 0.45 MPa.

The third deposit type, the sand-gypsum-mixture, was also used in the second parameter study. It was cleaned for 3 s with 0.63 L s^{-1}. The surface varied for four different probes from 20 °C, to 250 °C, 335 °C and 540 °C.

Afterwards, a third study has been concerned with the influence of the momentum. To realise the experiments, four constellations were selected.

- Sand–gypsum mixture, 540 °C surface-temperature, 0.36 L s^{-1} water, 3 s.
- Sand–gypsum mixture, 540°C surface-temperature, 0.63 L s^{-1} water, 3 s.
- Sand–gypsum mixture, 325°C surface-temperature, 0.36 L s^{-1} water, 3 s.
- Sand–gypsum mixture, 325°C surface-temperature, 0.63 L s^{-1} water, 3 s.

The difference in the surface temperature was necessary to determine the influence of the mechanical stresses.

Results and discussion

Influence of the deposit structure

As expected, all three deposits showed different cleaning behaviours. While the gypsum remained almost completely intact, the more porous gypsum–styrofoam mixture had large removals in the core area. This porous and fine-grained deposit broke immediately through cracking. Probably, this was a result of the high thermal stress during the immediate cooling. The gypsum–sand mixture showed the most visible effect. The whole surface area was removed; large parts were split-off up to the base, so that all three thermocouples were exposed. A prediction of the dominant cleaning mechanism was impossible owing to the brittle structure of the model deposit. Both the momentum and the thermal stress could be responsible for the shattering of the deposit.

Influence of the deposit temperature

Besides the material properties, the deposit temperature affects the cleaning efficiency. While the material properties are relevant for every cleaning principle, the temperature mainly affects the thermal stress within the deposit. The lower the deposit temperature, the smaller is the temperature gradient between the water and the deposit. A high temperature gradient results in large thermal stress. The following hypothesis is derived: If thermal stress contributes to the cleaning result of a deposit type, the cleaning effect must be larger for hotter deposits.

The gypsum–sand mixture showed a good cleaning ability during the first parameter study. Nonetheless, a statement whether the thermal stress or the mechanical stress was responsible for this result was not possible. Thus, this mixture was very suitable for the second parameter study. The results showed that the deposit removal strongly depended on the deposit temperature. The reason was the increase of the thermal stress inside the deposit for higher surface temperatures. At ambient temperatures, the cleaning was achieved through a mechanical impact. The heated deposits were subject to larger temperature gradients as they became hotter and, thus, to thermal stresses. In detail, the results were the following.

The deposit with 20 °C surface temperature showed only 14 mm abrasion in the area of the water jet. The surrounding area remained unaffected. The deposit with a surface temperature of 250 °C was reduced by 20 mm. Additionally, lesser removal was visible in the surrounding area. The probe with a surface temperature of 335 °C already showed abrasion up to 24 mm and removal of the deposit over the whole surface. Finally, the hottest deposit, with a surface temperature of 540 °C, was removed to a depth of 40 mm with strong wear over the whole surface area. As a result, both the mechanical and thermal stress served for an effective cleaning of the deposit; with increasing deposit temperature, the effect of the thermal stress grew strongly. It was not possible to determine the absolute increase in thermal stress, because the change of the material strength owing to higher ambient conditions was unknown. Possibly, the material strength decreased for hotter deposits. However, undoubtedly the results showed a high contribution of the thermal stress to the cleaning efficiency.

Influence of the momentum

The third parameter was the momentum. The hypothesis to this parameter is the following: If the cleaning improves at low surface temperatures with an increasing momentum, the momentum affects the mechanical stresses. A repetition of this experiment at a high surface temperature determined the effect of the momentum on the thermal stresses. If both experiments

Table 2. Results of the parameter studies.

Material	Characteristics	Surface temperature	Amount of water	Result
Gypsum	Compact, hard, fine-grained	570 °C	0.63 L s^{-1}	Removal of thin layer at the surface
Gypsum + Styrofoam	Porous, hard, fine-grained	570 °C		Large removal in core area
Gypsum + Sand	Gritty sand grains (app. 1 mm), relatively loose connected, brittle	540 °C		Large area of deposit removed completely up to the base
		20 °C	0.36 L s^{-1}	Removal of core area: 14 mm; surrounding area unaffected
		250 °C		Removal of core area: 20 mm; removal of surrounding area visible
		335 °C		Removal of core area: 24 mm; removal of whole deposit surface visible
		540 °C		Removal of core area: 40 mm; removal of whole deposit surface visible
		540 °C	0.36 L s^{-1} 0.63 L s^{-1}	Larger amount of water results in larger material removal
		325 °C	0.36 L s^{-1} 0.63 L s^{-1}	No increase of removal through increase of amount of water

show no significant change in the cleaning result, the influence of the momentum is negligible.

The results showed an increase in the deposit removal for a higher momentum at a surface temperature of 540 °C. By contrast, the cleaning efficiency did not improve with a higher momentum at a surface temperature of 325 °C. This indicates that the dependency of the thermal stresses on the momentum is larger than the dependency on the mechanical stresses to the momentum. As in incinerators, the surface temperatures are higher than in the experiments carried out, an increase of the momentum is a possible option to improve the cleaning process.

Summary of the results

The first measurement campaign implied a strong dependency of the occurring thermal stress on the deposit structure. To validate this hypothesis, a second study investigated single parameters and their effect on the cleaning through thermal stress. The analysed parameters were the deposit structure, the deposit temperature and the momentum of the jet. The results for all three parameter studies are summarised in Table 2.

To illustrate these results more clearly they are qualitatively shown in Figure 5.

The figure shows distinctly the dependency of the surface temperature and the deposit removal, as well as the dependency of the material and the deposit removal. The white bars stand for the original deposit height, while the grey bars show the remaining deposits after the water cleaning. A repetition of the experiments showed similar results.

Conclusion

Owing to the results of the first measurement campaign at the incinerator in Kassel, we were able to identify three different deposit types at the specific measurement positions. Further types at other positions (e.g. the superheater section) are very likely. The presented types vary in material properties and layer thickness. It was ascertained that the reaction to the thermal stress induced by spraying with water is strongly dependent on the material properties. Thus, not every deposit type could be cleaned through the thermal stress. In future, we recommend the method used in Study 1 to investigate more deposit compositions and their reaction on thermal stresses. This is not only useful at other sections, but also for different fuel compositions. Additionally, we suggest an extension of the experimental setup, to enable a study of other cleaning effects. To support the findings, a second measurement study followed. It consisted of three parameter studies, namely the material properties, the deposit temperature and the amount of water. All three parameter studies showed an influence on the cleaning result. Summarised, the main findings are the following.

- The material properties strongly influence the cleaning result. Crucial are the deposit's porosity, grain-size and material strength.
- Thermal stresses are an important cleaning mechanism; the larger the temperature gradient, the better the cleaning result.
- An increase of the amount of water is especially useful if this leads to an increase of the thermal stress, i.e. for high surface temperatures.

The presented results give an overview of the influence single parameters have on the cleaning result of deposits inside waste incinerators. Dependencies could be isolated and investigated separately; however, the present data only allows qualitative conclusions. To realise a more quantitative analysis, the current results have to be implemented into a mathematical model. Such a model would allow more precise parameter studies. Further

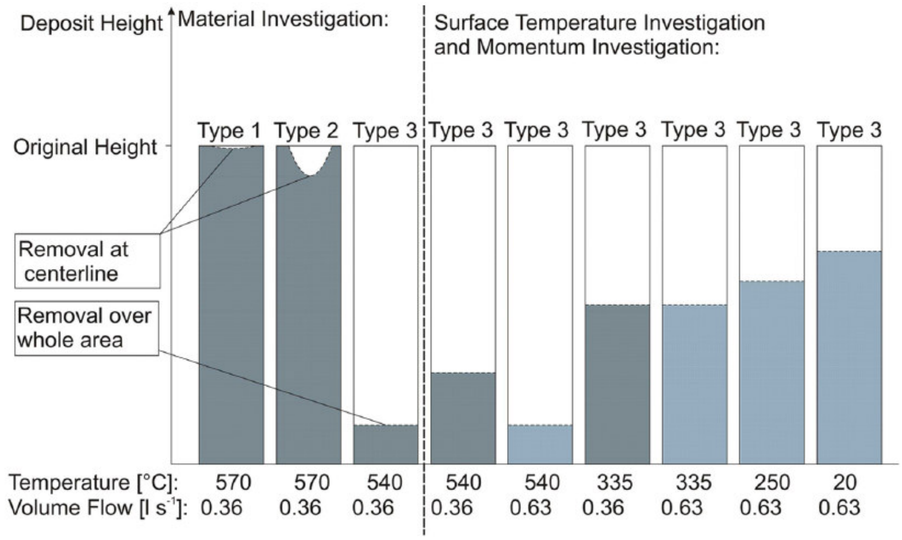

Figure 5. Qualitative visualisation of deposit removal in the parameter studies.

experiments can contribute to the knowledge about deposits and help validate modelling assumptions. A continuation of the measurement campaign has to change from the qualitative level to a more systematic analysis that gradually changes all cleaning parameters instead of picking selective parameters. This study can include the following parameters: Nozzle size, lasting time of the water jet, water pressure, probe temperature, flue gas temperature and probe material.

Declaration of Conflicting Interests

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