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Measurement Method of Deposit Material Properties on Water Walls of Steam Generators

Control # 14

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1 ABSTRACT

Temperature fluctuations inside a furnace are propagated through the deposit layer towards the furnace wall. These temperature fluctuations are also dampened as they propagate through the deposits which results in a time shift of the measured signal. This behavior is dependent on the deposit material properties density, thermal conductivity, and specific heat capacity. These effects can be utilized for estimating the corrosion potential of the deposit, as well as, for characterizing the corrosions' structure and material properties. Hence an optimization of the cleaning procedure, an in-situ diagnosis of the membrane wall condition, and a correspondingly higher profitability are possible.

Problems particularly occur more frequently in waste incinerators and biomass-fired power boilers as a consequence of heavy deposition and corrosion in complex interactions with the heterogeneous fuel. A more detailed knowledge of the deposit situation on the heat exchanging surfaces is therefore a key condition in order to achieve high availability and an economically and energetically optimized plant operation. Thus, it is necessary to remove deposits during operation as required. For a more targeted cleaning, procedures and methods of analyzing the deposit condition during operation and also the corrosive potential are vital to adjust the operating parameters of the plant promptly.

It is, therefore, imperative to identify the location and quantity of deposits in order to be capable of setting the intensity and duration of the cleaning procedure accordingly. This is only possible when the structure of the deposit, its density, and layer thickness (hence the type of deposit) are characterized and measured at all deposit locations.

In the following paper, an appropriate method for online signal analysis of heat flux and temperature measurement signals will be presented which may help promptly adjust the operating conditions in steam generators in the future.

2 INTRODUCTION

For the design and operation of steam generators, the fouling and slagging of the heat exchanger surfaces always present a special problem. Fundamental factors influencing the fouling are the chemical and physical properties of the fuel mineral matter, which form the deposits, and secondly, the related operational, combustion and design (membrane wall structure) conditions of the respective system. [1, 2, 3, 4]

So far the interaction of the individual variables can neither be detected in a unified physical theory, nor can they be empirically precisely detected for a general use because of the high complexity and dynamics of interactions.

For heterogeneous fuels in particular, the problems are intensified by the difficult interplay of influencing quantities. A crucial condition, specific for waste incineration plants, is a more accurate knowledge of the deposit situation on the heating surfaces in terms of high availability and an economical operation. In order to keep the flue gas losses low and to avoid difficulties in the system operation, it is necessary to remove deposits during operation as required. For a more targeted cleaning, on the one hand, it has to be well known where and in what quantity deposits occur and, on the other hand, the intensity and the duration of the cleaning action must be set correctly. This is only possible when the locally present structure, density, and layer thickness (i.e., the type of deposit) are known.

Measurement methods for the characterization of deposits which have been developed in the past cannot be used in the vast majority of cases due to high installation costs and great expense, or due to lack of a detailed knowledge of specific deposit properties, which can be ascribed to lacking material properties. The measurement and analysis method presented in this paper are based on the determination of material properties by an analysis of transient temperature and heat flux measurement signals, which are always inherently present in the fluctuating energy release of heterogeneous fuels. To validate the measurement and analysis method, the results of initial investigations on an industrial steam generator will be included.

3 MODEL CONCEPT OF THE MEASUREMENT AND ANALYSIS METHOD

The method for characterizing material properties of deposits, which is presented in this paper, can be divided into two approaches:

1. the recording of the temporal progressions of temperature and heat flux measuring signals with suitable measurement methods,
2. the evaluation of these measurement signals with respect to the determination of material properties of the deposit with a specific method of analysis.

The transient sequences in temperature and heat flux measuring signals are used to determine material properties of the deposit over a time varying temperature field. A detailed description of the procedure is given in *Grahl*[1] and *Grahl & Beckmann*[5]. The essential principles are summarized below.

The Fourier equation of heat conduction is applied to describe the non-stationary temperature field. To simplify the considerations, the following assumptions have been made initially:

- The heat input into the deposit layer occurs by an adjacent fluid, adhering to a periodic time law.
- Within the deposit layer, heat conduction alone occurs and there are no sources or sinks.
- The entire membrane wall construction may consist of several layers whose geometric conditions and material properties are assumed to be known.
- For all layers, including the deposit, there is homogeneity and isotropy. The mathematical model applies to each layer. Additionally, there are no sudden temperature changes at the transitions of the individual layers.
- The body formed by all individual layers, including the deposit, corresponds to the model of a one-sided infinite wall.
- The heat transfer within the deposit layer is considered as one-dimensional. This means that it solely occurs in the reverse direction of the normal vector of the heat transfer surface, which is formed by an imaginary tube wall plane in which all tube axes lie.
- To meet the last three above-mentioned requirements, the geometry of the deposit layer must be equivalent to a planar layer. The deposit layer adheres without thermal contact resistance to an intermediate layer which is located in front of the web-tube geometry. This

intermediate layer has a planar surface and extends parallel to the deposit at the transition to the tube wall plane.

These initially quite extensive restrictions may be lifted later under certain conditions to some extent, or by advanced or more accurate model concepts. A tube wall lined with ceramic refractory represents a typical wall construction for a waste- or biomass-fired steam generator. This wall structure complies sufficiently well with the above-mentioned requirements.

According to these model concepts[5], for the location x and time t dependent temperature field $\vartheta(x,t)$ of the deposit layer, the following equation can be obtained after the diminishing of the initial conditions for a sufficiently long time ($t \to \infty$):

$$\vartheta(x,t)_{t\to\infty} = \vartheta_{m,D,S} - \frac{x}{\lambda}\dot{q}_m + \sum_{n=1}^{\infty} \Delta\vartheta_n \exp\left(-x\sqrt{\frac{\pi n}{aN\tau_{SI}}}\right)\cos\left(\frac{2\pi n}{N\tau_{SI}}t - x\sqrt{\frac{\pi n}{aN\tau_{SI}}}\right). \quad (1)$$

Therein, $\vartheta_{m,D,S}$ is the mean temperature of the deposit surface in contact with the flue gas; λ is the thermal conductivity of the deposit; $\dot{q}_m$ is an average constant and thus quasi-static heat flux density from the flue gas to the boiling water; $\Delta\vartheta_n$ is the amplitude of the nth-order temperature harmonic at the deposit surface; a is the deposit's thermal diffusivity; N is the period length (observation period) and τ_{SI} the sampling interval for digitalization of the analog input temperature. The thermal diffusivity

$$a = \frac{\lambda}{\rho c} \quad (2)$$

includes the physical properties thermal conductivity λ, density ρ, and specific heat capacity c of the deposit. The first two terms on the right side of equation (1) correspond to a stationary heat transfer through the membrane wall with the deposit, which are superimposed by the sum of a periodic temperature oscillation in the third term.

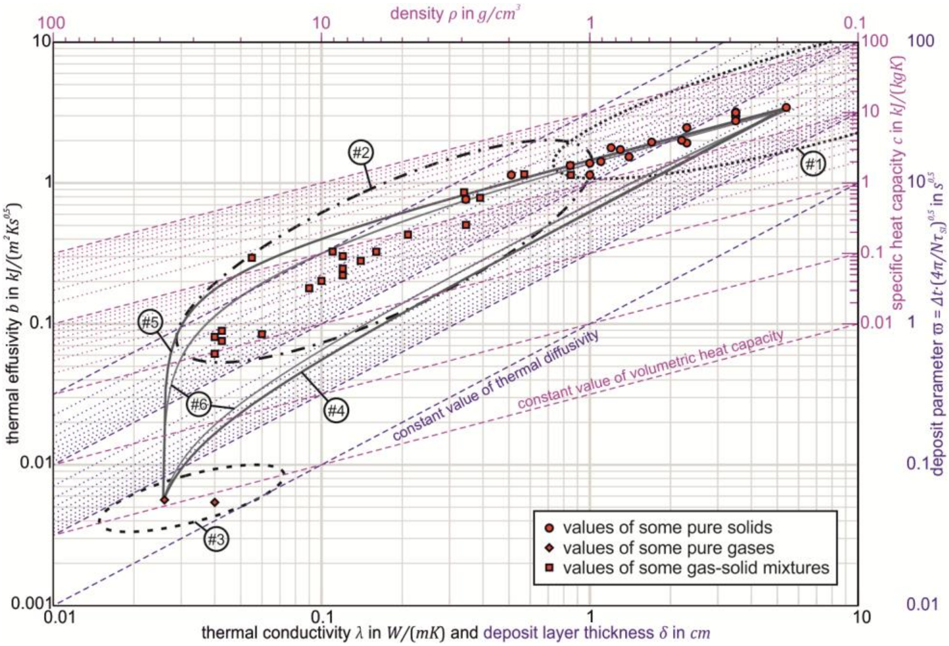
In order to determine equation (1), a Newton boundary condition is specified on the deposit surface. This occurs, for example, when the temperature of the deposit surface is determined directly by means of an infrared camera. In practice, this measuring method can provide information about the present temperature over a large area. At the same time, it is possible in this manner to avoid a plurality of measurement difficulties for the calculation of heat transfer from the flue gas to the deposit; and this measuring method is, therefore, particularly suitable to

determine the deposit surface temperature as an input quantity for signal analysis.
To definitely determine the temperature field, a second boundary condition is necessary. An appropriate measuring position must, therefore, be located in the direction of the heat flux behind the temperature measurement. This can be done either directly in the deposit layer, or in a subsequent layer (rear casting compound, refractory tile, tube wall), for example with a thermocouple.
In addition, the heat flux density can be determined from the temperature field. Both quantities are linked by the thermal conductivity and the temperature gradient at each location of the temperature field. With the introduction of the heat flux density, the thermal effusivity results from the combined material properties

$$b = \sqrt{\lambda \rho c} = \frac{\lambda}{\sqrt{a}}, \tag{3}$$

and contains, similar to thermal diffusivity, the deposit properties thermal conductivity λ, density ρ and specific heat capacity c. For the determination of the thermal effusivity neither the layer thickness nor the thermal conductivity need be explicitly known. This turns out to be advantageous for measuring the heat flux density according to the web-tube- method[6] at the insulated side of the furnace. The advantage is the durable measurement, which works without a safety-critical change to the pressure vessel of the steam generator and which allows an easy and affordable network measurement. More details of this measurement method in English language can be found in *Grahl & Beckmann*[5].
It is, therefore, possible to determine material properties of an unknown deposit layer by comparing any combination of two temperature or heat flux density progressions (including combinations of two temperature or heat flux density measurement signals). However, a problem arises at this point because no measurement method for determining the material properties or the layer thickness of deposits exists in practice so far. Thermal diffusivity and thermal effusivity respectively cannot be determined independent of the layer thickness. This means, that for present case, it is possible to identify the heat transfer resistance, but conclusions about the magnitude of the thermal conductivity or the layer thickness cannot be drawn because there are more unknown parameters than associated independent equations.

Figure 1. Diagram for estimating deposit material properties based on the thermal effusivity.[1]



For that reason, an analysis method is presented in *Grahl & Beckmann*[5], by which, on the basis of correlation at atomic and molecular levels, the material sizes are not arbitrarily combinable with each other. The value ranges of the possible material values must lay within certain limits instead. To illustrate this, a special deposit characterization diagram has been developed, in which the correlations, as Figure 1 shows, are visually represented. The diagram is constructed in a specific way, so that from a known thermal effusivity, the thermal conductivity can initially be calculated sufficiently accurately. Afterwards, conclusions on the density and layer thickness of the deposit can be drawn from other statistically proven assumptions and models for heat transport in porous layers. Moreover, the thermal diffusivity can be used as an input variable for determining deposit properties. Concerning the signal analysis, the thermal effusivity has the advantage of disregarding the deposit layer thickness and of arising from a comparison of coefficients between equation (1) and the equation of the heat flux density. The thermal effusivity can be determined as follows:

$$b = \frac{\hat{q}(\delta_D, t_2)}{\hat{\vartheta}(0, t_1)} \sqrt{\frac{1}{2\pi} \frac{N\tau_{SI}}{t}} e^{\xi}. \tag{4}$$

In equation (4) $\hat{q}$ denotes the amplitude of the heat flux density at the transition between the deposit and the membrane wall

$$\hat{q}(\delta_D, t_2) = \Delta\vartheta_D \; b \sqrt{2\pi \frac{t}{N\tau_{SI}}} \; e^{-\xi}, \tag{5}$$

$\hat{\vartheta}(0, t_1) = \Delta\vartheta_D$ is the amplitude of the surface temperature of the deposit, $(2\pi \, t/N\tau_{SI})^{-0,5}$ is a factor depending on the oscillation period, and e^{ξ} is a correction of the damping caused by the deposit between the temperature and the heat flux density measuring points. The exponent ξ of the damping can be determined from the phase shift of the measurement signals and substitutes the phase shift term

$$\xi = 2\pi \frac{\Delta t}{N\tau_{SI}} = x \sqrt{\frac{\pi}{aN\tau_{SI}}} = \varpi \sqrt{\frac{\pi}{N\tau_{SI}}} \tag{6}$$

of equation (1). In equation (6) $\varpi = x/\sqrt{a}$ denotes the later used deposit parameter. The assumption that the heat input into the deposit layer over an adjacent fluid follows a periodic time law is usually not fulfilled in practice. For the combustion process, rather, a stochastic energy release is always inherently present by a strong heterogeneity of the fuel, particularly in waste incineration plants. For that reason, an adaptation of the model concept to these conditions is necessary.

The diagram uses a double-logarithmic scale for a clear depiction of a large value ranges. In order to determine the thermal conductivity on the lower abscissa, the thermal effusivity, depicted on the left ordinate, should be specified. In addition, other combinations of input values, such as density, specific heat capacity, the deposit layer thickness, and the phase shift of the measuring signal by the deposit, can be used to calculate the parameters. Since usually only the phase shift is known in practice, further ways to use this diagram are not addressed at this point and a reference is made to the explanations in *Grahl*[1]. One additional important parameter for the determination of physical properties is the volumetric heat capacity, which ties the thermal conductivity with the thermal effusivity and is shown in broken lines of magenta color for constant values. Other vital parameters are constant values of thermal

diffusivity, which are dependent on the thermal conductivity and volumetric heat capacity and are illustrated in broken lines of blue color. From the materials listed in Figure 1, it can be seen that, on the one hand, very large value ranges of several orders of magnitude exist for the individual parameters. On the other hand, for combinations of material properties, which result in the volumetric heat capacity and in thermal conductivity or in the thermal effusivity, much smaller value ranges are always to be expected. The specific heat capacity and the density of a mixture can be determined with good accuracy according to the law of mixtures by the respective mass fraction. However, a suitable model for the thermal conductivity, which describes the structure of the deposit, is needed. A principal limitation of available values is due to the fact that the mixture (value range of porous solids, #2) of solid (value range of pure solids, #1) and gas (value range of pure gases, #3) can be considered either as a pure parallel connection (#4) or as a pure series connection (#5) of thermal resistances. The simultaneous variation of the gas content in the mixture between 0% and 100%, provides the boundary curves for gas and solid. The value range of the thermal conductivity, which is dependent on the thermal effusivity, is spanned between the two end points (the pure substances) of the limiting curves.
Using the diagram to help determine that the thermal conductivity is a function of the thermal effusivity, the thermal effusivity must be determined first. In addition, a suitable model for heat transport in the porous deposit layer has to be found (cf. *Gupta et al.*[7], *Schlünder & Tsotsas*[8], *Leach*[9], *Godbee & Ziegler*[10]). According to the present temperature level, the fuel being used, the structure, and the position of heat exchanging surfaces, adapted models (for instance the one from *Rayleigh* shown in Figure 1, #6) for the relevant deposits should be applied by account for local conditions (cf. *Grahl*[1]). In this way, the original assumption that only thermal conductivity may occur in the deposit layer can be replaced by a mathematical model of porous structures, including energy transport by radiation. The requirement of homogeneity and isotropy for a uniform temperature profile can only be satisfied in the plane perpendicular to the heat flux. For that reason, the deposit may consist of individual layers with different properties in the direction of the heat flux.

4 TEST RESULTS AT A LARGE-SCALE STEAM GENERATOR

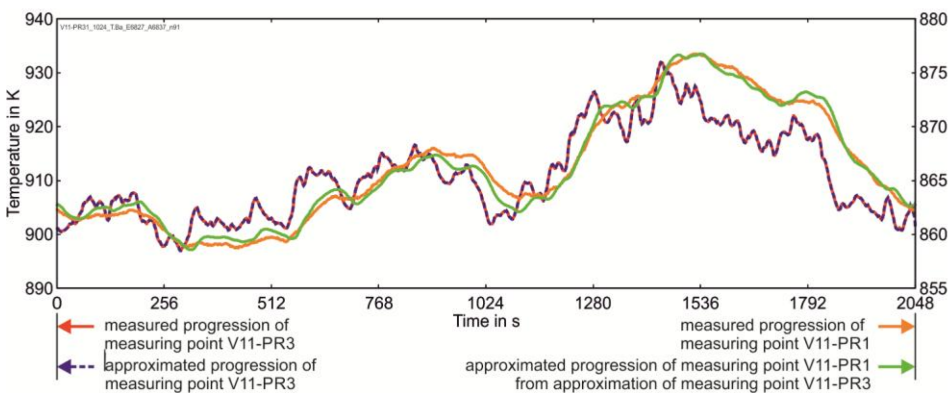
To test the measurement and analysis method under practical conditions, experiments were carried out at the waste incineration plant *KVA Oftringen* in the Swiss canton of Aargau. So far there is no opportunity to measure the deposit surface temperature during plant operation. For that reason, a rear cast refractory tile, and a rear ventilated one were prepared with drill holes in the above-mentioned plant. Thermocouples were installed within the drill holes at defined distances along the axis of the holes to determine the temperature progressions in various depths of the refractory tiles (cf. *Grahl & Beckmann*[11], *Martin*[12], *Grahl et al.*[13]). The drill holes were then filled with casting compound.
Stochastic changes in temperature resulted from the combustion of the heterogeneous fuel being used. These temperature variations are damped and phase-shifted to different degrees at different depths of the refractory tiles, where they can be measured at the predefined measuring locations. Damping and phase shift crucially contribute to determining the material properties of the casting compound, which surrounds the thermocouples and consists of silicon carbide (SiC60).
For this purpose, an appropriate adjustment of the temperature field to the boundary and initial conditions is necessary and done as follows:

1. equidistant sampling of the continuous analog temperature signal, resulting in a digital, time-discrete digital measurement signal;
2. selection of the observation period for the measurement signal analysis under the condition of stationary measuring signals;
3. development of the discrete input signal vector (measuring signal temperature progression, measured with an IR camera) in a Fourier series;
4. adoption of a deposit parameter $\varpi = x/\sqrt{a}$ and calculation of the corresponding response approximation;
5. least squares minimization between the discrete output signal (temperature measurement signal, measured with a thermocouple) and its approximation by adjusting the deposit parameter.

All other parameters in equations (4) and (5) are derived from the measured values or, in the case of the individual oscillation period, from the selected sampling interval and the underlying observation period. As a result, this procedure provides either the thermal effusivity or the deposit parameter. By means of the former, thermal conductivity and layer thickness of the deposit material can be determined directly,

considering the relation shown in the deposit characterization diagram. Due to the insufficient number of defining equations, a direct determination of other parameters is, by means of the deposit parameter, only possible if the average heat flux density and the thermal resistance of the deposit layer are known.
The result of this approach is shown in Figure 2. Utilizing the presented analysis method, incorporating the measurement signal of a thermocouple close to the flue gas (red) into a Fourier series (blue) and a corresponding adjustment of the approximated deposit parameter (violet), the measured curve of a more distant thermocouple (green) is approximated.

Figure 2. Fourier series approximation for the measurement points *V11-PR3* and *V11-PR1* at a time interval of 2048 s for 1024 samples and a deposit parameter value of 8.681 $s^{0.5}$.[1]
Readable on the left ordinate: the red curve shows the measured temperature progression of measuring point *V11-PR3* and the blue broken one its approximation by a Fourier series. Readable on the right ordinate: the green curve shows the measured temperature of measuring point *V11-PR1* and the violet one its approximation by a variation of the deposit parameter in the previously developed Fourier series.



The approximation of the signal progression with the measured signal is sufficient in order to achieve a concordance between the calculated thermal conductivity with the one determined in a laboratory test, regarding the given distance between the thermocouples.

5 SUMMARY AND OUTLOOK

The investigations which have been presented in this paper show that a determination of deposit parameters on the basis of fluctuating temperature and heat flux density signals is generally possible and applicable in practice. The above-mentioned measurement and analysis method has already been successfully tested on refractory tiles of a large-scale steam generator.

The measured temperature signals in the refractory tiles correlate very well with the thermal voltage differences that arise in the determination of the heat flux density at the membrane walls in the application of the web-tube measurement method. These thermal voltage differences are approximately directly proportional to the occurring heat flux densities over a wide measuring range. This indicates that through the combination of the heat flux density with the deposit surface temperature measurement, the deposit material properties can be characterized with a sufficient accuracy for practical use.

So far the model concept of the deposit layer is based on a planar one-dimensional temperature profile below the deposit layer. In general, such a planar temperature profile can only be achieved by the existence of a refractory lining. An extension to two-dimensional assumable membrane wall geometries, unlined tube walls for instance, is generally possible. However, this requires certain preconditions for the distribution of the deposit layer thickness along the web-tube contour. Workable solutions for such an extension of the mathematical model already exist, but the focus still remains primarily on the development of a measurement sensor for practical use.

The non-invasive and cost-effective installation of the web-tube measurement method allows a large-area network measurement of the heat flux density. However, since this can only be utilized for a quasi-static determination of heat transfer, it is not yet possible to calculate material properties of the deposit. The direct determination of deposit material properties with the above-mentioned measurement and analysis method is, therefore, still pending and an ongoing testing phase is inevitably needed.

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