SLAGGING AND FOULING IN BIOMASS CO-COMBUSTION

by

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Deposits formation on heat transfer surfaces, namely slagging and fouling, is one of the main problems associated to biomass combustion. Reducing deposits formation can optimise plant operation. Literature review and experience show a clear research demand towards methods for on line detection of deposits in large-scale boilers. A system consisting of a monitoring model and an on-line measurement method is presented. Results of testing campaigns show the appropriateness of the model to visualise deposit tendencies, and the possibility to determine the influence of ash deposits on heat transfer using the measurement method.

Key words: *combustion, solid fuels, slagging, deposits, heat flux*

Introduction

The growing interest in global warming due to carbon dioxide emissions has drawn attention to the use of biomass as fuel for power and heat production. The thermal use of biomass or waste, compared to other renewable energy sources, represents a cheap and technically feasible option to contribute to the reduction of the CO_2 emissions. Biomass combustion and biomass/coal co-firing activities, both in retrofit and new plants, are expected to expand considerably in the world in the coming years.

Deposits formation on heat transfer surfaces (referred to as slagging and fouling) is one of the biggest problems for all solid fuel fired boilers, especially in biomass combustion. Reducing slagging and fouling will lead to reduced investment and operational costs, increased performance efficiency and reduced emissions.

Methods for an on-line detection of slagging are currently not available; operators have to rely on their operation experience and on the off-line analysis of deposits. Prediction and on-line detection of slagging will help to optimise plant operation, increasing plant availability and reducing maintenance requirements.

Research is conducted at the Technical University of Delft, Thermal Power Section, to develop a system for slagging on-line monitoring. Heat transferred from the furnace to the heat exchanger is conducted through the deposits as they form and then to the water/steam flowing inside the tubes. The effect of deposits to reduce heat transfer rates to furnace walls, superheater tubes and other heat transfer surfaces is studied with a view to monitor slagging and fouling. Research involves both the development of a model and of experimental techniques. An on-line monitoring model to visualise slagging and fouling tendencies in a real power plant and an experimental method to establish the relationship between deposits and heat transfer, are being developed.

Literature review

Slagging and fouling fundamentals

All solid fuels contain a mineral fraction that is mostly non-combustible and produces what is called "ash". One of the aspects of energy production from fossil fuels that needs more attention is the formation of fire-side ash deposits. Formation of deposits depends mainly on fuel quality, boiler design, and boiler operation. Two main types of deposits can be found: slagging and fouling (S&F). Slagging occurs in the boiler sections that are directly exposed to flame irradiation. The mechanism of slagging formation involves stickiness, ash melting and sintering. Slagging deposits consist of an inner powdery layer followed by silicate and alkali compounds. Fouling deposits form in the convective parts of the boiler. The mechanism of fouling is mainly due to condensation of volatile species that have been vaporised in previous boiler sections and are loosely bonded [1]. Figure 1 shows the typical location of S&F deposits in a pulverized fuel boiler.

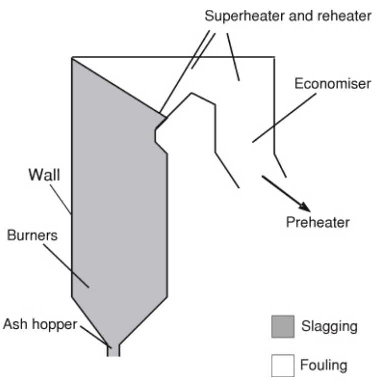

Figure 1. S&F in a pulverized fuel boiler

The main cause of S&F problems is an inadequate design of the combustion chamber in relation to the fuel being burned. The factors that have to be considered when designing a boiler are mainly: heat transfer/boiler size, global and local thermal level, combustion conditions, and soot blowing strategy. When these factors have not been chosen according to the fuel burned, S&F problems appear [2]. Design is based on a range of ash deposition indices and on experience. The deposition indices are based on the ash chemical composition and on the results of laboratory tests on small samples of ash. As these values are not reliable, boiler manufacturers have to learn by experience. This is even truer if biomass is considered for introduction as a secondary fuel in existing coal-fired boilers. It is necessary to develop comprehensive boiler monitoring systems and better instrumentation to improve the understanding of operating conditions and to provide information to help the operator understand and minimise ash deposition problems [1].

The mechanisms of deposits formation have been investigated during the last years and comprehensive overviews have been published about S&F phenomena, from the physical and chemical fundaments to the operational problems induced [1, 3-5]. Ash formation and behaviour in boilers is a very complex issue, understanding S&F involves knowledge of both fuel characteristics/ash behaviour and boiler design and operating conditions. Ash formation, transport and deposition mechanisms have been proposed [6-13]. Literature reviews present S&F issues specifically related to co-firing of coal with biomass fuels [14].

Databases of biomass fuels composition are available. Alkali and alkaline earth metals, combined with silica and sulphur existing in the fuel, and facilitated by the presence of chlorine, are at the origin of S&F problems in boilers [15]. In the Deposit Prediction project (by IVD, Stuttgart and others) experimental tools have been developed to characterise the fuels in order to predict the S&F behaviour. This project provides a database with valuable information especially for manufacturers of plants to consider the fuel quality in the design [16].

To help both diagnosis and prediction of unwanted ash deposition, research has been conducted following different methodologies: definition of predictive indices based on fuel and boiler characteristics, test work at full scale boilers [2, 17,18] and/or using pilot combustors [19, 20-23], modelling global plant performance or deposits behaviour. S&F predictions based on traditional fuel and ash analyses are currently enhanced by advanced mineralogy analysis [24]. The main development in the empirical approach is the addition of CCSEM and other advanced analytical data (IR spectroscopy, X-ray diffraction and chemical fractionation) [4, 25] to the solid fuel and laboratory ash analyses on which traditional indices are based. Models have been proposed to characterize the deposition process. They incorporate formation, boiler aerodynamics, transport regimes and sticking of the particles to the deposition surface [26-28]. A first approach to develop a model for on-line detection of S&F has been started in the SLAGMOD project, where a model based on the data of the steam cycle detect the change of heat transfer. It is an indirect approach for slagging detection. However it cannot provide all the information since the slag formation itself is not monitored [29].

Results from previous and ongoing activities described before, as well as experience from the operation of biomass fired boiler, clearly show a research demand towards methods for on line detection of S&F in large-scale boilers. On-line information about the deposits being formed in the boiler is of utmost importance to the operators for the application of operational changes, cleaning procedures, and use of different fuel qualities ensuring low risk of slagging, fouling or corrosion phenomena. Methods to obtain this on-line information are not yet available.

Monitoring methods: State of the art

Tests and instrumentation needed to assess S&F impacts of solid fuels have been described (EPRI Fireside Test Guidelines), including furnace exit gas temperatures and other temperature measurements through the system, S&F probes, radiant heat flux measurements, direct observations by camera or video, furnace wall measurements, coal feed and ash deposit sampling [1]. Different probes to monitor gas-side fouling build-ups were already identified in previous surveys, including local heat flux meters, mass accumulation probes designed to determine the mass of the deposit quantitatively, optical devices limited to laboratory investigations and deposition probes to collect deposits on a qualitative basis. The ideal standardized probe for industrial applications should be simple, robust, inexpensive and accurate [30]. Proposed monitoring methods based on deposits properties are summarized in fig. 2

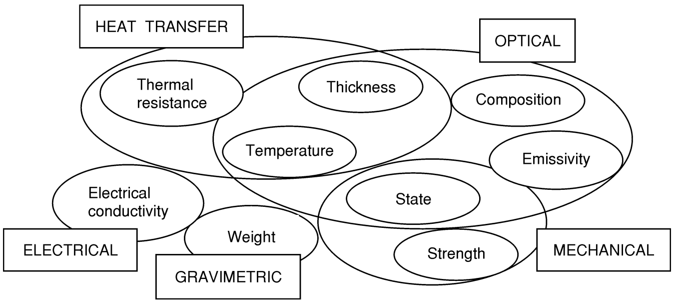

Figure 2. Physical properties / Measurement methods

One of the main effects of deposits formation on boiler operation is that they reduce the heat transfer process between the fire-side and the water-steam side. That results in a sensible increase of the flue gas temperature. Thermal absorption diagnostics have been done by direct measurement of heat flux by instrumentation installed in the heat transfer tubes and through mass and energy calculations. More developments are needed in both senses. The uncertainty of heat flux measurements is high due to the calibration problems of these sensors. The data interpretation and statistical analysis needs also to be improved [31].

The thermal properties of the deposits influence the heat transfer process. These thermal properties are effective total emissivity and thermal conductivity, which accounts for radiation-convection-conduction through the deposit. These thermal properties depend on the processes by which deposits are formed, and on their physical and chemical character. A number of researchers have measured the thermal conductivity of ashes obtained from full-scale power plants. This parameter depends on the physical structure, temperature, porosity, sintering time and to a smaller extent, chemical composition. It has been found out that the thermal conductivity increases with increasing temperature, it is higher for sintered than for unsintered ash samples, it is irreversible with temperature and sintering time, it increases with decreasing porosity and is only slightly influenced by chemical composition. Models have been developed to predict the thermal conductivity [32] and to assess the dependence of the average thermal conductivity on macroscopic and microscopic structural properties [33, 34]. A technique has been developed to make *in-situ*, time resolved measurements of the effective thermal conductivity of ash deposits formed under simulated fouling conditions [20, 35]. FTIR has been used on-line to identify the changing composition of ash deposits as they form and results have been related to strength and tenacity of the deposits [36].

Optical methods have also been reported and research is being done currently in this sense. The thickness and growing rate of the slag layer could be monitored on-line by an appropriate image acquisition and treatment system. Different technologies are proposed: traditional high temperature cameras, thermographs and edge detection [37] and advanced laser diagnostics [38].

Other methods have taken into account the hydrodynamic functioning of heat exchangers measuring increasing pressure drops, due to fouling [39].

Methodology

Modelling activities

Principle

The main objective of the modelling activities is to visualise S&F tendencies by applying an online monitoring model. Governing equations (mass and energy balances) are developed to model heat transfer between the flue gases and the water/steam cycle and deposits formation on heat exchanger surfaces. The model is intended to characterize the heat transfer at the evaporator, economiser, superheater (SH) and reheater (RH) sections of the boiler. Analysing model results and correlated measured data of the plant help to uncover the S&F tendency in an early stage of the process.

Facility

A pulverised fuel boiler is studied. It produces 200 MW thermal energy for district heating and 100 MW electrical energy, design steam parameters are 520 °C/125 bar. The biomass fuel consists of 70% peat and 30% wood chips. Problems concerning S&F occurred suddenly during plant operation. This boiler is of the once-through type. It consists of two economisers, an evaporator, three superheaters and two reheaters. Soot blowing is done with steam taken after the LP turbine, at fixed times during operation. See fig. 3.

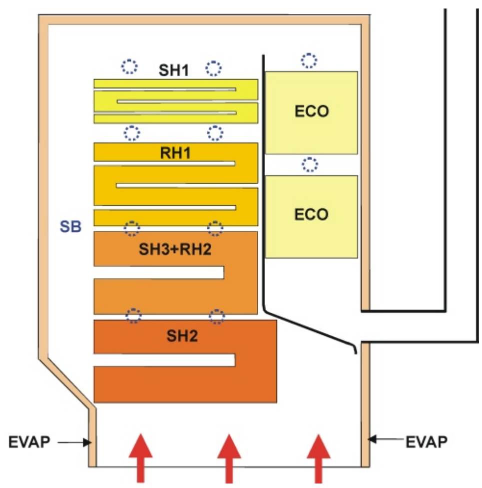

Figure 3. Structure of the boiler

Model

An overall plant model, depicted in fig. 4, and a deposit-monitoring model, derived from the overall one, have been developed. The plant codes are built and solved by applying the modelling program Aspen Custom Modeller (ACM). To improve the modelling accuracy, in order to detect and analyse S&F, heat exchangers are divided into small volume elements. The two different types of flow streams, namely the water/steam and flue gas and the metal wall elements are discretised. For these small volume elements mass, momentum and energy balances have been solved. Flow streams are equally divided into a number of so-called thermal nodes and flow nodes, a so called staggered grid [40] is applied to stabilize the numerical solution. In each of the thermal nodes the energy and mass balances are solved, properties of the neighbouring flow nodes are used. Thermal nodes are connected with the wall elements to transfer the heat flux. Wall elements contains only a heat balance. The momentum balance is calculated in the flow nodes in between, properties of the neighbouring thermal nodes are used. The flow nodes are also taking into account friction losses and cross- sectional area changes. This modelling concept was originally applied to a study in design and control of a nuclear gas turbine plant [41].

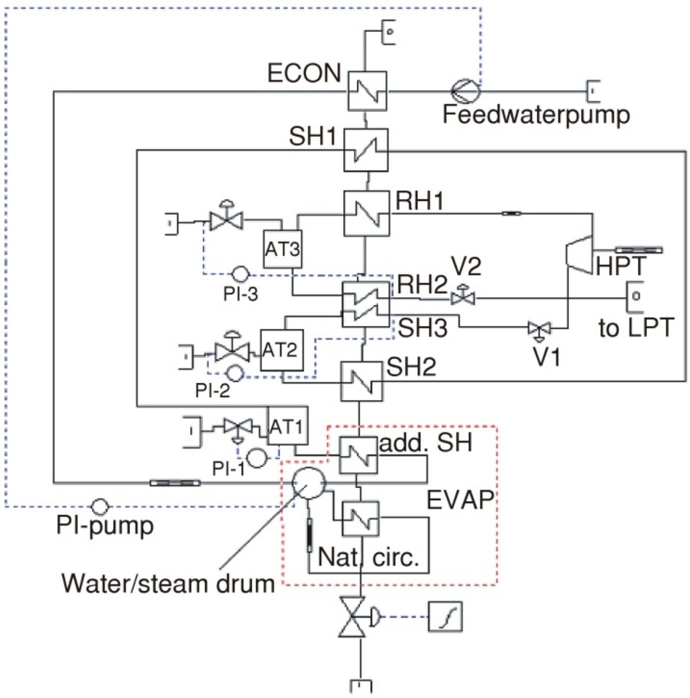

Figure 4. Flow sheet of the overall plant model

The monitoring model is derived from the overall plant model. Due to limited measurements, the deposit monitoring is focusing only to the superheaters and reheaters. Its purpose is to detect S&F and to follow their course over time. The monitoring can be done by applying on-line plant data in the model. The model receives specified on-line plant data at fixed time intervals and calculates a steady state solution. The calculation provides values of all free variables in the model, including a slag thickness, which does not distinguish between S&F deposits. These values can be visualised with graphs and written to an output file for later processing and analysis.

Experimental activities

Principle

Since an homogeneous slag layer has been assumed in the modelling, it is impossible to calculate an exact value and the distribution of the slag thickness. A relation between uniform deposit thickness and wedge shaped deposit height needs to be found experimentally in order to complete the model. The fact that heat transferred to a tube is conducted through the deposit includes the possibility to lump the mechanisms into one variable: the effective thermal conductivity coefficient. The majority of the reported thermal conductivity measurements are based on post mortem analysis techniques that destroy or significantly alter the physical structure of the deposit. The elucidated *in situ* measurement by Robinson *et al.* [35] allowed direct examination of the thermal conductivity of actual deposits. The results show a decrease in heat transfer due to the deposit and thus the possibility to perform such measurements. The reported experiments were carried out at relatively low probe temperatures (300-400 °C), so no sintering of the deposits occurred.

Description of the experimental campaign

The goal of experiments is to determine *in situ* the influence of deposit formation on heat transfer from the flue gas to a cooling medium. In order to calculate the effective thermal conductivity the following parameters should be measured: surface temperature of the probe, surface temperature of the deposit, heat transfer rate through the deposit and deposit height (the latest could not be measured).

An *in situ* probe has been designed, fig. 5. This probe is an air-cooled metal tube with an inserted metal rod. The rod houses four thermocouples with which metal temperatures (inner wall) and air temperatures can be measured. The head of the probe tube is closed on one side by the rod housing the thermocouples, and on the other side hot air is vented through a flexible pipe to a safe place. Cooling air inlet comes from a side orifice at the probe head. Deposits form on the probe located inside the furnace, where combustion of pulverized fuel is taking place. After each test the tube was removed and photographed and a new tube was inserted. The in- and outside (36 mm) probe diameters influ-

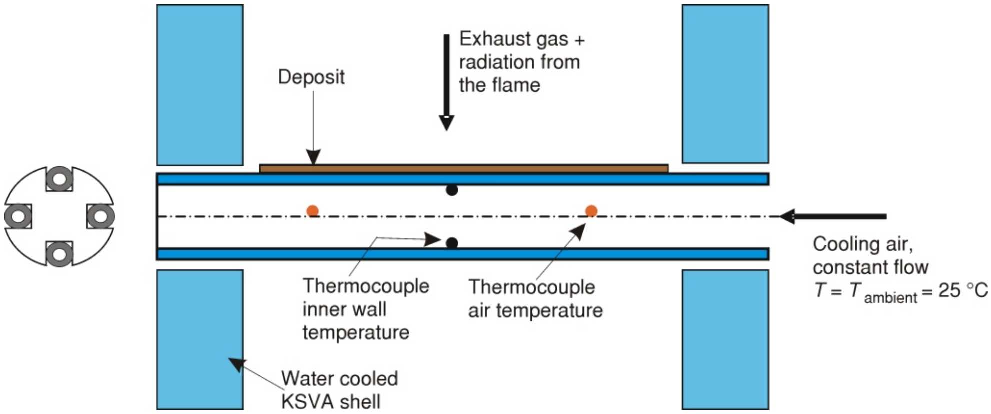

Figure 5. Probe and inner rod with four thermocouple housings

ence the heat transfer to and from the probe. These diameters assure a turbulent cooling airflow and a measurable air temperature increase. The probe total length is 135 mm and wall thickness is 2 mm. The probe and rod material is heat resistant steel. Steel has been chosen instead of ceramics because it can resist larger thermal/mechanical stresses. Disadvantages of steel compared with ceramics are the relatively lower outside wall temperature (decreased deposition rate) and temperature range. The cooling airflow remained constant during each experiment.

The outside temperature of the probe has been measured with a two-colour-pyrometer. With the pyrometer the side of the deposit probe (not the top) can be monitored and the temperature of the probe outside wall/deposits surface can be measured. It is obvious that the pyrometer temperature measurement will be influenced by ash particles in the exhaust gas and furnace wall radiation. On-line deposit height measurement is impossible with the pyrometer.

Test rig

The *in situ* tests have been performed in the KSVA (Pulverized Coal Combustion Facility) facility at IVD, Stuttgart. The KSVA is a pilot plant for pulverised fuel combustion, with a maximum thermal output of 500 kW. It consists of a top fired cylindrical combustion chamber of 0.75 m diameter and 7 m length that reaches high combustion temperatures of about 1400 °C. Sampling ports are available all along the furnace. The fuel used during the tests week altered frequently according to other priority tests carried out at KSVA at that time. The conditions of the deposition process have been simulated at the test rig.

Results

Modelling part

The monitoring model has been tested off-line and on-line. Input data are read from the plant process computer, and are filtered to reduce measurement noises. Existing databases of measured data are used for off-line tests. Results are given in an output data file. In order to illustrate the ability of the model two different soot blowing took place. A "strong" soot blowing, which takes two hours and uses all soot blowers, and a "light" soot blowing, which uses the soot blowers close to the SH2/RH3. Soot blowing takes place every eight hours and is activated on basis of secondary data (NO_x levels, attemperator flow) and experience.

Based upon the measured data the monitoring model has calculated for the superheater and reheater: flue gas temperature, slag thickness (see fig. 6), heat transfer coefficients on the hot flue gas, and heat transfer for each of the monitored heat exchangers. Some measured plant data, which are not used as input variables, have been analysed and verified with the calculated results of the monitoring model, like the mass flow of the attemporator.

It must be remarked that little attention should be paid to the total values of the slag thickness, since the model assumes a homogeneous deposit layer for the total heat exchanger, which is actually not the case. Local deposit building is not taken into ac-

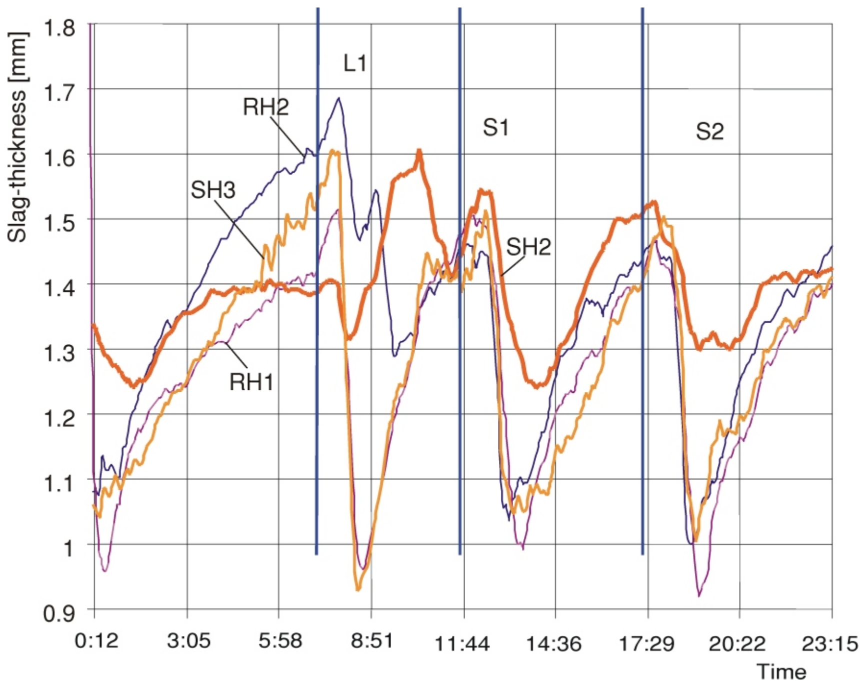

Figure 6. Slag thickness / Soot blowing (L – light, S – strong)

count. Slag thickness increases continuously and is periodically removed during soot blowing. Only SH3, RH1, and RH2 are cleaned during the light soot blowing (L) cycle, while SH2 is not affected due to its position in the boiler. SH2 has a strong increase in the transferred heat, in particular during the automatic soot blowing, although relatively little deposit seems to have been removed. This is due to the fact that its position in the boiler close to the combustion zone, where it is exposed to radiation, maximize the influence of deposit formation on heat exchange. Since SH2 takes over the heat exchange after soot blowing, SH1 has in opposite a reduced heat rate. The cleaning effect is within 2-4 hours equalised. The slag thickness calculation is independent from the current load condition. The furnace exit temperature is increasing until soot blowing takes place.

Experimental part

Three measurements have been performed burning different fuels. Process conditions differed for the different eight hours periods. Since other experiments were running at the same time, the unavoidable opening of sampling ports influenced the operating conditions. The most representative results were obtained between 14:00 and 22:00, when combustion conditions remained constant and coal was burned, fig. 7. The oscillation of the pyrometer temperature is due to the fact that fly ash an unburned fuel particles crossed the path of the pyrometer. With the obtained data, which are summarised in tab. 1, some basic heat transfer calculations were performed in order to classify the influence of a deposit on heat transfer.

Table 1. Measured parameter

Instrument	Unit	Parameter	Short name
Thermocouple	C	Air input temperature	T_{airin}
Thermocouple	C	Air output temperature	T_{airout}
Thermocouple	C	Inner wall temperature, Upper	T_{wup}
Thermocouple	C	Inner wall temperature, Lower	T_{wdown}
Pyrometer	C	Outside wall temperature	T_{pyro}

Calculations have been done to determine: the heat transferred to the cooling air, the heat transfer coefficient from the tube wall to the cooling air using the measured data, the same heat transfer coefficient using an empirical formula for the Nusselt number inside the tube, the heat conducted through the cylinder wall. Radiation has the biggest influence on the heat transfer from the furnace to the probe. Convection can be calculated by determining the flow conditions outside the tube and applying a matching Nusselt relation. The pyrometer temperature, taken as outside wall temperature, is mostly influenced by flue gas and furnace wall temperature. Different values of the heat transferred to

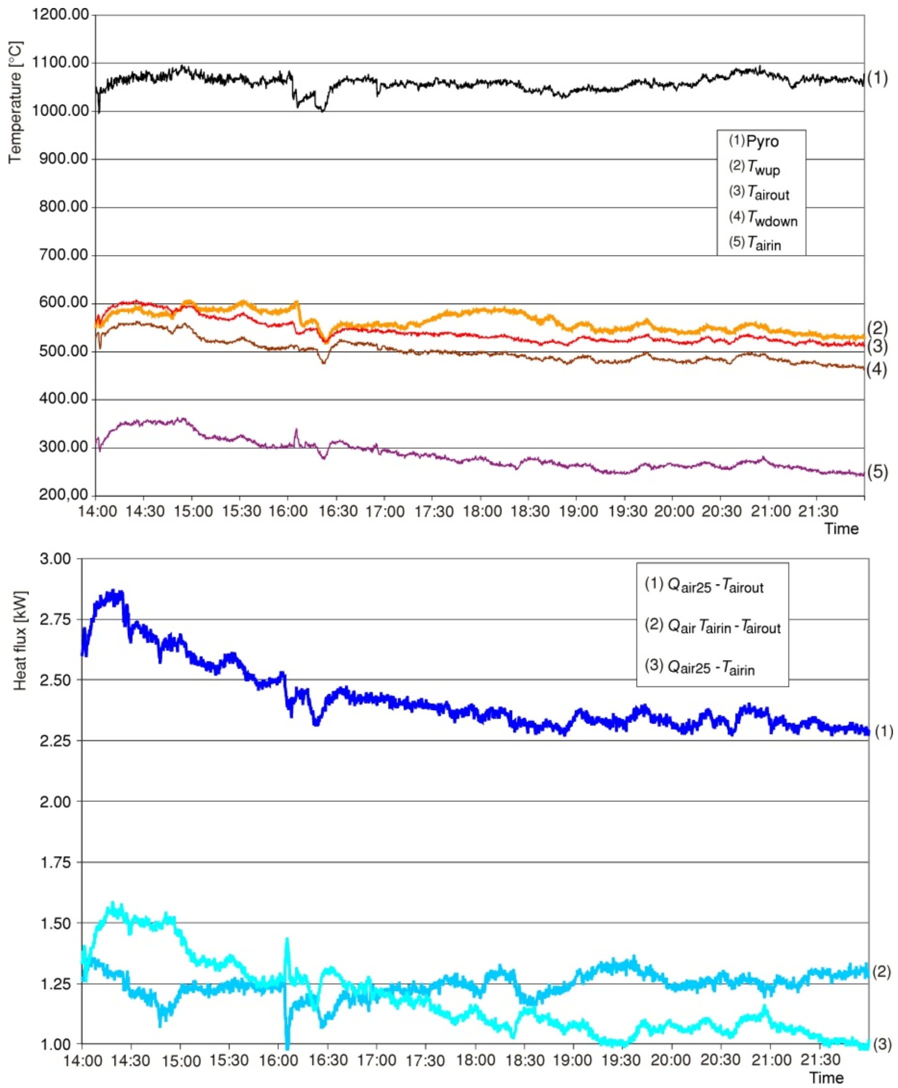

Figure 7. Experimental results: temperatures and heat flux

the cooling air have been calculated: to heat up the air from 25 °C up to T_{airin}, to heat up the air from T_{airin} to T_{airout}. Cooling air flow rate was kept constant during the experiments.

During this period, combustion conditions remained approximately constant, thus the decrease in total heat flux to the cooling air (Q_{air25}-T_{airout}) can be due to the influence of deposits being formed. From simple calculations it follows that the thermocouples measuring the inner wall temperatures are lower than expected. This could be due to the fact that these thermocouples are affected by cooling air convection or even due to lack of thermal contact or other installation effects. Results obtained during other testing periods were mostly affected by changing operating conditions.

Conclusions

The monitoring model is appropriate for visualising deposit tendencies under all load conditions. It calculates a homogeneous deposit layer over the complete heat exchanger without predicting local deposits. In spite of the strong fluctuations of many input variables and the limited number of reliable input variables, the model is able to satisfy its purpose such as visualising the deposit thickness tendencies for individual heat exchangers. This information can be used to give advice for an optimal soot blowing frequency.

Using the designed probe and method it has been possible to determine the influence of ash deposits on heat transfer. Further tests performed at a tightly controlled furnace are recommended to find out a quantitative relation between heat transfer and amount of deposition. From the experience gained with this experiments an improve design of the probe will be proposed. Optical monitoring of the deposit layer would complete the experimental method.

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