Thermal Engineering, Vol. 43, No. 6, 1996, pp. 514–523.

An Expert System for Controlling Processes in a Power-Station Boiler Furnace

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Abstract—An approach for developing an expert system to control processes in a power-station boiler furnace is considered. This expert system has a modular structure. Each module is assigned its objective function; the set of objects to be controlled is identified, the parameters to be diagnosed are chosen, and the required knowledge base is developed.

Presently, progress in the power sector is focused on the development of large power stations, which make it possible to combine the efficiency of electricity generation and possibilities for better control of the environment. However, the advantages of large power-station boilers can be realized only if their actual characteristics meet the conditions of reliable and efficient operation of the system [1].

Recent advancements in electronics and information technology offer new possibilities for using them in energy-engineering systems [2, 3]. In particular, advancements in computer technology have enabled us to increase our capability to analyze system behavior [4]. Progress in numerical modeling has made time and space analysis of the equipment possible. Such modeling, in particular, can be used for boiler furnace operational analysis and on-line correction.

AN EXPERT SYSTEM TO CONTROL PROCESSES IN THE BOILER FURNACE

In the early 1980s, the need for developing a diagnostic system to monitor processes in the boiler furnace was recognized [5]. Almost at the same time, progress in boiler furnace modeling was achieved by way of predicting the internal design parameters of the boiler furnace [6, 7].

The design of the boiler expert system is based on identification of the objectives and domains of the modules, selection of the diagnostics parameters, and design of the knowledge-base structure [8, 9]. In this respect, each module is considered a separate entity with its own function. The definition of the objectives for a function of a certain module takes into account the necessity of ensuring effective operation of the expert system, as a whole, in determining violations of given working conditions or malfunctioning and degradation of the power unit.

(1) The Objective Functions of the Expert System

We shall distinguish the following specific objective functions of the expert system. It is to

estimate boiler efficiency in order to determine short- and long-term trends in the degradation of boiler furnace conditions; here, particular attention is paid to determining the corrective actions required to recover the efficiency of boiler performance;

identify deviations of the operating parameters that result from degradation of individual elements of the boiler; particular attention is devoted here to identification of situations that lead to tube rupture in the boiler furnace;

identify the internal parameters of the boiler furnace that indicate the beginning of fouling on the heat-transfer surfaces and that characterize the rate of fouling.

The data on boiler surface degradation is used for extending expert's advice needed for efficient operation of the furnace.

(2) The Architecture of the Expert System

Figure 1 shows the boiler expert system that was developed for controlling furnace processes. It consists of three modules, namely, an efficiency assessment module, a furnace-waterwall failure detection module, and a fouling assessment module. The modular structure enhances flexibility of design and adaptability to eventual build-up in further development. Such a design also provides efficient utilization of the computer hardware and an adequate speed of execution to ensure meaningful support for the plant operator. The design of the individual modules is adapted for personal computer hardware and commercially available software.

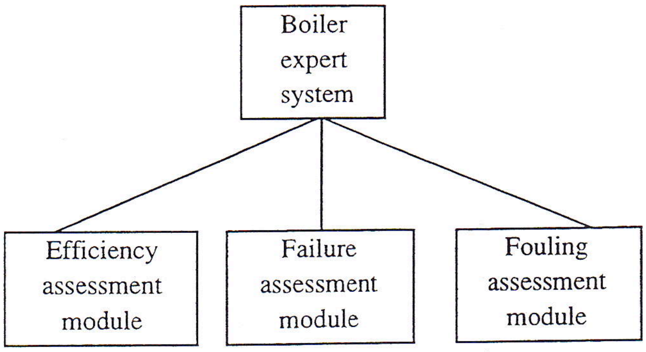

Fig. 1. The structure of an expert system for controlling boiler-furnace processes.

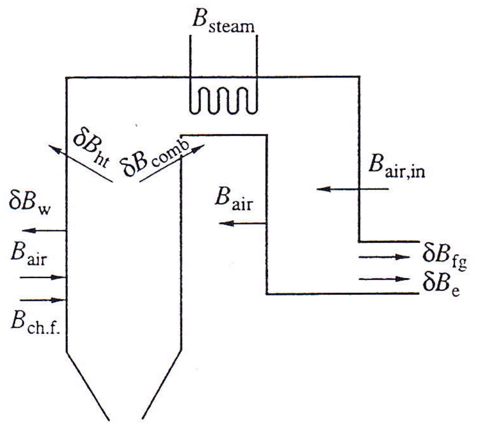

Fig. 2. The exergy balance of the boiler.

THE EFFICIENCY ASSESSMENT MODULE

The efficiency assessment module is designed as an on-line system with the diagnostic parameters and their domain chosen to ensure the exergy balance of the boiler [10].

(1) Selection of Variables

Figure 2 shows the exergy balance of the boiler. This balance is written as follows:

$$B_{\text{ch.f.}} + B_{\text{air,in}} = B_{\text{steam}} + B_{\text{air}} - B_{\text{air}} + \delta B_{\text{comb}} + \delta B_{\text{ht}} + \delta B_{\text{w}} + \delta B_{\text{fg}} + \delta B_{\text{e}}, \tag{1}$$

where $B_{\text{ch.f.}}$, B_{air}, and B_{steam} are the exergies of the fuel, the air, and the steam, respectively; δB_{comb} and δB_{ht} are the degradation in exergy due combustion and heat transfer processes, respectively; and δB_{w}, δB_{fg}, and δB_{e} are the exergy losses due to wall heat transfer, flue gas heat and heat losses to the environment, respectively. Dividing this equation by $B_{\text{ch.f.}}$ and neglecting $B_{\text{air,in}}$, we obtain

$$1 = \frac{B_{\text{steam}}}{B_{\text{ch.f.}}} + \frac{\delta B_{\text{comb}} + \delta B_{\text{ht}}}{B_{\text{ch.f.}}} + \frac{\delta B_{\text{w}} + \delta B_{\text{fg}} + \delta B_{\text{e}}}{B_{\text{ch.f.}}}. \tag{2}$$

Denoting the second-law efficiency by $\varepsilon = B_{\text{steam}}/B_{\text{ch.f.}}$, the exergy degradation by $\Delta\varepsilon_{\text{deg}} = (\delta B_{\text{comb}} + \delta B_{\text{ht}})/B_{\text{ch.f.}}$, and the exergy losses by $\Delta\varepsilon_{\text{loss}} = (\delta B_{\text{w}} + \delta B_{\text{fg}} + \delta B_{\text{e}})/B_{\text{ch.f.}}$, we obtain

$$1 = \varepsilon + \Delta\varepsilon_{\text{deg}} + \Delta\varepsilon_{\text{loss}}. \tag{3}$$

The second-law efficiency of the boiler is defined as the ratio of the increase in the exergy of the water passing from the liquid to the steam state to the exergy input due to fuel combustion [11]:

$$\varepsilon = \frac{B_{\text{steam}}}{B_{\text{ch.f.}}} = \frac{D(i_{\text{ss}} - i_{\text{in}})}{FLCV\beta}\frac{T_m - T_0}{T_m} = \frac{D[c_{p\text{w}}(T_{\text{s}} - T_{\text{in}}) + h_{\text{ev}} + c_{p\text{ss}}(T_{\text{ss}} - T_{\text{s}})]}{FLCV\beta}\frac{T_m - T_0}{T_m}, \tag{4}$$

where T_{ss}, T_{s}, T_{in}, T_0, and T_m are the superheated steam, the saturation, the inlet, the environment, and the mean energy receiving temperatures of the working fluid, respectively, with T_m being equal to

$$T_m = \left[c_{p\text{ss}}(T_{\text{ss}} - T_{\text{s}})\frac{T_{\text{ss}} + T_s}{2} + h_{\text{ev}}T_{\text{s}} + c_{p\text{w}}(T_{\text{s}} - T_{\text{in}})\frac{T_{\text{s}} + T_{\text{in}}}{2}\right] / [c_{p\text{ss}}(T_{\text{ss}} - T_{\text{s}}) + h_{\text{ev}} + c_{p\text{w}}(T_{\text{s}} - T_{\text{in}})].$$

Here, i_{ss} and i_{in} are the corresponding values of the enthalpy; c_p is the specific heat; LCV is the low heating value of the fuel; β is the ratio of the standard chemical exergy to the LCV.

In order to calculate ε, the following parameters have to be known: the steam output D, T_{in}, T_{ss}, the saturation pressure p, and the fuel flow rate F, with $c_{p\text{w}}$, $c_{p\text{ss}}$, and LCV being assumed constant within the range of the parameters considered. These are the diagnostic variables for second-law efficiency.

Exergy degradation consists of two parts: exergy degradation due to the combustion process and exergy degradation due to heat transfer in the boiler. If we assume that the combustion contribution to exergy degradation is small compared to that of heat transfer, it follows that

$$\Delta\varepsilon_{\text{deg}} = \frac{A_s T_0}{LCV}\left[\frac{T_{\text{g}} - T_{\text{s}}}{\frac{1}{\alpha_1} + \frac{\delta_1}{k_1} + \frac{\delta_0}{k_0} + \frac{\delta_2}{k_2} + \frac{1}{\alpha_2}}\right]\left(\frac{1}{T_{\text{s}}} - \frac{1}{T_{\text{g}}}\right), \tag{5}$$

where α_1 and α_2 are the heat transfer coefficients from the gas and the steam-water sides; k_0, k_1, and k_2 are the thermal conductivity coefficients of the wall material, and the outer and the inner depositions; δ_0, δ_1, and δ_2 are the wall thickness and the thicknesses of the corresponding depositions; and A_s is the heat-transfer surface area.

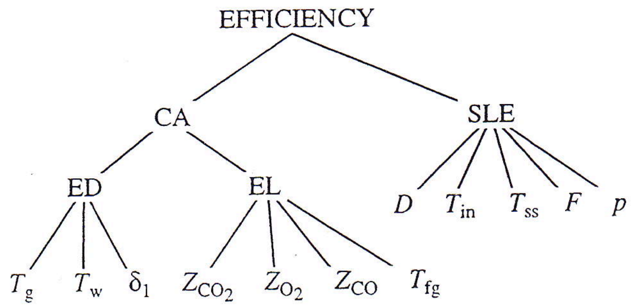

Fig. 3. The EFFICIENCY knowledge base structure.

If we assume that $\alpha_2 \gg \alpha_1 = \text{const}$ and δ_0, δ_2, k_1, k_2, and k_0 are constant, as well, then $\Delta\varepsilon_{deg}$ will depend on δ_1 and T_g. This leads to the conclusion that the diagnostics variables for exergy degradation due to heat transfer are T_g, T_s, and δ_1, and they should be diagnosed.

Exergy losses due to heat transfer from the outside surface of the boiler to the environment and exergy losses by the flue gases are united in the total exergy losses term. The exergy losses due to heat transfer from the outside surface is small and will not be considered by us. The chemical exergy losses of flue gases can be written as follows:

$$\delta B_{ch} = F\left\{RT_0\left[\ln\left(\frac{z_{CO_2}}{\overset{0}{z}_{CO_2}}\right) + 2\ln\left(\frac{z_V}{\overset{0}{z}_V}\right) + 10.53\ln\left(\frac{z_{N_2}}{\overset{0}{z}_{N_2}}\right) + 0.8\ln\left(\frac{z_{O_2}}{\overset{0}{z}_{O_2}}\right)\right] + \Delta G + RT_0 \ln z_{CO}\right\}, \quad (6)$$

where z_i and $\overset{0}{z}_i$ are the molar fractions of the corresponding gas and the water vapor in the flue gases and in the environment, respectively; $\Delta G = (\bar{g}_C + \bar{g}_{O_2} + \bar{g}_{CO_2})(T_0, p_0)$, where $\bar{g}_C$, $\bar{g}_{O_2}$, and $\bar{g}_{CO_2}$, are the Gibbs' free energy of formation for carbon, oxygen, and carbon dioxide at T_0 and p_0, respectively.

The thermal exergy losses with the flue gases are

$$\begin{aligned}\delta B_{fg} = W_g\{&[h(T) - h(T_0) - T_0\langle s(T) - s(T_0)\rangle]_{CO_2} \\ &+ 2[h(T) - h(T_0) - T_0\langle s(T) - s(T_0)\rangle]_V \\ &+ 10.53[h(T) - h(T_0) - T_0\langle s(T) - s(T_0)\rangle]_{N_2} \\ &+ 0.8[h(T) - h(T_0) - T_0\langle s(T) - s(T_0)\rangle]_{O_2}\},\end{aligned} \quad (7)$$

where h and s are the enthalpy and the entropy of the corresponding components of the flue gases, and W_g is the flow rate of the flue gases.

In this analysis, it is assumed that only z_{CO_2}, z_{O_2}, z_V, c_{CO}, and $T = T_{out}$ are the variables that bring about changes in the exergy losses in the boiler. Therefore, they are selected as the diagnostic variables for the exergy losses.

Thus, for the boiler efficiency assessment module, the domain of the objects for control will be the above diagnostics variables, which are necessary for calculating exergy efficiency, exergy degradation, and losses. Corresponding correlations for calculating these quantities are included in the knowledge base. The latter ensures that proper assessment of the actual conditions in the boiler furnace will be accomplished by the module. The knowledge base structure is made up of blocks on the second-law efficiency, exergy degradation, and exergy losses. The diagnostics variables are the attributes of these blocks.

The actual value of one attribute or another should be recognized by the expert system as an indication of the inception of a certain situation in the boiler furnace. The knowledge base includes a set of rules that are necessary for such a conclusion. Individual situations are recognized within the domain of variants specified by the exergy efficiency assessment module.

(2) The Structure of the Knowledge Base

The knowledge base is organized as an object-oriented structure. The object of this structure is EFFICIENCY (EF). The EF object is composed of two subsystems: a second-law efficiency (SLE) subsystem and a CA subsystem. The latter recognizes the reasons for changes in the SLE. The CA subsystem, in turn, consists of two subsystems: the degradation of efficiency subsystem ED and the loss of efficiency subsystem EL. The SLE is defined by the attributes: D, T_{in}, T_{ss}, p, and F. The ED has the following attributes: the temperature of the wall T_w and also T_s and δ_1, while the EL has the following attributes: the concentrations of CO_2, O_2, and CO and the temperature of the outlet flue gases T_{out}.

In the terminology that is common for knowledge-base engineering, the EFFICIENCY object can be described in LISP language as follows:

$$\begin{gathered}\text{EF}(\text{SLE}(D(0 + \Delta - \Delta)T_{in}(0 + \theta_{in} - \theta_{in})T_{ss} \\ \times(0 + \theta_{ss} - \theta_{ss})p(0 + \pi - \pi)F(0 + \varphi - \varphi)\text{CA} \\ \times(\text{ED}(T_w + \theta_2 - \theta_2)T_s(0 + \theta_s - \theta_s)\delta_1 \\ \times(0 + \Delta\delta_1 - \Delta\delta_1)\text{EL}(z_{CO_2}(0 - \xi_{CO_2} - \xi_{CO_2})z_{O_2} \\ \times(0 + \xi_{O_2} - \xi_{O_2})z_{CO}(0 + \xi_{CO} - \xi_{CO})T_{out} \\ \times(0 + \theta_{out} - \theta_{out})))).\end{gathered}$$

Figure 3 shows a schematic representation of the EFFICIENCY object structure.

When developing the knowledge base, several characteristic situations of the EF object can be specified and thereby should be recognized in the diagnostics procedure. These situations correspond to different combinations of values that are taken on by the diagnostic parameters. The specified situations are retrieved in the course of diagnostics data treatment by these combinations.

The second part of the knowledge base is composed of a set of rules, which are organized to recognize an expert assessment of the specific causes of boiler malfunctioning. Specifically, the following situations are taken into consideration: fuel quality, air humidity, excess air, and fouling of the heat transfer surfaces.

These rules are designed in if/then form and organized generically in order to comply with multiple situation recognition.

The following examples are given to demonstrate the use of the rules in the knowledge base.

Example 1. Fuel quality changes. Fuel quality changes are often the cause of a decrease in the efficiency of the power plant. In this respect, on-time diagnostics of fuel quality changes can be employed in planning appropriate plant rescheduling operations. A decrease in the superheat temperature is usually an indication of a change in fuel quality. This means that as a result of the decrease in the superheat temperature, the exergy efficiency of the boiler will fall; the exergy losses will increase as a result of an increase in the carbon dioxide concentration.

The corresponding situation can be recognized diagnostically in accordance with the following statement:

$$\text{If } (\mathrm{EF}(\mathrm{SLE}(D(0)T_{\mathrm{in}}(0)T_{\mathrm{ss}}(-\theta_{\mathrm{ss}})p(0)F(+\varphi))$$
$$\mathrm{CA}(\mathrm{ED}(T_g(0)T_s(0)\delta_1(0))$$
$$\mathrm{EL}(z_{\mathrm{CO}}(0)z_{\mathrm{CO_2}}(\xi_{\mathrm{CO_2}})z_{\mathrm{O_2}}(0)T_{\mathrm{out}}(0)))),$$

then a decrease in the fuel quality has taken place.

Example 2. The formation of fouling deposits. Fouling of heat transfer surfaces is a common problem in present-day boilers. The formation of deposits is usually accompanied by a decrease in the superheat steam temperature, which leads to a decrease in the exergy efficiency. The increase in exergy losses is the result of a higher outlet temperature of the flue gases. This could be diagnostically recognized by the following statement:

$$\text{If } (\mathrm{EF}(\mathrm{SLE}(D(0)T_{\mathrm{in}}(0)T_{\mathrm{ss}}(0)p(0)F(+\varphi))$$
$$\mathrm{CA}(\mathrm{ED}(T_g(+\theta_g)T_s(0)\delta_1(0))$$
$$\mathrm{EL}(z_{\mathrm{CO}}(0)z_{\mathrm{CO_2}}(0)z_{\mathrm{O_2}}(0)T_{\mathrm{out}}(+\theta_{\mathrm{out}})))),$$

then the formation of fouling deposits takes place.

Other situations, in particular, changes in excess air, fuel moisture, etc., can be described similarly.

THE FAILURE ASSESSMENT MODULE

The failure assessment module serves to assist in diagnosing failures of boiler furnace elements. Among the most frequent failures encountered are tube leakages leading to ruptures. In the design of this module, most attention is focused on early detection of the boiler tube leakage in order to present the operator at the power station with information that can be used in making changes in the operation schedule in due time and for maintenance of the boiler. It serves to detect small leaks at an early stage of the development of a rupture. Particular attention is devoted to investigating the effect that the steam flow rate has on the radiation heat flux distribution at the boiler-furnace surface [12, 13]. It was shown that the furnace surface heat flux is a sensitive internal parameter affected by the appearance of water vapor at different locations in the boiler-furnace volume. A typical heat flux pattern for a tube rupture is shown in Fig. 4 [14].

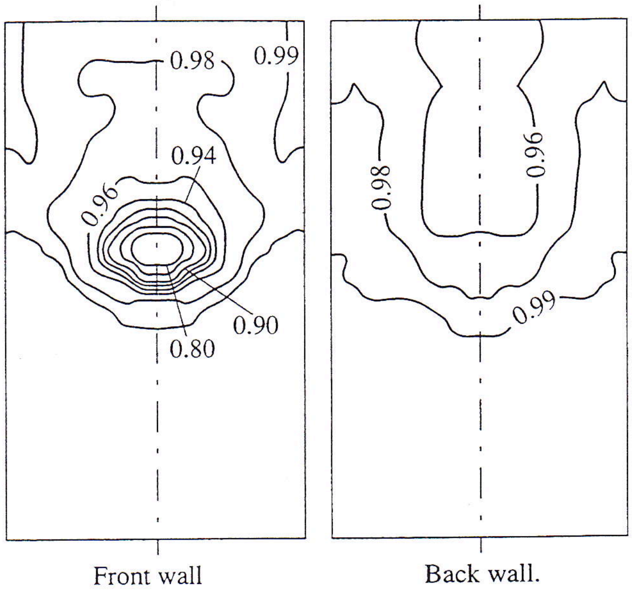

Fig. 4. The radiant heat-flux distribution with high-intensity leakage at the front wall.

(1) Selection of the Variables

The knowledge base of the leakage module uses relative values of the incident radiation heat flux in the boiler. The relative values of the radiation heat flux are the ratio of the actual values to the standard value, which is for the radiation heat flux without any leakage:

$$r^s_{i,j,m} = q^s_{i,j,\mathrm{leak}} / q^s_{i,j,\mathrm{stand}}, \quad (8)$$

where $q^s_{i,j,\mathrm{leak}}$ and $q^s_{i,j,\mathrm{stand}}$ are the incident radiation heat flux at coordinates i and j on the furnace side s with a boiler tube leakage of size m and without any leakage, respectively. Each case of leakage forms its specific distribution $r^s_{i,j,m}$.

Since in normal boiler operation $r(x, y, t)$ is a continuous function of space and time, for this analysis it will

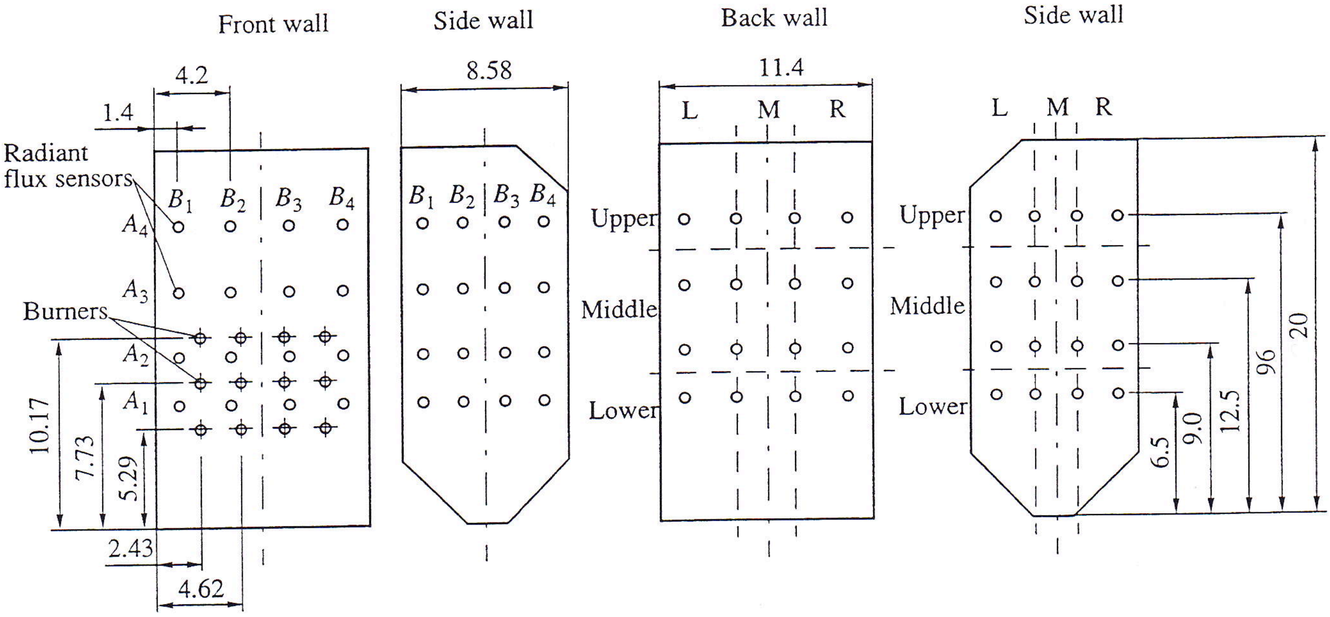

Fig. 5. The location of the radiant heat-flux sensors in the boiler furnace.

be assumed that r takes on discrete values at specific points that are not time dependent. It is assumed that $r^{s}_{i,j,m}$ covers only m values of the leakage rate; s stands for the walls of the boiler furnace, namely, the front, back, side 1 and side 2 walls. The position of the individual sensors is defined by the number of its row and column (Fig. 5).

(2) The Knowledge Base Structure

The pattern of the distribution $r^{s}_{i,j,m}$ is defined as the object of the knowledge base structure with the name LEAKAGE. In this respect, LEAKAGE has the following subclasses: stream and sensor. The stream subclass specifies quantitatively the size (intensity) of the leakage and its location determined by the level and orientation (see Fig. 5). The sensor subclass defines the intensity of heat flux and the location of the sensor, that is, the wall, the row, and the column. Each wall has five rows and five columns of sensors.

In the terminology common for knowledge engineering, the object LEAKAGE can be described in LISP language as follows:

LEAKAGE (stream (size (small, medium, large)) place (level (upper, central, lower) orientation (left, middle, right)) sensor (intensity (n_1, n_2, n_3, n_4) location (wall (front, back, side 1, side 2)), position (row (A_1, A_2, A_3, A_4, A_5) column (B_1,B_2, B_3, B_4, B_5)))).

LEAKAGE is an object with a set of instance variables: size, level, orientation, intensity, wall, row and column. Figure 6 shows the structure of the object LEAKAGE. We see that all possible combinations of the instances of the object can be described by this definition of the object LEAKAGE. In this respect, it can be assumed that any leakage instance in the furnace can be represented by a certain combination of the parameters of the object. However, if only a limited number of leakage situations are assessed, there will be subclasses of the leakage, which should be considered as being specific (that is, not accounted for in the knowledge base). However, the operator should receive information concerning all situations (subclasses). The forecast subclasses will define the functionality of the object (the boiler) itself and will characterize the leakage and its development. They are defined in accordance with the specific size and place of the leakage. Thus, when developing the knowledge base, a certain number of leakage situations will be taken to be characteristic situations, which are referred to as situations that should be assessed. For each individual boiler, the situations to be taken into consideration shall be determined from numerical simulation of the boiler, which results in proper distributions of the radiation heat flux.

In order to illustrate how the knowledge base is formed, we will consider the case of a large leak and define the object LEAKAGE accordingly. It corresponds to a large leak of central orientation and upper level on the front wall and was shown above in Fig. 4. We see that the large flow rate of the liquid being discharged can be easily recognized from the radiant heat flux distribution. The corresponding description of the object LEAKAGE is as follows:

LEAKAGE (stream (size (large) place (level (central) orientation (middle))) sensor (intensity (n_1, n_2, n_3, n_4) location (wall (front) position (row (A_1, A_2, A_3) (column (B_2, B_3, B_4)))).

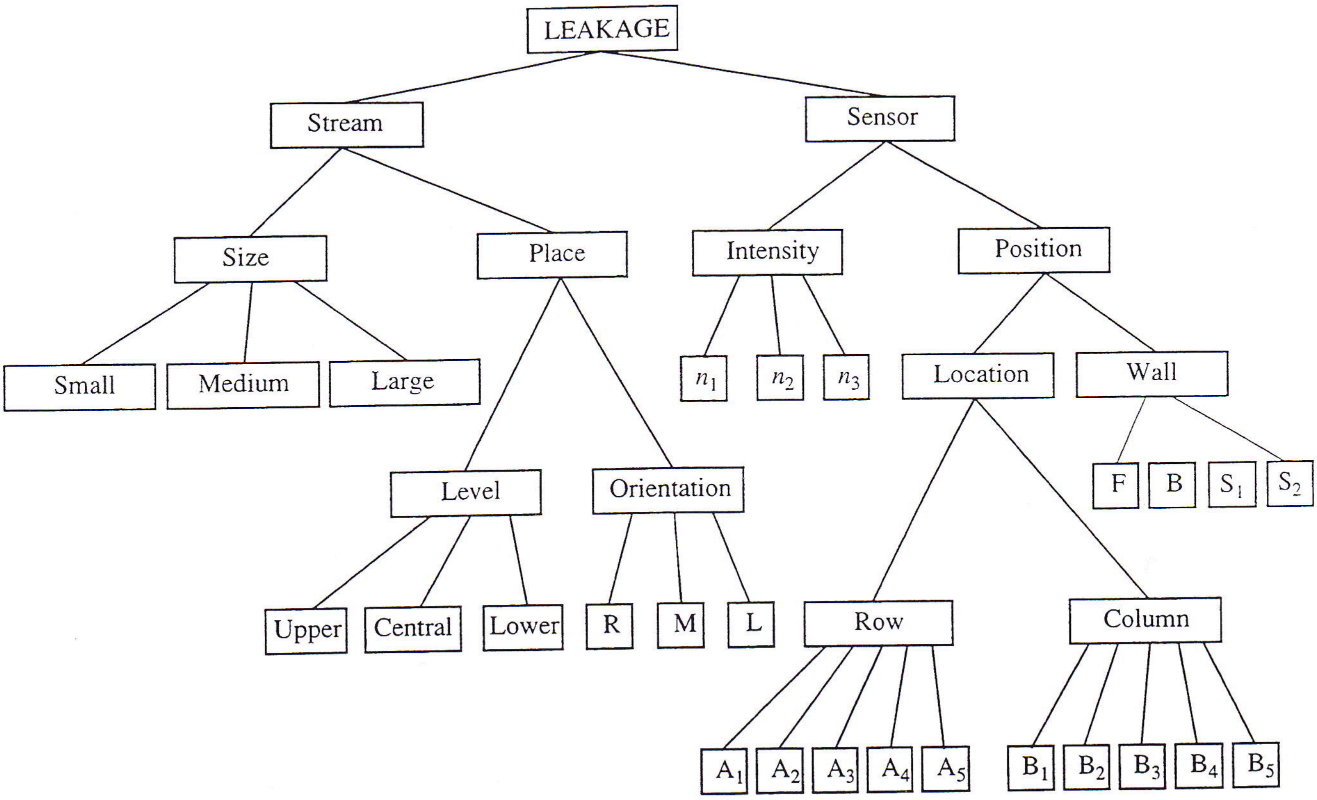

Fig. 6. The LEAKAGE knowledge base structure.

THE FOULING ASSESSMENT MODULE

The fouling process in the boiler furnace is manifested by the formation of deposits on the walls. The thermal resistance of a layer of deposits is proportional to its thickness. In order to find the thickness of the deposits, the heat flow rate through the layer will have to be determined. In this respect, the diagnostic parameter for assessing fouling is the ratio of the heat flux on a clean heat transfer surface to that on a contaminated one. According to [15]

$$\delta \approx Cq_{\text{clean}}/q_{\text{foul}}, \quad (9)$$

where δ is the thickness of the deposit, q_{clean} is the radiation heat flux at the boiler surface without deposits, and q_{foul} is the radiation heat flux at the boiler surface with deposits.

(1) Selection of the Variables

The thickness of the deposits is a position-dependent parameter, that is, it is a function of their location in the boiler furnace. Thus, the diagnostics variables are space-dependent:

$$\delta_{ij} \approx (q_{\text{clean}}/q_{\text{foul}})_{ij}. \quad (10)$$

At a given point, the degree of fouling is described by two parameters (attributes): the thickness of fouling

$$\delta_{ij} \approx q_{\text{clean}ij}/q_{\text{foul}ij} \quad (11)$$

and the rate of fouling

$$K_{ij} \approx \frac{1}{\delta_{ij}}\frac{d\delta_{ij}}{dt}. \quad (12)$$

Moreover, the furnace efficiency is employed as a subclass of the furnace-condition description

$$\psi^s = \sum_{ij}^{s} q_{ij}^s/Q. \quad (13)$$

The degree of fouling has the following levels: no fouling, light fouling, heavy fouling, and critical fouling. The fouling rate can be classified as slow fouling, fast fouling, and very fast fouling. The efficiency indicates the start of recovery of the previous situation. Therefore, in the design of this module, special attention was devoted to assessing the effect of fouling on the efficiency of the boiler furnace.

(2) The Structure of the Knowledge Base

To describe the object under consideration, that is, the degree of fouling, the expert system uses current, as well as expected values of the attributes (the specific characteristics). The expected values are those that will

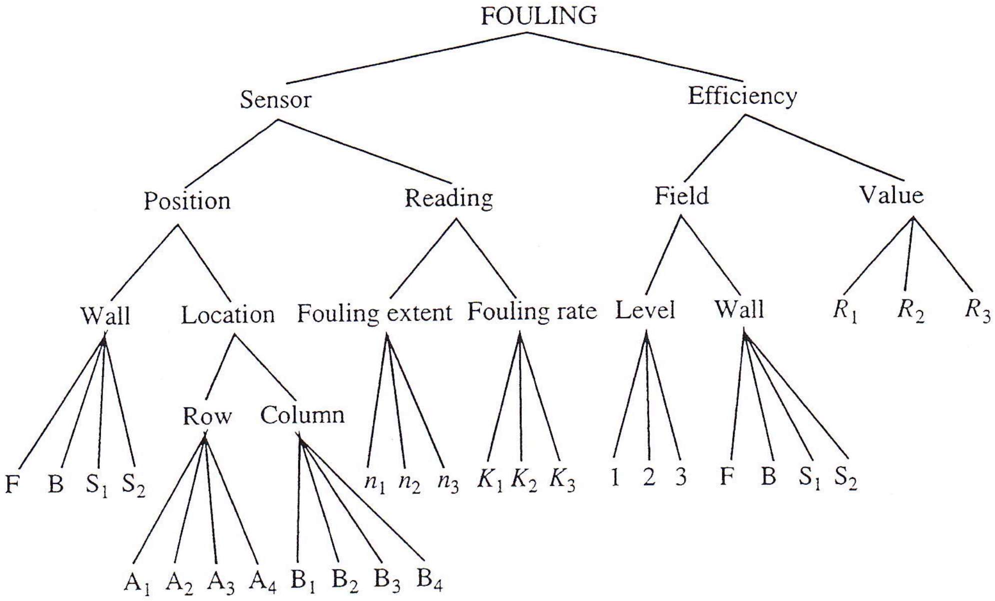

Fig. 7. The FOULING knowledge base structure.

be obtained as a result of recovery. Thus, FOULING, as an object of description, appears as a certain abstraction comprised of parameters, which can describe potential situations. These situations are the ones that should be assessed by the expert system. FOULING is composed of two subsystems: sensors and efficiency (Fig. 7). The subsystem of sensors includes a description of their location and their readings. The first subsystem gives their location, whereas the second one gives the degree and the rate of growth of fouling. The efficiency subsystem describes the geometry of the fouling field and gives local furnace efficiencies, that is, efficiencies for a certain strip of furnace surface, for each of the four walls of the furnace, and for the furnace as a whole. Following the described structure of the FOULING object, we can design a knowledge base, which allows the expert system to assess several expected situations, bearing in mind the necessity of recovery of the required condition of the furnace surfaces. In LISP language, the FOULING object is defined as follows:

FOULING (sensor (position (wall (front, back, side 1, side 2) location (row (A_1, A_2, A_3, A_4)) column (B_1, B_2, B_3, B_4)) reading (n_1, n_2, n_3, n_4) rate (K_1, K_2, K_3)) efficiency (field (level (1, 2, 3) wall (front, back, side 1, side 2)) value (ψ_1, ψ_2, ψ_3, ψ_4))).

Organization of the knowledge base uses descriptions of different specific situations of deposit formations on the various segments of the furnace heat-transfer surface. In order to demonstrate the sensitivity of expert-system diagnostics, two cases will be considered below.

Case 1. Deposit formation on the entire surface. This case is shown in Fig. 8a–8c. Data is given for different values of the thermal resistance (thickness) of the deposits: δ/K = 0.001, 0.003, and 0.006 (m^2 K)/W, respectively. The change in absolute values and in the distribution of the heat flux on the furnace wall is clearly seen.

Case 2. Deposit formation on the upper level. The formation of deposits on the upper level is typical for boilers. Therefore, case 2 is devoted to the situation in the boiler furnace, in which deposits are formed in the upper part of the furnace with δ/K = 0.006, and in the lower part with δ/K = 0.001 (m^2 K)/W. We see that a change in the location of the deposits can be recognized as an individual diagnostics situation. The corresponding heat flux distribution is shown in Fig. 8d.

THE MONITORING SYSTEM

The boiler expert system is designed to be an on-line system based on continuous monitoring of the diagnostics variables (Fig. 9). At the same time, it is desirable to develop a generic structure, which will serve as the main frame for accommodating different modules of the expert system. The monitoring system includes the following elements:

(1) The Sensor Unit. The sensor elements are subdivided into two groups: operational sensors and special sensors. Operational sensors are standard instruments used in the boiler control system. The special group consists of sensors that are specially designed to monitor the diagnostic parameters (attributes) required for assessment of the processes, which are related to the specific objects of the modules. In the group of operational sensors, we find sensors for the boiler pressure, the water inlet temperature, the water mass flow rate, the fuel mass flow rate, the steam superheat tempera-

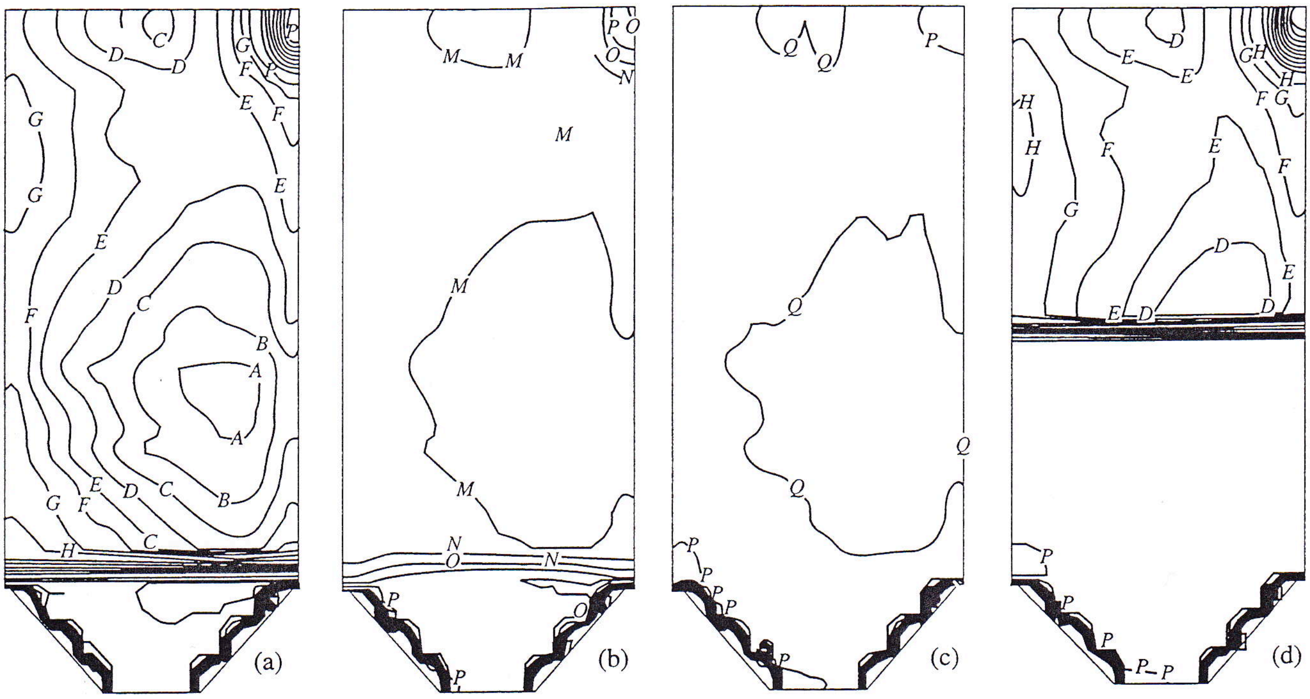

Fig. 8. The heat flux distribution with deposits on the furnace walls. (a–c) deposits on the entire furnace surface; (d) large deposits on the upper part of the furnace; δ/K, (m^2 K)/W: (a, d) 0.006; (b) 0.003; (c) 0.001. Radiant heat flux isolines, kW/m^2: $A = 2.15$; $B = 2.10$; $C = 2.05$; $D = 2.00$; $E = 1.95$; $F = 1.90$; $G = 1.85$; $H = 1.80$; $I = 1.70$; $J = 1.65$; $K = 1.60$; $L = 1.55$; $M = 1.50$; $N = 1.45$; $O = 1.40$; $P = 1.35$; $Q = 1.30$; $R = 1.25$; $S = 1.20$; $T = 1.15$; $U = 1.10$.

ture, the stack gas temperature, and the flue gas temperature at the furnace exit. It is assumed that the accuracy of these sensors is within the limits ensured by the validation and signal conditioning elements of the monitoring system.

Among the sensors in the special group, there are two types of gages for radiation heat flux measurements; namely, the clean heat-flux sensor and unclean heat-flux sensor. The clean heat-flux sensor is based on blowing off the boundary layer [16, 17]. Figure 10a shows the design of such a sensor. It is assumed that the inlet–outlet temperature difference of gas flow through the porous insert is proportional to the radiation heat flux at the insert surface. By proper sensor calibration for a constant gas flow rate through the porous insert, the correlation between the radiation heat flux and the temperature difference between the inlet and outlet of the porous insert is determined.

Figure 10b shows the unclean type heat-flux sensor used for monitoring the local radiation heat flux under conditions of fouling. It is a development of the Garner type heat-flux meter. Such sensors are positioned at locations that are specified by the knowledge base of the boiler expert system [18, 19].

(2) The Validation and Acquisition Units. The monitoring system for the boiler expert system has validation and acquisition units. Validation consists of two stages. In the first stage, the measuring instruments are validated using a comparison and checking technique for the sensor readings. This makes it possible to detect any malfunction of the sensor and prevents incorrect diagnostic variables from being introduced in the diagnostic assessment procedure. The second stage of the validation process applies a causal relation technique

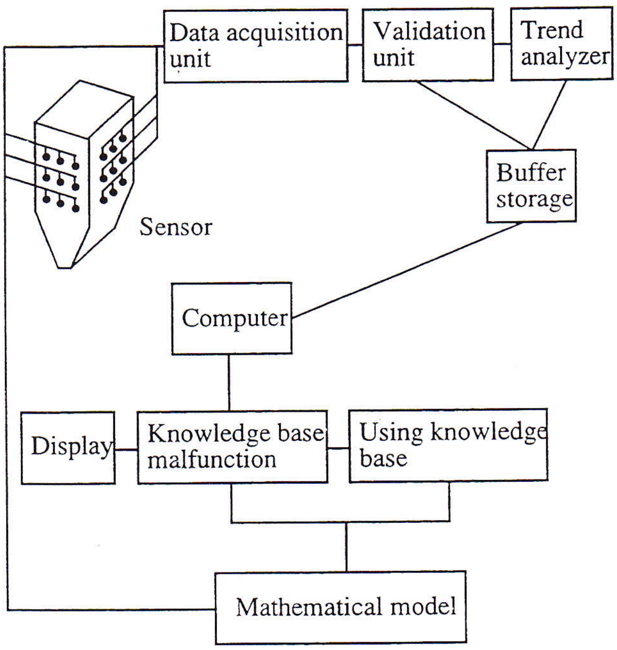

Fig. 9. The monitoring system.

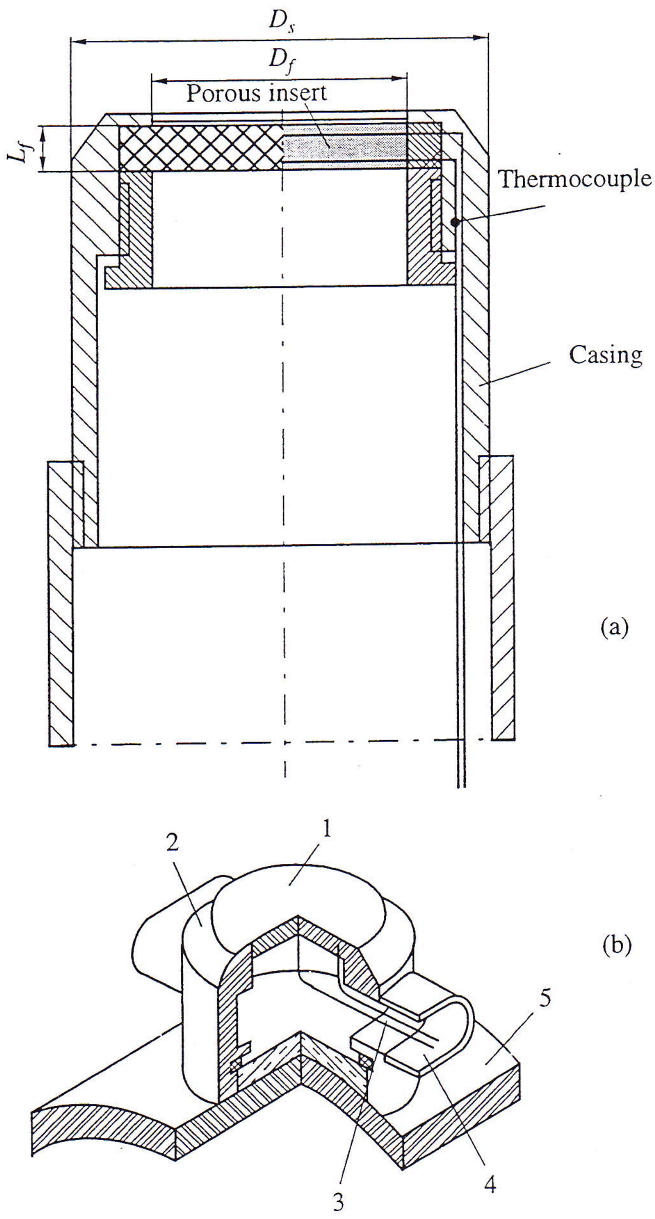

Fig. 10. Radiant heat flux sensors. (a) clean surface; (b) unclean surface; (1) receiving element; (2) casing; (3) thermocouples; (4) steel tubes; (5) boiler tube.

for comparing sensor readings in order to exclude readings that are not consistent with the others.

The acquisition system incorporates an A/D converter, a signal calibration device, a recording system, and logic control elements.

(3) The Trend Analyzer. The parameters to be used in the diagnostics process of the on-line expert system are read with a certain time interval. Since the characteristic time scales for the various processes are different, a trend analyzer is needed. The trend analyzer is an item of software used for correlating the time rate of reading the individual variables with respect to different time scales [20].

CONCLUSION

(1) The boiler expert system presented is an on-line expert system designed for diagnosing and assessment of the condition of a boiler furnace. It consists of three modules: an efficiency assessment module, a failure assessment module, and a fouling assessment module.

(2) The monitoring system of the boiler expert system incorporates standard control instruments and specially developed sensors for measuring radiation heat flux.

(3) Further development is needed in order to come to the demonstration stage of the boiler expert system. Emphasis has to be focused, in particular, on large-scale experiments for gaining practical operating experience in a real power station.

REFERENCES

1. Styrikovich, M.A., Prospects for Utilization of Organic Fuel with Regard to the Ecological and Social Factor, in *Fuelling in the 21st Century*, Washington: Hem. Publ. Corp., 1986.
2. Divakaruni, S.M., Koklik, G., Sopocy, D.M., and Frigner, D., Review of Fossil Plant R&D Project Prioritization for AI Application, *Expert System Application for Electric Power Industry*, Washington: Hem. Publ. Corp., 1991.
3. Armor, A.F., Expert System: An Opportunity for Improved Power Plant Performance, *Expert System Application in Power Plant*, Boston, 1987.
4. Valverde, L.J., Stephan, A., Gohl, M., *et al.*, Fossil Power Plant Application of Expert System: An EPRI Perspective, *Expert System Application for Electric Power Industry*, Washington: Hem. Publ. Corp., 1991.
5. Afgan, N., Pavlovich, P., Iovanovich, Lj., and Jovic, L., *Steady and Unsteady Radiant Heat Flux Measurement on Screen Tubes of Power Plant Boiler Heat Transfer in Flame*, Washington: Hem. Publ. Corp., 1973.
6. Coelho, P.C. and Carvalho, M.G., Evaluation of Three-Dimensional Mathematical Model of a Power Station Boiler, *ASME J. of Gas Turbines and Power* (New York), (in print).
7. Coelho, P.C. and Carvalho, M.G., Evaluation of Three-Dimensional Mathematical Model for Prediction of Heat Transfer in Power Station Boiler, *J. Inst. of Energy* (Lisbon), (in print).
8. Afgan, N.H., Bloch, A.G., Radovanovic, P.M., *et al.*, Boiler Expert System, *ICHMT Forum on Expert System and Mathematical Modeling of Energy System*, Erlangen, 1991.
9. Afgan, N.H., Carvalho, M.G., Radovanovic, P.M., and Bloch, A.G., Design Concept of Boiler Expert System, *ICHMT Intern. Symp. on Heat and Mass Transfer in Energy System and Environmental Effects*, Cancun, 1993.
10. Afgan, N.H. and Carvalho, M.G., Concept of Boiler Efficiency Assessment Expert System, *Second Int. Conf.: Combustion Technologies for a Clean Environment*, Lisbon, 1993.

11. Ahern, J.E., *The Exergy Method of Energy System Analysis*, New York: Wiley, 1980.

12. Bogdan, Z., Duic, N., Schneider, D.R., *et al.*, Leakage Detection in Power Plant Boiler, *INFUB*, Lisbon, 1995.

13. Duic, N., Bogdan, Z., Schneider, D.R., *et al.*, Tube Leakage Effect on Radiation Heat Flux in Boiler, *ICHMT Int. Symp. on Radiation Heat Transfer*, Kusadasy, Turkey, Aug. 14–18, 1995.

14. Afgan, N.H., Coelho, P.C., and Carvalho, M.G., Boiler Leakage Detection Expert System, *Heat Recovery System & CHP*, 1995.

15. Radovanovic, P.M. and Afgan, N.H., Boiler Furnace Efficiency Monitoring due to the Heat Transfer Surface Fouling Process, *10th Int. Heat Transfer Conf.*, Brighton, 1994.

16. Afgan, N.H. and Leont'ev, A.I., Instrument for Thermal Radiation Flux Measurement in High Temperature Gas Flow, *Heat Recovery System & CHP*, 1995, vol. 15, no. 4, pp. 345–356.

17. Martinis, N., Carvalho, M.G., Afgan, N.H., and Leont'ev, A.I., A New Method for Radiation Heat Flux Measurement, *10th Int. Heat Transfer Conf.*, Brighton, 1994.

18. Brajuskovic, B., Matovic, M., and Afgan, N., A Heat Fluxmeter for Deposit Monitoring System: I. Ash Deposit Prevention, *Int. J. of Heat and Mass Transfer*, 1991, vol. 34, pp. 2291–2301.

19. Brajuskovic, B. and Afgan, N.H., A Heat Fluxmeter for Deposit Monitoring System: II. Clean Heat Fluxmeter Characteristics, *Int. J. of Heat and Mass Transfer*, 1991, vol. 34, pp. 2303–2315.

20. Garland, W.J., Pochelman, W.F.C., Solnself, N., *et al.*, Intelligent Rm Management (personal communication), 1989.