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CONCEPT OF EXPERT SYSTEM FOR BOILER FOULING ASSESSMENT

N. Afgan, M. G. Carvalho and P. Coelho
Technical University of Lisbon, 1096 Lisbon, Portugal

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Abstract—The expert system for fouling assessment development is one of the possible approachs to the mitigation of deposit formation on boiler heat transfer surfaces. This paper presents the evaluation of the diagnostic variables and their domain based on the criteria for the fouling assessment. In agreement with the boiler furnace design, respective fields for the deposit control are selected to be instrumented with the 'clean' radiation heat flux and 'not-cleaned' radiation heat flux for the on-line reading. The ratio of the 'clean' and 'not-clean' radiation heat flux is proved to be a sensitive diagnostic variable for the deposit thickness. The rate of change of radiation heat flux ratio, together with the efficiency of the heat transfer surface, are diagnostic variables used for the design of the expert system knowledge base. The knowledge base structure is based on the object oriented concept. In this respect the FOULING object is defined. Its structure is composed of the respective attributes and values linked with the number of situations to be selected for the assessment.The examples given are related to a 300 MWe power-plant boiler furnace. It includes the number of situations reflecting different deposit formation situations: total and upper level of side surface of fouling deposit. Copyright © 1996 Elsevier Science Ltd.

Keywords—Heat exchanger fouling, boilers, expert system, diagnostic variables.

INTRODUCTION

Deposit formation on boiler surfaces is an eminent problem for fuel-oil and coal-fired fouled boilers. It is a result of the fouling process of solid particles in the flue gases on the boiler heat transfer surfaces, affecting heat transfer processes from the flue gases to the working fluid. Since the fouling process is strongly connected with the efficiency of the boiler performance, the study of this process has been devoted to the different aspects of its mechanisms [1], material structure [2], relation to the other parameters of the system [3], and fuel origin [4]. It was recognised that the fouling process affects the efficiency of the boiler by the following parameters: emissivity of the deposit [5], thickness of the deposit [6], 1981), structure and conductivity of the deposit [7] and physicochemical parameters of fuel, flue gases and solid particles [8], and surface parameters [9]. From the state of the art [10] of the fouling process it was noticed that the complexity of the parameters and their interdependency in time and space make the problem of the boiler fouling mitigation very difficult. In this respect it is of interest to investigate the different aspects of this problem, in order to concentrate attention on all possible methods which are of interest to be used in the prevention and control of the fouling process.

There are several approaches to the mitigation of the fouling process in liquid- and solid-fuelled power-plant boilers. Obviously, in the first place experience is gained in the design of fouling-free boiler furnaces. With the acceptable reference the modern boiler designs are specified with the preselected heat rating, including volume and surface heat rating [11], corresponding to the different fuels and representing limitation for the fouling-free designs. However, the variety of fuel and its time-dependent properties my cause a change in the operational parameters outside the design limits, resulting in favourable conditions for the fouling process. The use of different additives which aim to affect the fouling process and decrease the intensity of the fouling deposit foliation has been investigated [12]. In particular, some additives have proved to be of interest for specific fuels.

Besides the thermal design limitation and chemical additives for the fouling mitigation, there have still been many operational problems affecting the efficiency of the system. For this reason, it is of interest to investigate the possibility to adopt a diagnostic procedure which may contribute to the operational scheduling of the boiler, in accordance with the respective assessment of the fouling process intensity and efficiency degradation. In this respect, the expert system diagnostic may prove to be an efficient tool for fouling process control and assessment. The on-line expert system assessment is based on the respective monitoring system with adequate sensors for fouling deposit measurement and a knowledge base to be used for logical reasoning in the fouling assessment of the boiler furnace surfaces. It has been shown that the expert diagnostic [13] is a powerful tool for efficiency degradation monitoring and assessment, with expert advice for the operational scheduling of the plant and economic justification of the action to be taken.

THE EXPERT SYSTEM CONCEPT

The development of the expert system comprises several steps, namely: selection of the diagnostic variable's, definition of domain, formation of the knowledge base, selection of the reasoning strategy and design of the monitoring system. The expert system for fouling assessment is designed with the reference pattern, but taking into consideration specific aspects of the problem to be assessed.

Diagnostic criteria

Most of the heat generated in the boiler furnace is transferred to the working fluid by the radiation heat transfer. Flue gases with other combustion products transfer sensitive heat to the boiler water wall tubes. For the clean tube surface, the heat received by the tube can be defined as the 'clean' heat flux:

$$q = \sigma \epsilon_c T_g^4 - T_w^4,$$

where ϵ_c—emissivity of flue gases to tube surface; T_g, T_w—gas and wall temperature, respectively.

The fouling deposit layer on the boiler tube surface affects the heat transfer from the flue gases to the tube. Figure 1 shows a schematic representation of the heat transfer process with and without the fouling deposit layer. From this consideration, under the assumption that the emissivity of 'clean' and 'not-cleaned' surfaces are not substantially different, it follows that the ratio of 'not-clean' surface heat flux and 'clean' surface heat flux is

$$\frac{q_{\text{not clean}}}{q_{\text{clean}}} = \frac{T_{gn}^4 - T_{wn}^4}{T_{gc}^4 - T_{wc}^4},$$

where T_{gn}, T_{wn}—gas and wall temperature for the 'not-cleaned' surface, respectively; T_{gc}, T_{cw}—gas and wall temperature for the 'cleaned' surface, respectively.

It is known [14] that the thermal efficiency of the boiler furnace surface is defined as

$$R = \frac{q_{\text{net}}}{q_{\text{inc}}},$$

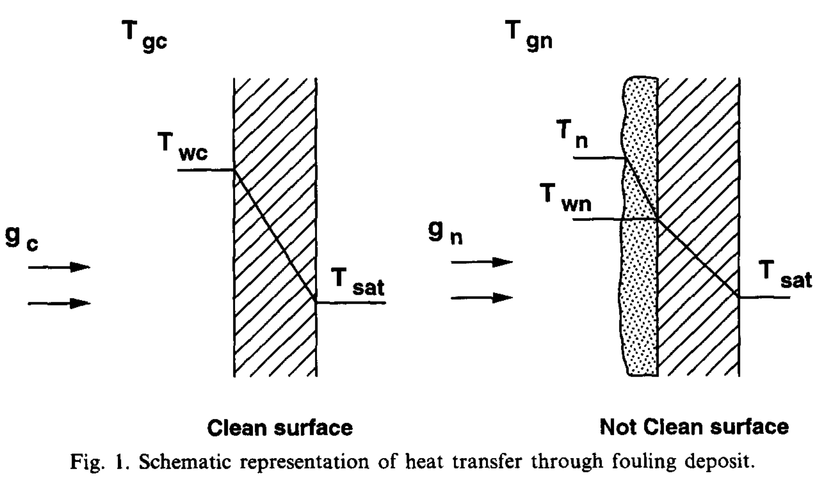

Fig. 1. Schematic representation of heat transfer through fouling deposit.

where q_{net}—heat flux on the boiler furnace surface; q_{inc}—incident radiation heat flux on the boiler furnace surface.

Radiation heat flux on the not-cleaned surface in the boiler furnace is identical to the net heat flux at the same surface. Under the assumption that the surface temperature of the clean surface is sufficiently low, the 'clean' heat flux will be identical to the incident radiation heat flux.

By the analysis of the expression for 'clean' to 'not-clean' heat flux ratio, it follows that under the assumption of a negligible difference between the emissivity and temperature of the tube surface without and with deposit, it results that [15, 16]

$$\frac{q_{\text{not clean}}}{q_{\text{clean}}} = f(\delta_d),$$

where δ_d—deposit thickness.

Also, it can be proved that for the limited range of the deposit physico-chemical properties, it could be adopted that

$$n = \frac{q_{\text{not clean}}}{q_{\text{clean}}} \approx K_0 * \delta_d$$

or

$$\delta_d \approx D_0 \frac{q_{\text{not clean}}}{q_{\text{clean}}} \approx D_0 * n,$$

where K_0, D_0—correlation constants.

It follows that the first criterion for the fouling assessment is the fouling deposit layer thickness as defined by this expression.

The fouling deposit rate is defined by the deposit thickness time change. From the investigation of the deposit thickness time change several models were recognised which reflect different mechanisms for the description of the fouling process. In this respect, for the fouling process in the boiler furnace it is adopted that

$$\delta_{d_r} = \delta_0[1 - \exp(-kt)/],$$

where δ_0—asymptotic deposit thickness when the deposit mass flow rate is equal to the removal mass flow rate; k—fouling rate constant.

It can be proved that under these assumptions

$$k = A \frac{\mathrm{d}}{\mathrm{d}t} \ln\left[1 - \frac{D_0}{\delta_0}\left(\frac{q_{\text{not clean}}}{q_{\text{clean}}}\right)\right]$$

defines the fouling rate for the specific fouling process. This expression for the fouling rate is used as the second criterion for the fouling assessment diagnostic. It gives the possibility to differentiate individual fouling processes by their mechanisms. By this grouping it is possible to recognise the diffusion-controlled fouling process and the mechanical-controlled fouling process as the upper and lower limitation of the fouling rate mechanisms.

The third criterion in the fouling assessment procedure is based on the efficiency of the heat transfer surface and is defined as

$$R = \frac{q_{\text{net}}}{q_{\text{inc}}} = \frac{q_{\text{not clean}}}{q_{\text{av}}},$$

where q_{av}—average surface heat flux for the total heat generated in the boiler furnace.

The efficiency criterion is defined for the specific fields in the boiler but also for the boiler furnace sides, boiler levels and for the total surface. The efficiency criterion is designed as the measuring parameter for the economic justification of the fouling process in the boiler. It is aimed to be used in the economic assessment of the adverse effect caused by the fouling on the boiler furnace surfaces.

Variable selection and domain

As defined by the diagnostic criteria the main diagnostic variables for the fouling assessment are (n); (k); (R).

In the design of the expert system for fouling assessment the variables are used to define the domain of the expert system. In this respect, the boiler surface is divided into measuring fields, which are determined by the side and position including horizontal and vertical location of the field (Fig. 2). Also, at each field the diagnostic variables are measured in the specific ranges, giving the possibility to estimate quantification of the individual variables within the respective scale. This implies that the domain of the expert system for the fouling assessment is determined by the variables as specified by the criteria and fields on the boiler surfaces. The second step in the design of the expert system concept is the development and structure of the knowledge base. For the fouling assessment expert system the object-oriented approach based on the object definition, including attributes and their values described by the respective expectations of the situations to be assessed in the retrieval procedure, is adopted. For this reason, the definition of the FOULING object as the abstraction comprising parameters which allow the description of the potential situations to be used in the assessment of the fouling process is adopted. The FOULING object is composed of two subclasses with position and readings, including their location and values and rates reading, and an efficiency subclass with field geometry and quantity of the efficiency which can be expressed for the level, side and total surface. Following the described structure of the FOULING object, it is possible to design the expert system knowledge base corresponding to the number of situations to be assessed by the adopted retrieval strategy. The knowledge base structure allows description of the fouling situations which are expected in the boiler furnace. In the LISP language the FOULING object is defined as

FOULING (sensor (position (side (front back side1 side2) location (row (A_1 A_2 A_3 A_4) column (B_1 B_2 B_3 B_4)) reading (value (n_1 n_2 n_3) rate (K_1 K_2 K_3)) efficiency (field (level (1 2 3) side (front back side1 side 2)) quantity (R_1 R_2 R_3))).

A graphical representation of the FOULING object is shown in Fig. 3.

Knowledge base structure

In order to demonstrate the application of the knowledge base structure to describe individual situations of the fouling process in the boiler furnace, a three-dimensional mathematical model of the combustion, fluid flow and heat transfer is used to determine incident radiation heat flux distribution pattern on the boiler surfaces for the assumed fouling deposit thickness [17, 18]. Three cases are used for the demonstration, namely: deposit of the silicon oxide with the thickness $\delta_d = 2$ mm at the total boiler surface and deposit of the silicon oxide with the same thickness at the upper level of the boiler furnace. Also, the calculation of the heat flux distribution is defined for the clean surface of the boiler furnace, in order to demonstrate the effect of the fouling process. The results obtained for the respective situations are presented in Figs 4 and 5.

The knowledge base for the object-oriented approach also comprises rules to be used for the retrieval of the situations in the knowledge base, in order to achieve the goal of the expert system and present assessment of the actual situation as it is obtained by the reading of diagnostic variables. In this respect, the object-oriented approach gives an interactive possibility which uses the rules to retrieve those situations which are in compliance with the situation obtained by reading actual values of the diagnostic variables. Once the actual situation is matched with the respective situation in the knowledge base the assessment procedure has reached its goal and corresponding advice can be obtained as it is assigned to the obtained result. It should be emphasised that the rule-based retrieval procedure is adopted in most of the development tools for the object-oriented expert system.

The organisation of the knowledge base is based on the number of the individual situations describing deposit formation on the different segments of the boiler heat transfer surface. In order to demonstrate the sensitivity of the expert system diagnostic performance, two cases are shown, including definition of the respective FOULING object.

Case 1—deposit on the total boiler surface. The fouling effect on the heat flux pattern of the heat transfer surface is demonstrated by the situation reflecting deposit formation on the side boiler

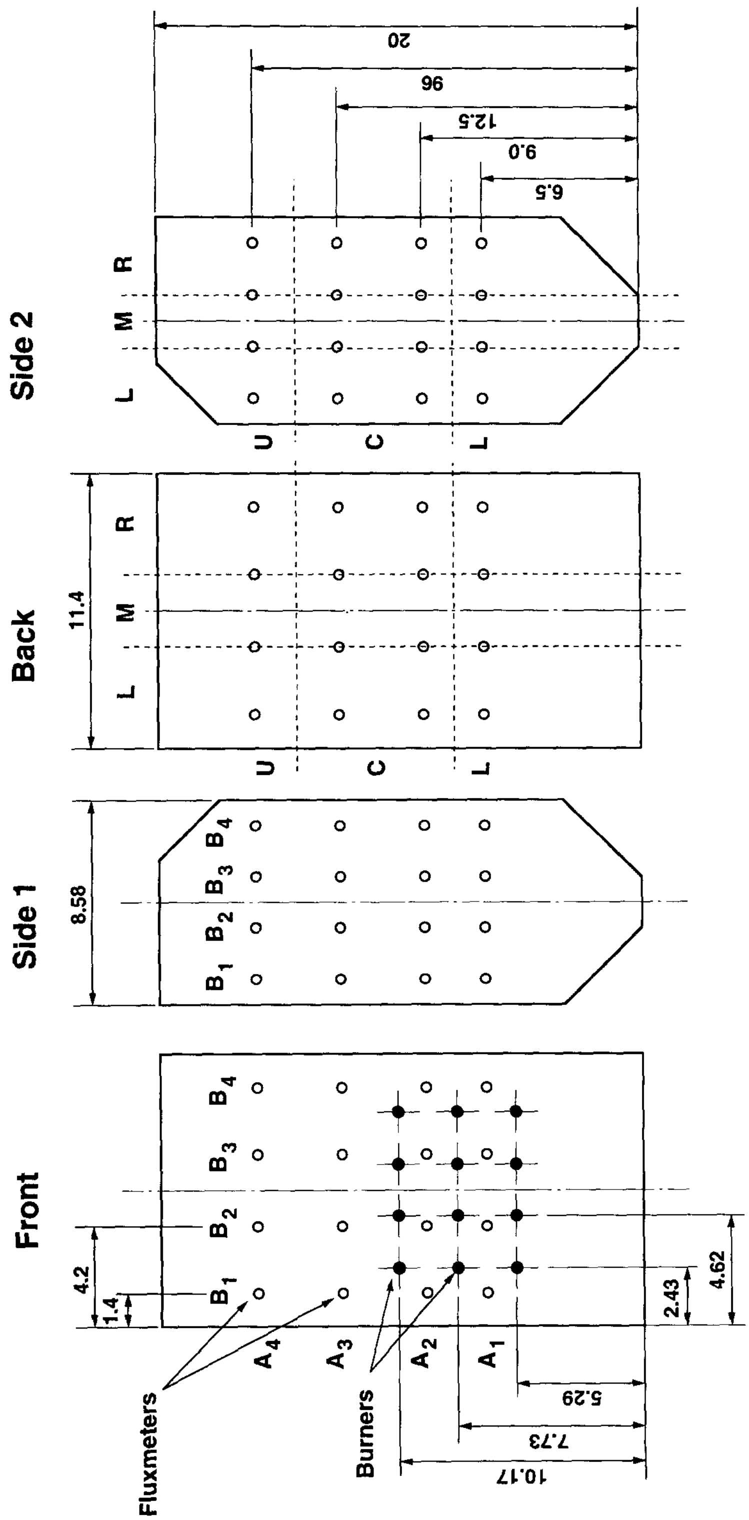

Fig. 2. Field distribution on the boiler furnace surfaces.

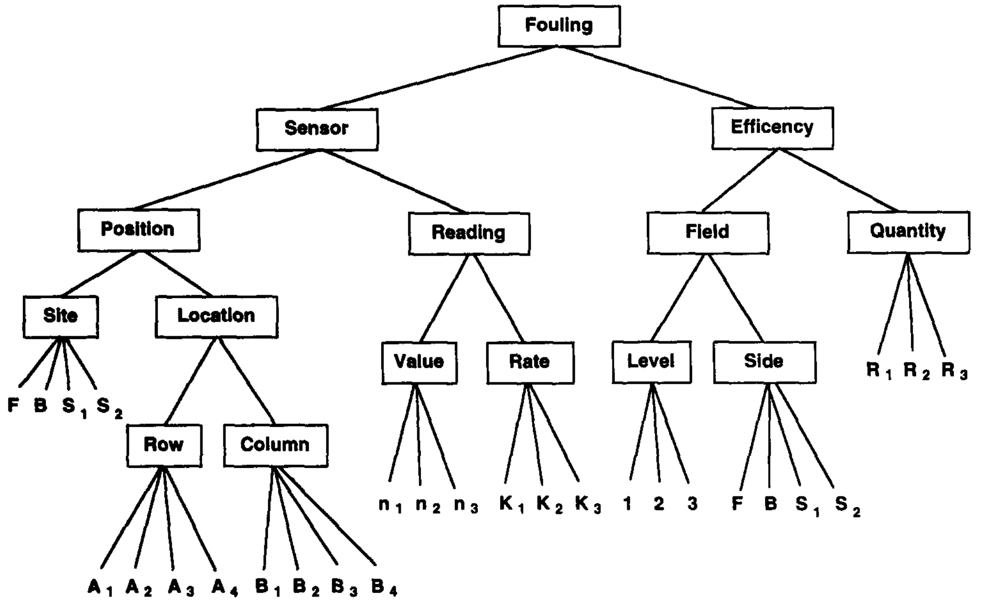

Fig. 3. FOULING object structure.

furnace suface. Case 1 corresponds to the ratio $\delta/k = 0.001$, $\delta/k = 0.003$, $\delta/k = 0.006$. The heat flux ration pattern is demonstrated representing the respective fouling deposit formation, as shown in Fig. 4.

Case 2—effect of the deposit formation on the upper level of the side surface. The effect of the deposit thickness on the heat flux pattern is demonstrated in Case 2. The upper half of the boiler side surface is assumed to be $\delta/k = 0.001$ and the lower side is a clean surface. It shows that the deposit formation on the upper level of the side surface can be recognised as the different diagnostic situation. It may also reflect the time-scale for the deposit change. The heat flux pattern on the side surface is shown in Fig. 5.

In the final stage of the expert system development an expert advice part which will contain the economic and operational justification will be specially designed, giving the management of the

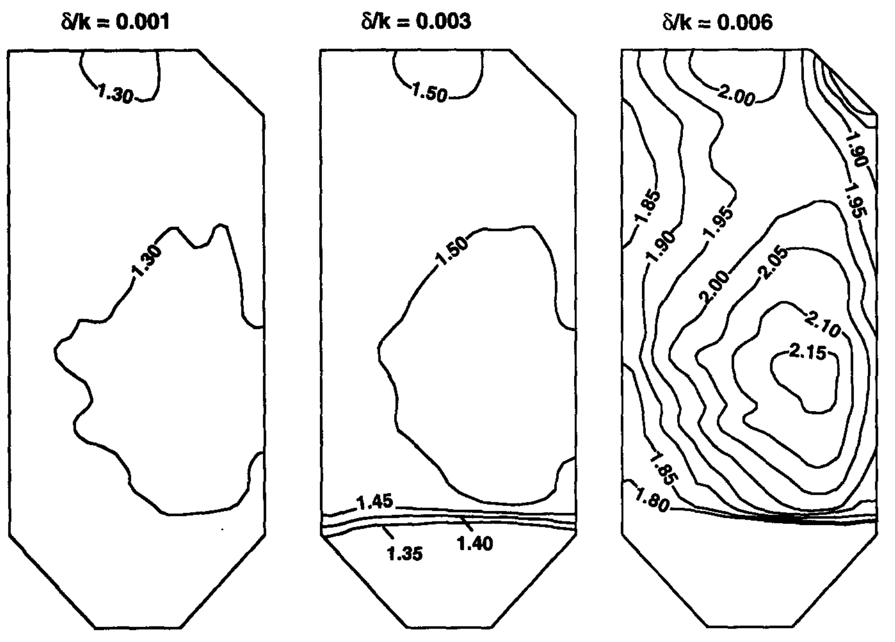

Fig. 4. Heat flux ratio pattern for total surface deposit.

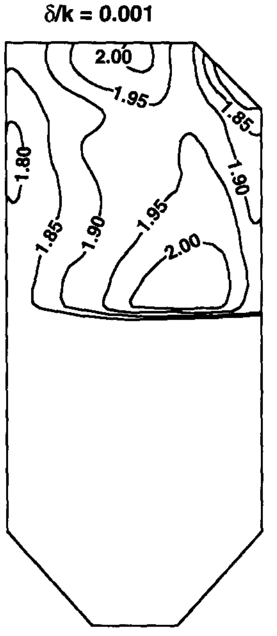

Fig. 5. Heat flux ratio pattern for upper part deposit.

plant the possibility of making its own assessment of the system, taking into account facts which are outside the domain of the expert system for fouling assessment.

MONITORING SYSTEM

Sensors

The on-line expert system requires continuous monitoring of the diagnostic variables and their reading, presented in the form to be used as the input data for the assessment of the state of the system and definition of the actual situation to be compared with the situations in the knowledge base, corresponding to the known set of the diagnostic variable readings. The expert system for fouling assessment, as is shown, is based on the on-line reading of the number of the sensors designed to measure radiation heat flux on clean and not-clean boiler furnace surfaces. The radiation heat flux measurement represents an active field of interest and there are a number of different sensors designed in accordance with specific needs [19]. Radiation heat flux sensors for the expert system for fouling assessment are adapted and developed, in order to meet specific requirements of the diagnostic variables of the expert system [20]. In this respect the 'not-clean' heat flux measurement is based on the Garner-type sensor (Fig. 6) with the heat flux proportional to the centre to periphery temperature difference in the disc exposed to the radiative heat source.

The 'clean' radiation heat flux sensor (Fig. 7) is based on the transpiration cooling of the porous disc exposed to the radiative heat source [21, 22]. At the critical mass flow rate of the blowing gas, the blow-off laminar boundary layer occurs so that the blowing gas temperature difference at the inlet and outlet of the porous disc is proportional to the radiation heat flux.

It can be noticed that with the blowing gas exceeding critical mass flow rate the sensor reads the 'clean' radiation heat flux. The selected design of the sensor will continuously ensure a reading corresponding to the clean surface radiation heat flux at a specific location.

The boiler furnace is divided into the number of fields to be instrumented by the 'clean' and 'not-clean' radiation heat flux sensors.

Validation and acquisition elements

The monitoring system of the expert system for fouling assessment includes the following elements besides the sensors: validation element, acquisition element and trend analyser (Fig. 8).

The validation element is designed to ensure that only the readings which are in agreement with

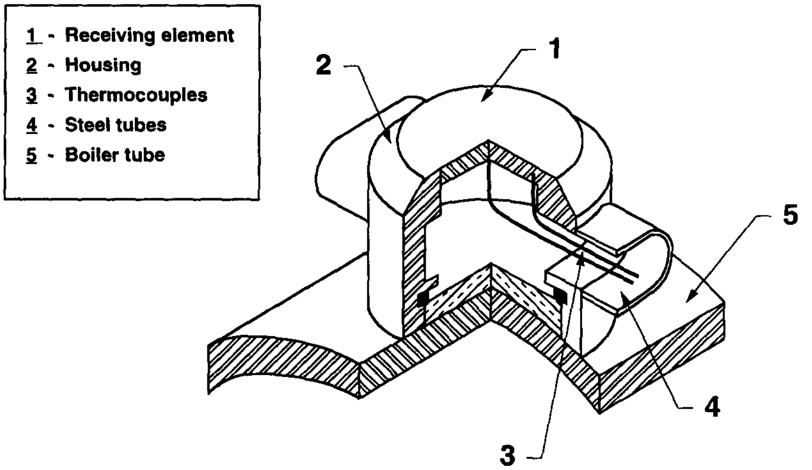

Fig. 6. Sensor for 'not-clean' heat flux measurement.

the validation criteria are taken for further consideration. There are two validation criteria: the variable continuity and the mutual relation among the variables. The continuity criterion takes care of the eventual discontinuity of the signal, in order to prevent any other cause for variable change except for the effect of the physico-chemical parameters in the furnace. The mutual relation criterion prevents unexpected changes of the signal which are not in compliance with neighbouring field sensor signals.

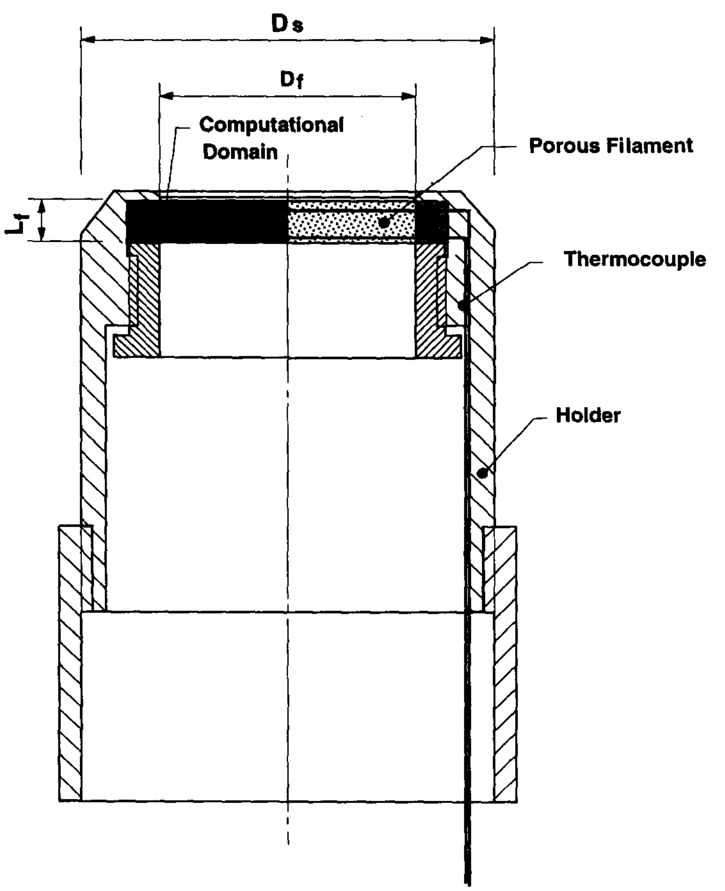

Fig. 7. Sensor for 'clean' heat flux measurement.

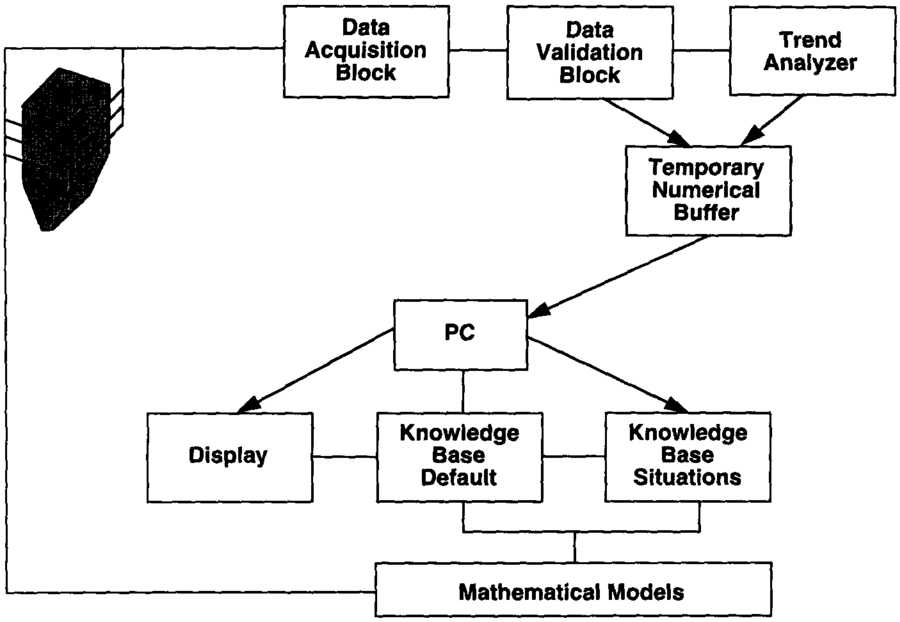

Fig. 8. Monitoring system.

One of the important elements of the monitoring system is the trend analyser. It is designed to determine the signal gradient in different time-scales. Every 10 successive signal readings are averaged, forming decade average variables with gradients in time-scale reflecting the rate of change for the respective time intervals. It is designed that the decades correspond to a maximum of a 2-month averaging interval.

The acquisition elements of the monitoring system comprise the signal conditioning, including analogue to digital conversion with logging procedure for the formation of the set of diagnostic variable readings corresponding to the instant values at a specified time interval. Diagnostic variable readings for each time-schedule are stored in the buffer memory as a set of diagnostic values corresponding to the actual situation in the boiler furnace.

The final element of the monitoring system for the expert system for fouling assessment is the computer, with the respective memory for the knowledge base, and software for the logical retrieval and respective reasoning for the diagnostic process. It is aimed to be PC-based hardware.

CONCLUSIONS

The expert system for fouling assessment based on the fouling, fouling rate and efficiency criteria has proved to be a feasible tool for the operational control and mitigation of the deposit formation on boiler heat transfer surfaces. The diagnostic variables and their domain defined for the design of the knowledge base are adequately selected and conform to the required sensitivity to be used in the description of the specific situations pertinent to the different fouling deposit situations in the boiler furnace.

The knowledge base structure based on the object-oriented approach has been proved to correspond to the reasoning strategy aimed for the fast retrieval of the situation leading to the final goal of the searching diagnostic procedure. The rule-based reasoning technique has been shown to be appropriately selected.

The monitoring system composed of the newly developed sensors with respective elements for conditioning, acquisition and validation of the signal is used in the design of the expert system for the fouling assessment concept. In further development of the expert system this part of the system will require corresponding improvement, in order to meet industrial requirements.

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