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Characterisation of Deposits on Membrane Walls of Steam Generators by Heat Flux Density Measurement

SASCHA KRÜGER, MICHAEL BECKMANN

Technical University of Dresden, Institute for Power Engineering,
Chair for Combustion, Heat and Mass Transfer

1 Introduction

Municipal solid waste and biomass are to be seen as difficult fuels. Gaseous and solid particles which are formed during the combustion process lead to deposits on surfaces inside the steam generator. These deposits have a negative effect on the efficiency and the operational availability of the plant as they cause corrosion of boiler and super heater components. Moreover the heat losses concerning the flue gas will rise since the deposits have a negative influence on the heat transfer from the flue gas to the steam generator.

This paper specially considers the application of heat flux density measurement to characterize deposits and as a sensor for the online cleaning system of the boiler. With this background firstly the theoretical correlation between the fouling condition and the heat flux density is outlined. These theoretical considerations are validated by measurement results. Furthermore investigations on the reaction time of the measuring sensor due to changes of the heat flux density (e.g. caused by fluctuations of the thermal load or changes of the fouling condition) are discussed. From the measured results, further information about the fouling condition can be derived by the analysis of frequency and amplitude spectrum of the signal.

2 Influence of Fouling Layers on the Energy Efficiency of Steam Generators

Fouling layers on heat exchanger surfaces of the radiation pass have a negative effect on the heat flux that occurs between the flue gas and the boiling water, since the deposits act as an isolator. The heat transfer through the membrane wall construction can be characterised by the flux density on the membrane wall [1].

For a membrane wall construction, firing as well as steam production parameters the conditions to achieve maximum heat flux are with a clean membrane wall (without deposition).

$$\dot{q}_{max} = k_{eff} \cdot \left(\vartheta_{fg} - \vartheta_{bw}\right) \tag{1}$$

$$\dot{q}_{max} = \frac{\left(\vartheta_{fg} - \vartheta_{bw}\right)}{\sum\limits_{wall}\left(\frac{\lambda}{s}\right)^{-1} + \sum \alpha^{-1}} = \frac{\left(\vartheta_{fg} - \vartheta_{bw}\right)}{R_{clean}} \tag{2}$$

When a fouling layer arises on the wall $\left(\sum\limits_{deposit} \frac{\lambda}{s} = \frac{1}{R_{deposit}}\right)$, the resulting heat flux density will decrease.

To illustrate the influence of the fouling layer on the heat flux density, the ratio of the heat flux densities $\left(\frac{\dot{q}_{deposit}}{\dot{q}_{clean}}\right)$ is specified.

$$\frac{\dot{q}_{deposit}}{\dot{q}_{clean}} = \frac{R_{clean}}{R_{clean} + R_{deposit}} \tag{3}$$

To clarify the above mentioned issue Fig. 1 shows exemplary the effect of a fouling layer on a membrane wall. The heat flux density is plotted as a function of the fouling layer thickness for different thermal conductivities and effective heat transfer coefficients (furnace side, heat transfer by convection and radiation). The curves in Fig. 1 show as expected, that at high effective heat transfer coefficients ($\alpha_{furnace}$ = 200 W/ (m²K)) the heat flux density decreases stronger with increasing fouling layer thickness than for the case of lower effective heat transfer coefficients ($\alpha_{furnace}$ = 50 W/ (m²K))

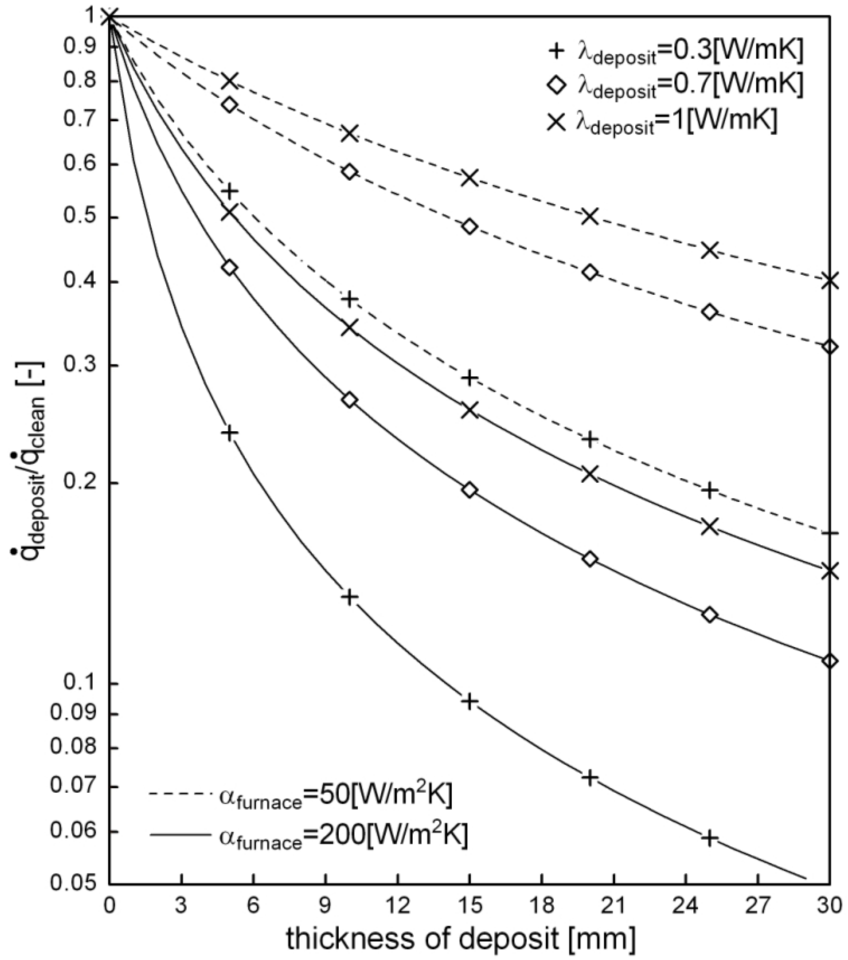

Fig. 1. *Influence of the deposit on the heat flux density.*

By the strong influence of a fouling layer on the heat flux density in boiler sections with high effective heat transfer coefficients, it is not easily possible (i.e. > 90 %) to keep the heat flux density at the same high level (by online cleaning) as in clean conditions, when starting the boiler. A thin fouling layer reduces sharply the heat flux density in a very short operational time.

The further course of the curves in Fig. 1 shows, that the relative change of the heat flux density - related to the initial state - decreases.

With reference to the online cleaning of membrane walls in the radiation passes it can then be summarised, that

- cleaning boiler sections with high heat transfer coefficients (e.g. first radiation *pass*) has a better influence on the flue gas cooling, as compared to the removal of the fouling layers in boiler sections with a low heat transfer coefficient,
- the online cleaning can not – or just for a short time – retain the clean conditions of a boiler system which was cleaned during a maintenance period.

3 Dynamics of the Heat Flux Density Measurement

For setting the sample rate of the data logging system it is important to know the reaction time of the heat flux density measurement, i.e. the time (delay) the sensor needs to react on a fluctuation of the heat flux density e.g. due to fluctuations of the thermal load. Dependent on the dynamics of the measuring signal further evaluation concerning the cause of the heat flux density fluctuation (e.g. changing heat release in the combustion chamber, deposition on the membrane wall or drum pressure fluctuations [2]) can be carried out.

The development of a non-invasive measuring technique for the determination of the heat flux density on membrane walls is the topic of a current DBU project (DBU 23893-24) [1]. The basic principle of the method is the measurement of temperature differences (between the fin and the vertex) on the exterior membrane wall (insulated side). The determination of the temperature difference is attained with very low complexity in the measurement technique and high accuracy due to the use of the membrane wall materials as two thermocouples are connected against each other. For a certain membrane wall construction, the heat flux density is directly proportional (system curve [2]) to the temperature difference $\Delta\vartheta_{\text{fin-vertex}}$.

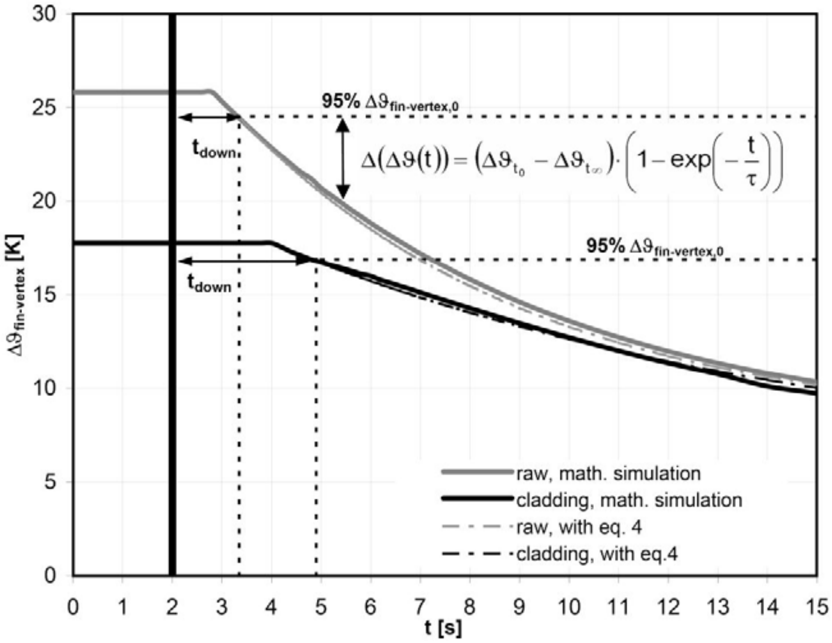

Fig. 2. Reaction time of the measurement technique – simulation.

The dynamics of the measuring technique was initially investigated by application of a mathematical simulation. Considered in this case are two different membrane wall constructions with a spacing of 75 mm – one cladded (here: alloy 625), and the other in a raw condition (without any coating, refractory or cladding) (see Fig. 2).

Both walls were loaded with a heat flux density of 100 kW/m^2. For the cladded membrane wall segment a heat flux density of 100 kW/m² leads to a temperature difference $\Delta\vartheta_{\text{fin-vertex}}$

of approx. 18K. For the raw membrane wall segment the same heat flux density causes a temperature difference $\Delta\vartheta_{\text{fin-vertex}}$ of approx. 26 K (see Fig. 2). If the flux density is suddenly reduced from e.g. 100 to 20 kW/m² the measuring signal starts decreasing after a down time[1] t_{down} due to the heat that was stored in the fin material (capacity). The down time in the case of the raw membrane wall segment is approximately 1.5 seconds and in the case of the cladded membrane wall it is about 3 seconds.

The suchlike reduction of the heat flux density can occur for example due to switching off or breakdown of the burners.

The course of the measuring signal is in accordance to the commonly known fundamentals in measurement und control engineering:

$$\left(\Delta\vartheta_{t_0} - \Delta\vartheta_t\right) = \left(\Delta\vartheta_{t_0} - \Delta\vartheta_{t\infty}\right)\cdot\left(1 - \exp\left(-\frac{t}{\tau}\right)\right), \tag{4}$$

whereby

$\Delta\vartheta_{t_0}$ denotes the temperature difference prior to the decrease (initial state),

$\Delta\vartheta_{\infty}$ denotes the temperature difference after the decrease when steady state is reached,

$\Delta\vartheta_t$ denotes the temperature difference to an arbitrary point in time during the decrease and

τ denotes the so-called time constant.

For the course of the simulated measured signal in Fig. 2 equation (4) gives a time constant of 6 seconds for the raw membrane wall construction and 10 seconds for the cladded membrane wall construction.

The greater delay in the case of the cladded membrane wall occurs due to the bigger mass (capacity) of the wall construction.

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[1] The down time t_{down} is denoted as the time for the change in the constant signal from 95% of the initial value.

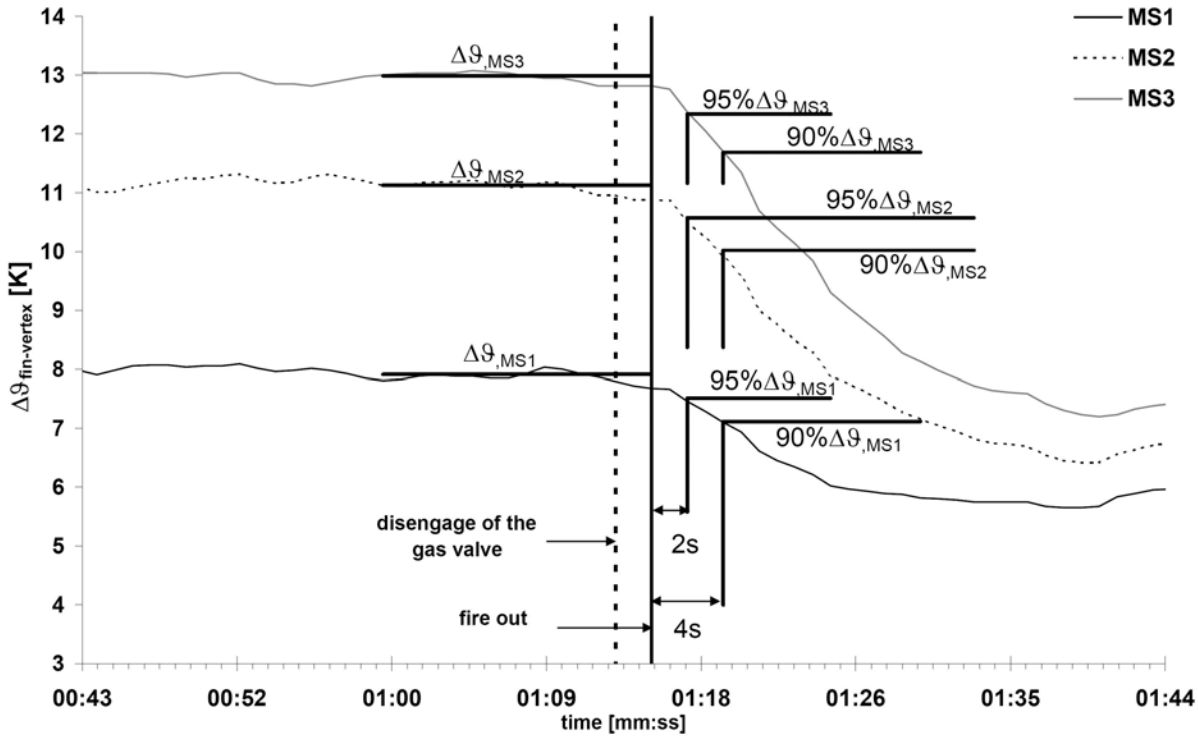


Fig. 3 *Reaction time of the heat flux density measurement – experiment.*

In order to validate the results of the simulation (see Fig. 2) and for the further analysis of the dynamics of the measuring technique, investigations on a gas fired boiler – with a thermal power of 80 MW - were carried out. This boiler is operated with two multi fuel burners (light fuel oil, converter gas and coal gas). On the front wall of the steam generator 6 measuring devices were installed, three in each axis of the two burners 1,5 m, 3 m and 4,5 m above the quarls.

Fig. 3 shows the courses of the signals (expressed as the temperature difference $\Delta\vartheta_{\text{fin-vertex}}$) of three sensors (MS1, MS2 and MS3), which occurs due to the shutdown of one burner. It can be seen that the sensors react synchronic. The time taken by the signals to reach 95% of their initial values is 2 seconds (see Fig. 3). 90% of the initial values are reached 4 seconds after the fire is out. The signals do not decrease until they reach a temperature difference $\Delta\vartheta_{\text{fin-vertex}}$ of 0 K since the other burner is still operating. Compared to the calculated down time from the simulation (see Fig. 2, 1.5 seconds for the raw membrane wall segment) the measured down time of 2 seconds is in the same range. This measurement shows that the heat flux density measurement can be used for flame monitoring; especially for combustion systems in which the use of an optical flame monitoring is limited (e.g. due to a high amount of dust in the firing that reduces visibility or a non intensive flame of converter gas combustion).

4 Discussion of Heat Flux Density selected from Industrial Application

In the following section the measured values from heat flux density measurements from a waste incineration plant and from a biomass incineration plant are discussed, focusing mainly on the aspect of fouling layers.

4.1 Quantitative Evaluation of the Measuring Signal

Fig. 4 shows the measured signal of a heat flux density measurement of a waste incineration plant. The measuring sensors are located in the area between the combustion chamber to the first radiation pass. The measured signal steadily decreases in a period of 18 hours from 160 to 60 kW/m^2, until it increases again to 160 KW/m^2 very fast. During this period the steam load and the temperature in the combustion chamber remained constant. The reason is such that under the assumption of a constant thermal conductivity (0.7 W/(mK)) and constant flue gas heat transfer conditions, the amount of fouling (deposition) can the calculated.

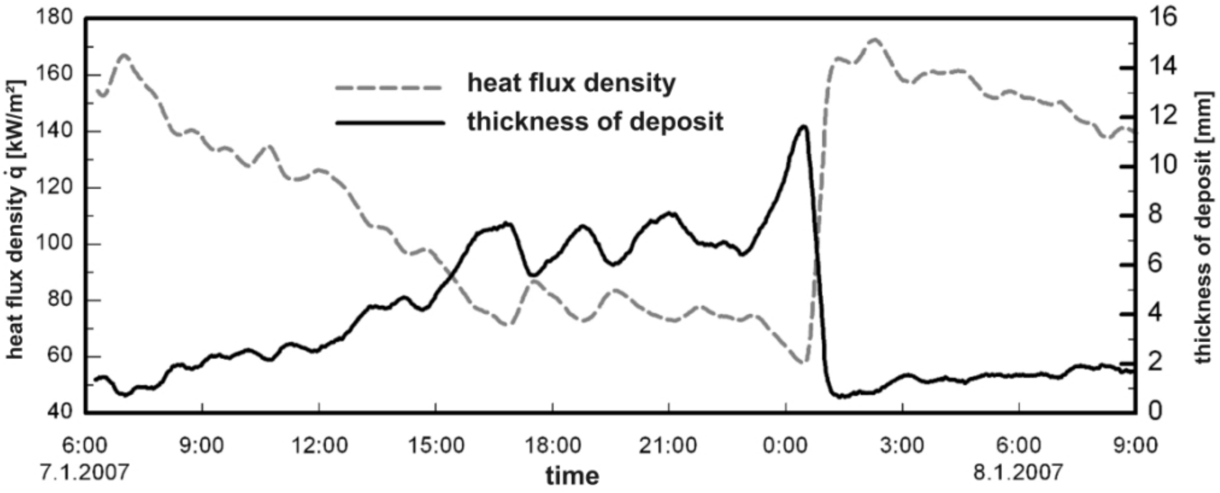


Fig. 4. *Transferred heat flux density and calculated thickness of the deposit.*

The fast increase of the heat flux density occurs due to the sudden drop off of the fouling layers. Such a sudden drop off is typical for nitride bounded SiC tiles which are mounted in areas with high heat flux densities. Fig. 4 shows – as already demonstrated by theoretical results in section 2 – that an increase in the thickness of the deposit (e.g. from 1 to 4 mm) for very thin layers leads to a stronger decrease of the heat flux density as compared to the increase of thickness of an already existing deposit (e.g. form 5 to 11 mm).

4.2 Signal Analysis

In section 3 investigations of a sudden change of the heat flux density were discussed in conjunction with the data acquisition system (sampling rate). The course of the measuring signals in Fig. 5 shows fluctuations which occur due to different influences. A separation of short-term and long-term variations can be done. Short-term variations – e.g. the sudden increase of the heat flux density occurs due to the effect of the online cleaning (see Fig. 5a and b).

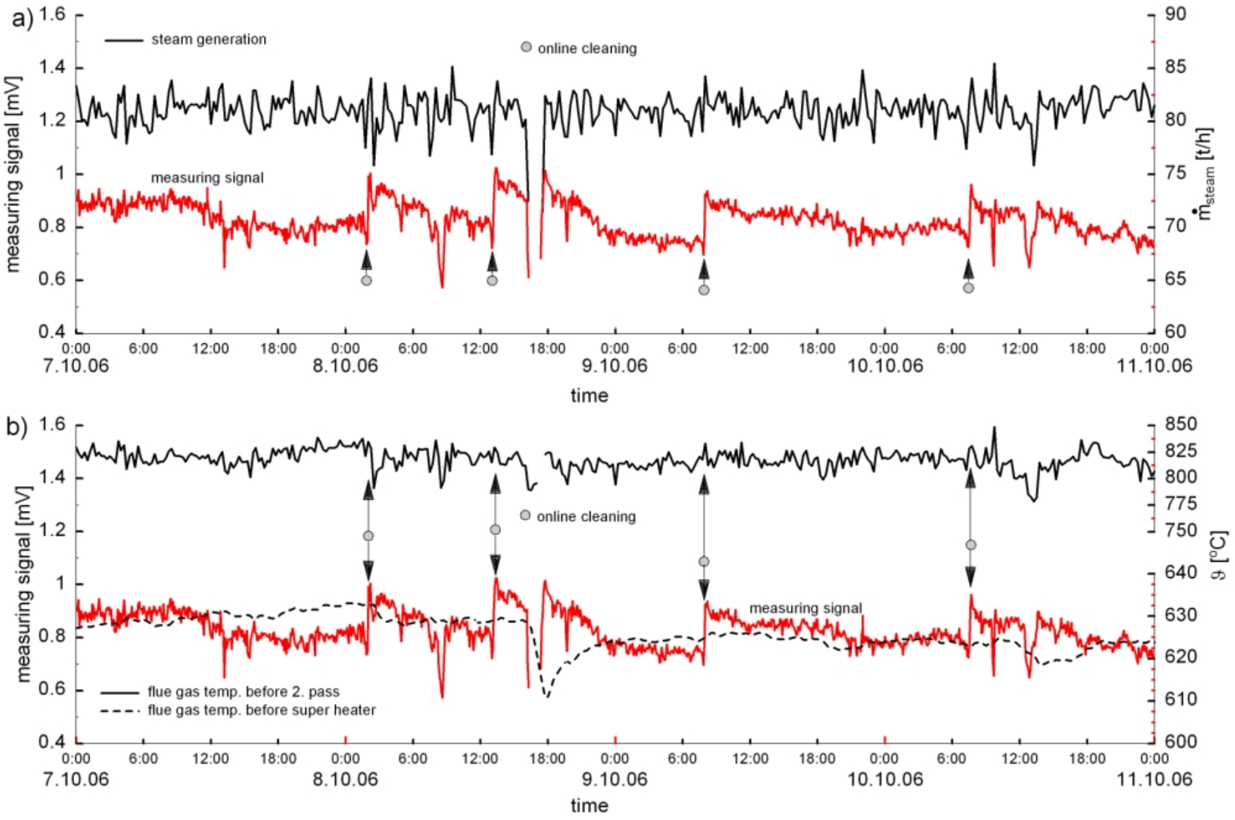


Fig. 5. *Influence of the online cleaning on the heat flux density measurement.*

After the sudden increase of the measuring signal – as a result of the online cleaning system – the measuring signal decreases slowly due to the building up of a fouling layer on the membrane wall. It can be seen that the signal of the heat flux density measurement decreases sharply directly after the online cleaning. In the further course the signal decreases more slowly. This correlation was already predicted by the theoretical results (see section 2).

Besides the absolute values of the measuring signal further information about the fouling conditions can be derived from the course of the signal i.e. from the amplitude and the frequency spectrum. Dependant on its mass and its heat capacity, the deposit has a damping influence on the heat flux dependent temperature variations of the fin.

The insulating and the damping influence of the deposit can be seen in the left hand side of Fig. 6. I.e. The heat flux density is on a low level - due to an existing deposit - with a strong damping of the signal. On the right hand side in Fig. 6 the measuring signal is on a relatively high level and the damping is relatively smaller (clean conditions).

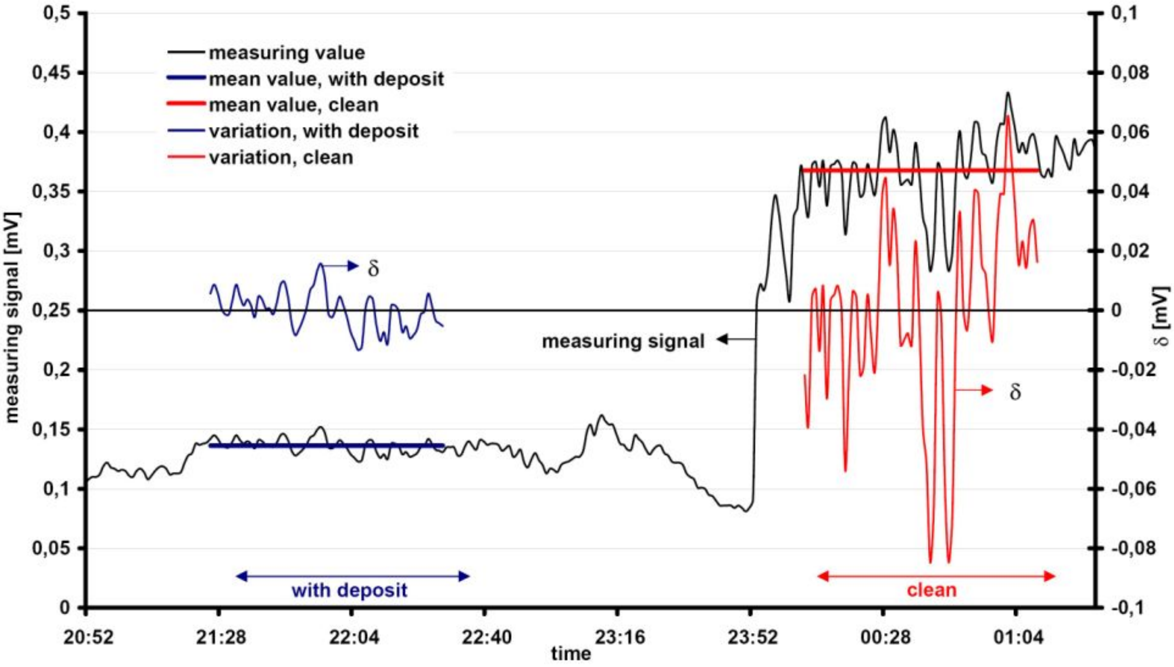
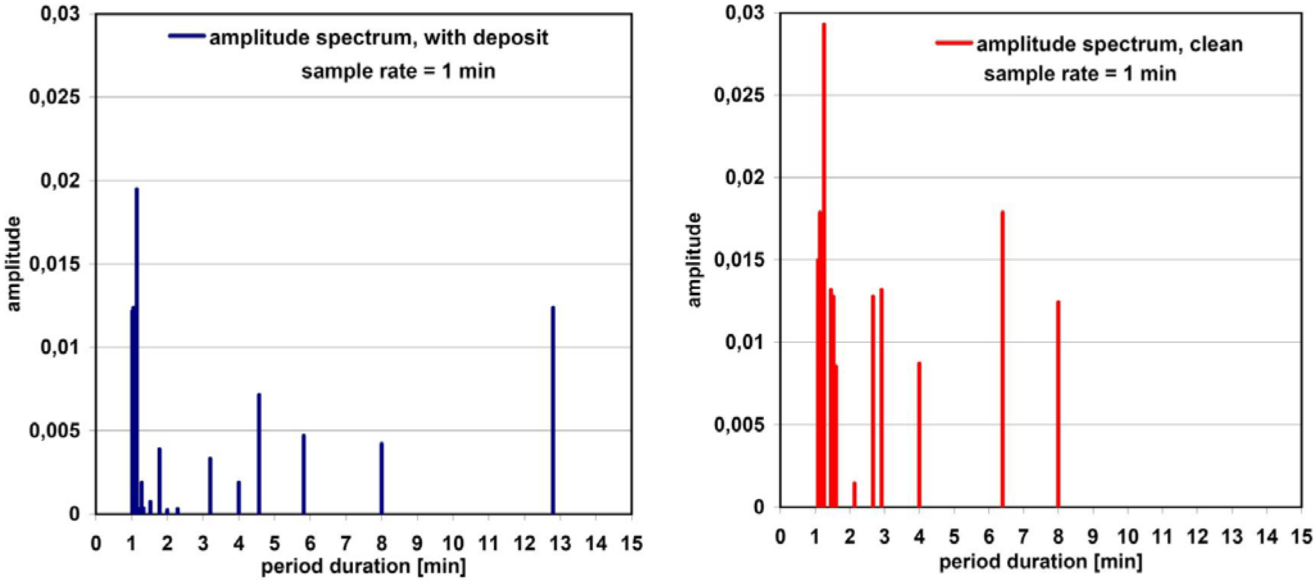


Fig. 6. *Influence of a deposit on the dynamics of the measuring signal.*

Fig. 6a and b show the amplitude spectrum of a discrete Fourier analysis of the fluctuations δ for the case of a fouling layer on the membrane wall (Fig. 6a) and for clean conditions (Fig. 6b).

For both cases (membrane wall with deposits and in a clean condition) an accumulation of period durations between one and two minutes occurs. In comparison to the case when deposits occur on the membrane wall (Fig. 6a) the analysis of the clean condition shows a higher number of period durations between one and two minutes and also a similar amplitude. The sample rate of the data shown in Fig. 5 was one minute. This means that a further investigation of the frequency and the amplitude spectrum with this data appears not to be meaningful.



a. membrane wall with deposits. b. clean conditions.

Fig. 7*. Influence of a deposit on the dynamics of the measuring signal – Fourier analysis.*

The accumulation of the amplitudes at the period duration of one minute indicates that the sampling rate of the data acquisition of all appearing heat flux density fluctuations should be considered smaller as one minute.

5 Summary

The incineration of waste and biomass leads to deposits on heat exchanger areas. These fouling layers are the main reason for corrosion which has a negative influence on the operational availability of an incineration plant. Moreover the deposits have influence on the plant efficiency as they act as an additional heat resistance on the heat exchangers.

The influence of the deposits on the reduction of the heat flux density strongly depends on the effective heat transfer coefficient from the flue gas to the membrane wall. For heat exchanger areas with high heat transfer coefficients a deposit has a stronger influence on the heat flux density compared to areas with low heat transfer coefficients. Thus it follows that an online cleaning of membrane walls in areas with high heat flux densities has a better efficiency on the flue gas cooling than a cleaning of areas with a low heat flux density. In many cases the flue gas temperature before the super heater and the amount of produced steam are used as an indicator for the fouling conditions of the radiation part of the boiler. Generally the amount of produced steam is used as a set point for the online cleaning system as the stream production deceases due to the increasing thickness of the deposits. However by the firing control system the amount of produced steam is kept constant by the control of the fuel feeding system. I.e. a decrease of steam production due to an occurring fouling layer is compensated by higher fuel supply rates. This automatically leads to a higher flue gas temperature before the super heater.

This effect is damped in the case of a well designed boiler system, so that the amount of produced steam and the gas temperature before the super heater are suitable to only a limited extend as a set point for the online cleaning system.

Moreover the produced steam and the gas temperatures before the super heater naturally have an integral character concerning the fouling condition, i.e the areas in the radiation part which are affected by fouling layers respectively which have to be cleaned can not be detected by evaluating the amount of produced stream and the gas temperature before the super heater.

For the investigation of the furnace side fouling condition as well as a signal for the online cleaning system the heat flux density on the membrane wall can be used. The correlation of heat flux densities with fouling conditions respectively the effect of the online cleaning could be worked out by on-site heat flux density measurements.

Moreover by the variations of the measured heat flux densities, i.e. by the frequency analysis of these fluctuations further information can be derived concerning the furnace side fouling conditions.

Acknowledgement:

We would like to thank the Deutsche Bundesstiftung Umwelt (DBU) for the financial support of the project Development of a measuring system for online detection of heat flux density on membrane walls.

6 Appendix

6.1 Symbols and abbreviations

Latin symbols			**Greek symbols**		
k	W/(m^{2}K)	heat transfer coefficient	α	W/m^{2}K	convective heat transfer coefficient
$\dot{m}$	t/h	mass flux	δ	mV	fluctuation
$\dot{q}$	kW/m^2	heat flux density, specific heat flux	λ	W/mK	thermal conductivity
R	(m^{2}K)/W	thermal resistance	ϑ	°C	temperature
s	m	distance	Δ	-	difference
T	K	temperature	τ	s	time constant
t		time			

Indices

clean	clean conditions	max	maximum
bw	boiling water	TC1	thermo couple 1
deposit	deposit in the membrane wall	TC2	thermo couple 1
down	t_{down} – down time	raw	raw condition of the membrane wall
eff	effective	steam	steam
fin-vertex	between fin and vertex of the tube (temperature difference)	wall	membrane wall construction
fg	flue gas	∞	t_∞ - time to reach steady state after a variation
furnace	furnace side	0	t_0 - initial condition
HDFM	heat flux density measurement		

6.2 Literature

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