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BOILER TUBE LEAKAGE DETECTION EXPERT SYSTEM

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Abstract—Efficient and reliable operation is the main requirement of the modern power plant. The most probable reason for failure in the power plant boiler is tube leakage. It is usually detected when urgent action is needed to prevent accidents in the plant. Advance detection of boiler leakage is of primary interest to secure maintenance planning and prevent the adverse effect of tube rupture. The development of the tube failure detection system is a demanding issue for the large power plant boilers.

The present paper describes the development of an expert system for detecting boiler tube leakage. The system is based on selected diagnostic variables obtained by radiation heat flux measurements. A sensitivity analysis of the diagnostic variables is performed. A three-dimensional mathematical model of the boiler furnace is used to obtain the confidence level for the minimum leakage to be detected. The design of the expert system is based on relative values of the radiation flux reading as the diagnostic parameter.

The leakage detection expert system is designed in the knowledge base environment, comprising the knowledge base containing facts, information on how to reason with these facts and inference mechanisms able to convert information from the knowledge base into user requested information.

The knowledge base is based on the object-oriented structure with the definition of the object LEAKAGE. The object class LEAKAGE is composed of subclasses SENSOR and CASES. The inference procedure uses a set of procedural processes in the preparation of diagnostic variables reading for the decision making process. A fuzzification process is used for conversion of actual diagnostic values into semantic values. The several steps of the inference procedure lead to the logic processing of individual and collective representation of diagnostic variables represented in the knowledge base. A number of examples are given for leakage detection based on the expert system reasoning and monitoring representative situations which are imminent to the set of parameters describing situations preceding boiler tube rupture. © 1998 Elsevier Science Ltd. All rights reserved

Keywords—Boiler tube leakage, leakage detection, expert system, radiation heat flux, knowledge base.

INTRODUCTION

Modern developments in power engineering are focused on the design and operation of large power plants. Increased efficiency and the possibility of better control of the environment have been the main driving forces in this direction. In this respect, the boiler is one of the main elements where the requirements for adequate design, operation and maintenance are needed in order to attain appropriate efficiency and reliability.

Recent advancements in information technology are offering a new possibility for its use as a tool in energy engineering systems [1, 2]. In particular, advances in computer technology have enabled us to increase our capability in the analysis of systems behaviour [3]. Progress in numerical modelling of energy systems has introduced the possibility for time and space analysis of the individual elements of the system and power plant. In particular, this has become important for boiler furnace modelling, which has proved to be an indispensable tool in modern energy engineering.

In the early 1970s, the need for the development of diagnostic systems to monitor internal processes in the boiler furnace was recognised [4]. Almost at the same time, the research in boiler furnace modelling has been in progress with the aim of predicting internal parameters of the boiler furnace [5, 6]. It was recognised that adverse effects resulting from the change in the initial and boundary conditions imposed by fluctuations of fuel quality, air temperature and humidity, uncertainties in the combustion processes and other unpredicted events are among those factors which lead to the malfunction of the boiler furnace.

The most probable failure in the power plant boiler is tube leakage. It is usually detected when urgent action is needed to prevent the occurence of an accident in the plant. Advance detection of boiler tube leakage is of great interest to secure maintenance planning and prevention of the adverse effect of the tube rupture. The development of the tube failure detection system is a demanding issue for safe and reliable operation of modern power boilers.

The design of a boiler expert system is based on the identification of objectives, domain, selection of diagnostic parameters and design of a knowledge base structure [7–9]. The definition of objectives is related to the function of the expert system in the identification of malfunction or degradation of the system.

The failure assessment expert system is aimed at assisting in the diagnostic of failure of the boiler furnace elements. The main emphasis in design is focused on the early detection of boiler tube leakage in order to provide operators with the information to be used for the operation schedule and maintenance. It aims to detect low leakage at the early state of the rupture development. The primary aim of this study is to design a concept of the boiler tube leakage expert system. In this respect, the main emphasis is given to the selection of the diagnostic variables and the domain of the expert system.

CONCEPTUAL DESIGN OF THE LEAKAGE DETECTION EXPERT SYSTEM

The leakage detection expert system is built in the knowledge base environment, comprising the knowledge base containing facts, information on how to reason with these facts and inference mechanisms capable of transforming information from the knowledge base into user requested information.

The knowledge base of the leakage detection expert system is based on an objective oriented paradigm defined within the domain of the system. The domain of the system is defined by a selected number of diagnostic variables represented by the relative values of incident heat flux measured at specific locations on the boiler furnace walls. The knowledge base uses the pattern of relative values of the incident radiation heat flux on the walls of the boiler. The relative values of radiation heat flux are determined as the ratio of the actual value to the standard value (the radiation heat flux not being disturbed by the leakage). So, at each measuring point the relative value of radiation heat flux is defined as

$$r^{\mathrm{s}}_{i,j} = \frac{q^{\mathrm{s}}_{i,j,\mathrm{leak}}}{q^{\mathrm{s}}_{i,j,\mathrm{stand}}}$$

where $q^{\mathrm{s}}_{i,j,\mathrm{leak}}$ is the incident radiation heat flux at co-ordinates i and j, and side s with boiler tube leakage present, and $q^{\mathrm{s}}_{i,j,\mathrm{stand}}$ is the incident radiation heat flux at the co-ordinates i and j, and side s not disturbed by the leakage.

For each leakage situation there will be a pattern of $r^{\mathrm{s}}_{i,j}$ values representing the corresponding situation. In this analysis, it will be assumed that $r^{\mathrm{s}}_{i,j}$ has discrete values at the specific points and is not time dependent. It will be assumed that $r^{\mathrm{s}}_{i,j}$ resumes the i and j co-ordinates of the sensor location; and the sides of the boiler furnace, i.e. front, back, side 1 and side 2. The semantic values of $r^{\mathrm{s}}_{i,j}$ are High, Medium and Low. For $r^{\mathrm{s}}_{i,j} > 0.98$ the semantic value is High, for $r^{\mathrm{s}}_{i,j} = 0.94$ is Medium and for $r^{\mathrm{s}}_{i,j} < 0.90$ is Low.

Knowledge base design

The state of the boiler furnace for tube leakage assessment is defined with leakage criterions. This implies that the state of the boiler furnace is defined by the pattern of sensor readings distributed on the control fields in the boiler. The control fields are instrumented with sensors to measure the incident radiation heat flux as specified by the criterions for the leakage assessment. Figure 1 shows a schematic distribution of sensor fields and leakage source positions.

Each diagnostic variable representing the control field is defined by the position, location and reading of the sensor. The expected situations are represented by the pattern of control field diagnostic variables and position of the leakage source. The knowledge representation method allows its presentation in a form adapted for the computer logic processing. For this reason, it

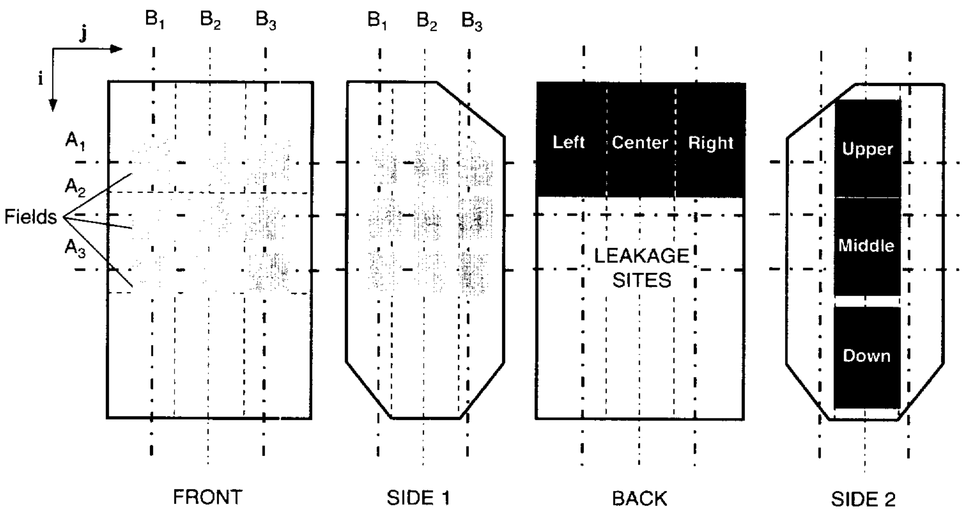

Fig. 1. Field and leakage source distribution.

is organised in the form of a knowledge base. The integral representation of the pattern of field variables is defined as the LEAKAGE object. So, every LEAKAGE object is defined by the pattern of field variables represented by the subclass SENSOR and corresponding position of the leakage source represented by the subclass CASE.

In order to accommodate the knowledge presentation adequate for the retrieval procedure, an object-oriented presentation of cases is used. Each case will comprise a pattern of field diagnostic variables on the boiler surfaces corresponding to a specific leakage situation. The cases are organised by the position of the leakage source and its intensity. So, the subclass CASE comprises a structure including the position and intensity of the leakage source. The pattern of the diagnostic variables values for the cases to be used in the knowledge base is obtained by numerical simulation of the boiler furnace. Mathematical modelling is used as a diagnostic tool for the assessment of the actual situation in the boiler. The model calculation of the pattern of diagnostic variables for the specific leakage case results in the expected reading of diagnostic variables at the fields. All the cases to be used in the diagnostic procedure are stored in the knowledge base.

The knowledge base is based on the object-oriented structure with the definition of the object LEAKAGE. It should be noticed that the object LEAKAGE is a semantic expression of the state of the boiler furnace described by the elements of the structure. The object class LEAKAGE is composed of the subclasses SENSOR and CASES, as stated above. Each one of these subclasses has sub-subclasses, as shown in Fig. 2.

The subclass SENSOR has sub-subclasses: Position and Reading. The sub-subclass Reading has sub-sub-subclasses Value and Rate. The values of the sub-sub-subclass Value are High, Medium and Low. Rate values are defined by Null, Slow and Fast. The sub-subclass Position has sub-sub-subclasses Location and Side. Location is divided into Row and Column. Row is defined by A_1, A_2, A_3 and Column by B_1, B_2, B_3. The sub-sub-subclass Side comprises the values Front, Back, Side 1 and Side 2.

The subclass CASE has sub-subclasses Site and Intensity. Intensity is defined by the mass flow rates $m_1 = 3.815$ kg/s, $m_2 = 1.97$ kg/s, $m_3 = 0.405$ kg/s. Site is composed of two sub-sub-classes: Surface and Place. Surface comprises the sub-sub-subclasses front, back, side 1 and side 2. Place comprises the sub-sub-subclasses Level and Orientation. Level is divided into Upper, Center and Down sub-sub-subclasses, and Orientation comprises Right, Central and Left sub-sub-subclasses. The set of instanciated values for each sub-sub-subclass will represent the LEAKAGE object. The description of any specific situation in the boiler furnace will be limited to the corresponding cases to be used for the assessment. Each situation defined by the object LEAKAGE will be assigned to the respective CASE subclass.

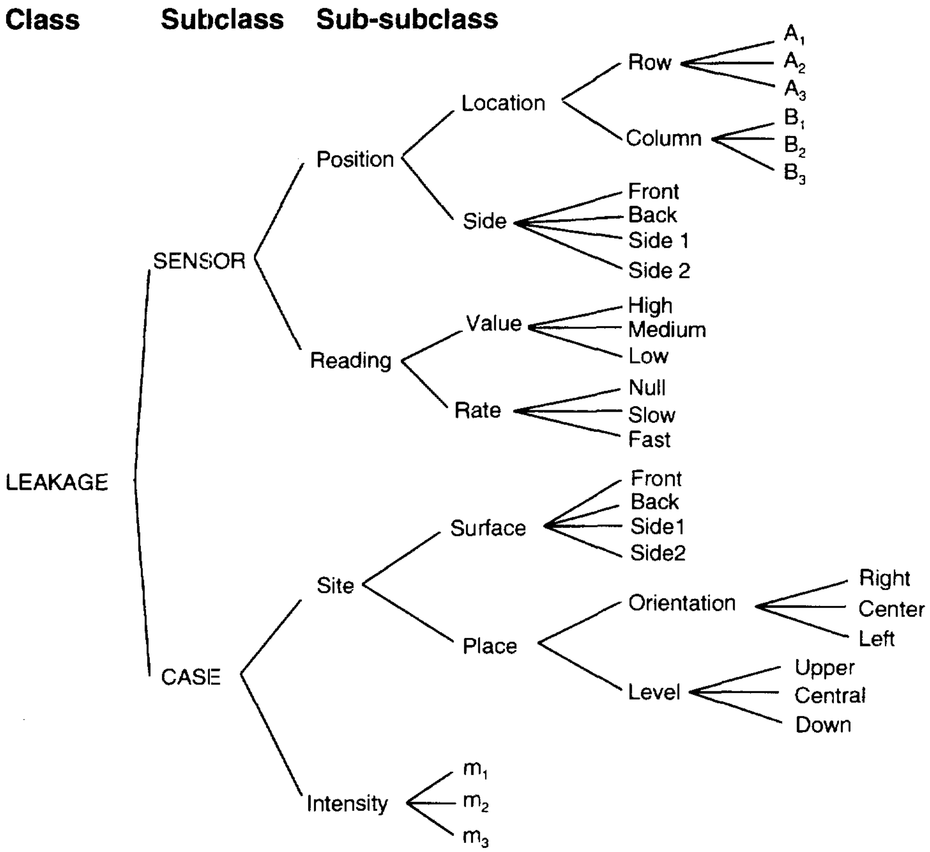

Fig. 2. Graphical presentation of the LEAKAGE object.

The inference procedure

In the design of the knowledge base system, the important phase is the development of the inference procedure. The inference procedure is a set of procedural processes to be used in the preparation of the diagnostic variables reading for the decision making process. It comprises several steps leading to the logic processing of individual and collective representation of the diagnostic variables represented in the knowledge base. The diagnostic variables as defined in the knowledge base are obtained by sensor reading conditioned for the inference processing. Each diagnostic variable is a continuous function of time representing the incident radiation heat flux at the specific location of the boiler furnace surface normalised by the respective standard values corresponding to the state without leakage. In a prescribed time interval the set of instantaneous values of all the variables is stored in buffer as the representation of the state of the system under consideration.

The actual value of the diagnostic variables is usually different from the value defined in the knowledge base. In order to obtain linguistic variables to be used for the retrieval of respective cases in the knowledge base, the fuzzification of the diagnostic variable has to be introduced [10, 11]. The fuzzification of the diagnostic variable is a process to determine the degree of truth value of the linguistic variable corresponding to the actual value. In order to perform this process, a membership function is selected for each variable. The membership function is the degree of truth of the actual value in comparison to semantic values of the diagnostic variable used to define the state of the system.

Figure 3 shows the fuzzification process for diagnostic variables. It is considered that semantic values of each variable are defined by three values, i.e. High, Medium and Low. The membership function for the semantic values is a linear function, as shown below:

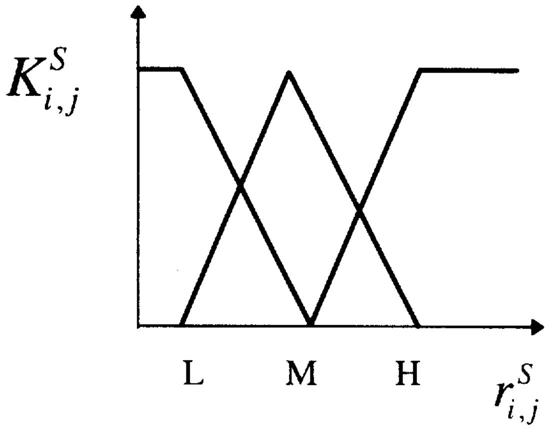

Fig. 3. Schematic of membership functions in the fuzzification process.

Semantic variable	Membership function	Range
Low	$K^s_{i,j} = 1 \frac{(x-L)}{(M-L)}$	Low—$r^s_{i,j}$—Medium
	$K^s_{i,j} = 1$	$r^s_{i,j}$<Low
Medium	$K^s_{i,j} = 1 \frac{(x-M)}{(H-M)}$	Medium—$r^s_{i,j}$—High
	$K^s_{i,j} = \frac{(x-L)}{(M-L)}$	Low—$r^s_{i,j}$—Medium
High	$K^s_{i,j} = \frac{(x-M)}{(H-M)}$	Medium—$r^s_{i,j}$—High
	$K^s_{i,j} = 1$	$r^s_{i,j}$ > High

Once the linguistic values and the membership functions of actual values are established for each diagnostic variable, the retrieval procedure can be initiated. This implies the determination of the object CASE in the knowledge base which represents the actual situation.

It can be expected that every reading of diagnostic variables with the respective semantic values will correspond to a number of cases stored in the knowledge base. In order to define the case which represents the most probable situation, the following procedure is used.

Adapting the linguistic values and the respective membership functions for all diagnostic variables, the cases representing potential diagnostic situations can be determined. Each potential case is defined with the respective number of semantic variables and membership functions. Since each variable is a fuzzy set, the intersection of those sets is defined by the min-operator whose membership function is

$$K(r^{\mathrm{A}}_{p.q})_{\mathrm{C}} = \min[r^{\mathrm{s}}_{i,j}, K^{\mathrm{s}}_{i,j}(r\,j_{i}.\mathrm{s})]$$

The minimum degree of the membership function will represent each of the potentially designated case situations. Since there is a number of cases with different minimum membership functions, we will select the case with the maximum membership function. The result of this evaluation process is obtained by aggregation of all consequences using the maximum operator. This means that

$$K^{\mathrm{con}}(r^{\mathrm{s}}_{i,j}) = \max_{r}\{\min[r^{\mathrm{s}}_{i,j}, K^{j}(r^{\mathrm{s}}_{i,j})]\}$$

This membership function will represent the diagnostic situation obtained from the adapted inference procedure.

SENSITIVITY ANALYSIS OF THE DIAGNOSTIC VARIABLES

The boiler failure assessment expert system is designed with sensors reading at specific locations as the diagnostic variables, and the radiation heat flux patterns as the diagnostic objects structured in the knowledge base.

In order to assess the sensitivity of the diagnostic variables to the tube leakage detection expert system, a three-dimensional mathematical model of the boiler furnace was used. This model is described in detail in ref. [12]. The model was evaluated against experimental data acquired in a 250 MW_e fuel-oil fired boiler, in case there is no leakage [13–15].

The mathematical model is based on the numerical solution of the Favre-averaged equations governing conservation of mass, momentum and energy and transport equations for scalar quantities. Turbulence is modelled using the k-ϵ eddy viscosity turbulence model. This model is based on the assumption of a linear relationship between the Reynolds stresses and the rate of strain. The turbulent fluxes of scalar quantities are calculated via a gradient diffusion hypothesis. The turbulent viscosity is calculated from the turbulent kinetic energy and its dissipation rate. Transport equations are solved for these two quantities.

The combustion model is based on the assumption that the reaction rates are very fast compared with the mixing rates. Hence, combustion is controlled by diffusion rather than kinetic mechanisms. It is also assumed that the mass diffusion coefficients of all the chemical species and the thermal diffusion are equal. Using these assumptions, the combustion process may be described by means of a strictly conserved scalar variable, often taken as the mixture fraction. The instantaneous values of mixture fraction and mass fraction of chemical species are related using the chemical equilibrium approach. Turbulent fluctuations may be accounted for by prescribing the probability density function of the mixture fraction.

The discrete transfer method is used to model radiative heat transfer. The radiative properties of the medium are calculated using the weighted sum of gray gases model, extended to account for soot particles.

Simulation of the tube leakage is accomplished by prescribing an inlet mass flow rate of steam at the place where the rupture has occurred, and by solving a transport equation for the steam mass fraction. It is assumed that the steam is an inert species. At any point of the boiler, if there is no steam, the mass fractions of the gaseous species are obtained from the local mixture fraction using the state relationships. If there is steam, the mass fractions are decreased by a factor which is calculated by setting the sum of the mass fractions of the species plus the mass fraction of steam equal to one. Therefore, the steam originated from the tube leakage and the water vapour resultant from combustion are treated separately.

The numerical solution of the governing equations is performed using a finite difference/finite volume method and a Cartesian co-ordinate grid system. Pressure and velocity fields are coupled using the SIMPLE algorithm. The sets of discretised algebraic linear equations are solved by the Gauss-Seidel line-by-line iterative procedure.

DEMONSTRATION OF THE KNOWLEDGE BASE STRUCTURE

The concept of the leakage detection expert system is demonstrated for an oil-fired power plant boiler with power $P = 250\ \mathrm{MW_e}$ producing steam at a pressure $p = 167\ \mathrm{kg/cm^2}$ and temperature $T = 543°\mathrm{C}$. The dimensions of the boiler furnace are $H = 20$ m, $L = 11.4$ m and $W = 8.57$ m. It is an oil-fired boiler with 12 burners distributed in three rows of four burners. Fuel consumption at the nominal power is $F = 54$ ton/h.

The demonstration of the leakage expert system and the development of the knowledge base structure is obtained by water leakage in the boiler furnace and respective calculation of the radiation heat flux. Water leakage is defined by two parameters, the mass flow rate and the position where the leakage was introduced. The mass flow rate of the leaked steam is $m_1 = 3.815$ kg/s, $m_2 = 1.97$ kg/s, $m_3 = 0.405$ kg/s. The leakage has been introduced at the symmetry plane of the front and back sides of the boiler furnace, at two different levels.

This paper is devoted only to the selected situations, characteristic for the demonstration of the presented concept of the expert system described above. The incident radiation heat flux pattern distribution without any leakage to be used as the standard case is shown in Fig. 4. If there is leakage, the relative isoflux contours shown below correspond to $r^{s}_{i\text{-}j} = 0.98, 0.94, 0.90$. Three cases with leakage are analysed as follows:

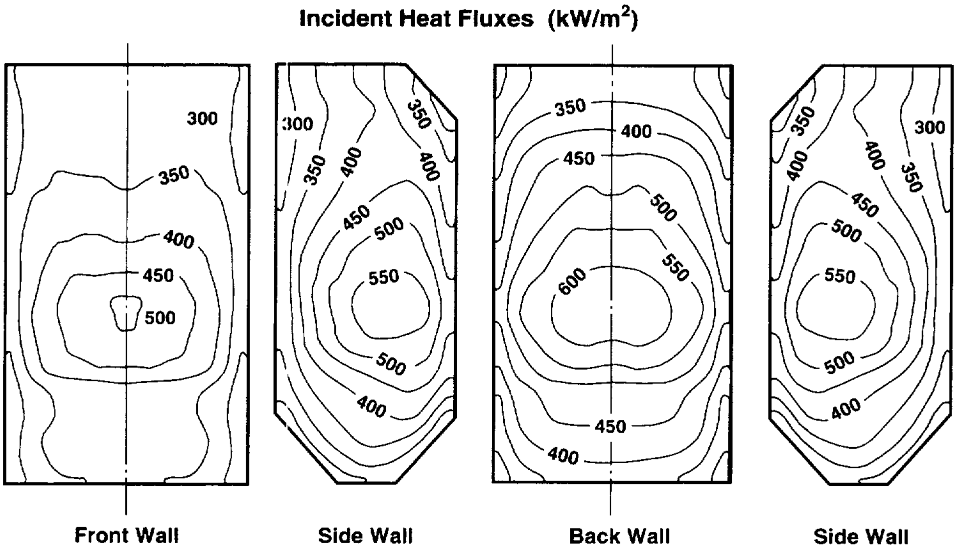

Fig. 4. Radiation heat flux distribution for no leakage case—standard case.

Large leakage at central level and middle orientation front wall

In order to demonstrate the sensitivity of the heat flux pattern to the change in the flow rate, the first studied case corresponds to a large flow rate at the centre of the front wall surface. It can be noticed (Fig. 5) that a sufficient and detectable change in the flux distribution pattern is obtained allowing the recognition of a characteristic set of the measuring parameters:

LEAKAGE (CASE (Intensity (Large) Site (Place (Level (Central)Orientation (Center)) Surface (Front))) SENSOR (Reading (Value (High, Medium, Low)Rate (Null)) Position (Side (Front) Location (Row (A_1, A_2, A_3) Column (B_1, B_2, B_3)))))—represented in Fig. 5 with large leakage at the place of central level and symmetry orientation on the front wall.

Medium leakage at the front wall

It is obvious that introducing a change in the intensity of the leakage stream changes the heat flux pattern. This will lead to the change in the set of the diagnostic variables representing the respective situation, as illustrated below:

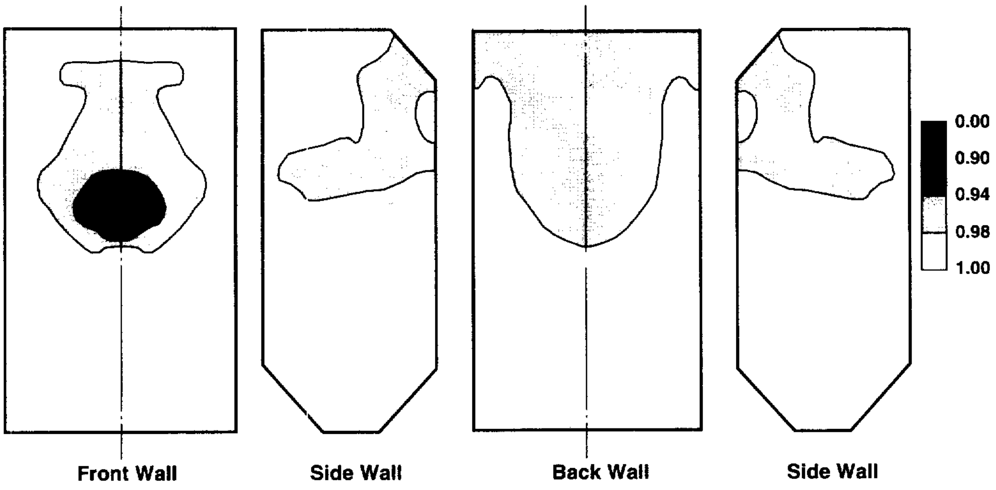

Fig. 5. Distribution of the relative value of the radiation heat flux for leakage at the front surface ($m_1 = 3.815$ kg/s).

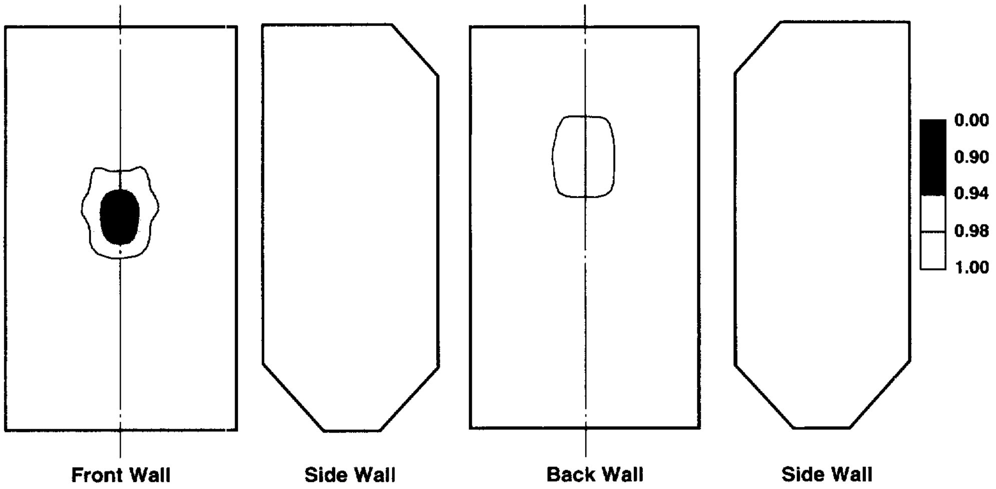

Fig. 6. Distribution of the relative value of the radiation heat flux for leakage at the front surface ($m_2 = 1.97$ kg/s).

LEAKAGE (CASE (Intensity (Medium) Site (Place (Level (Central) Orientation (Center))Surface (Front))) SENSOR (Reading (Value (High, Medium, Low) Rate (Null)) Position (Side (Front) Location (Row (A_1, A_2, A_3) Column (B_1, B_2, B_3)))))—represented in Fig. 6 with medium leakage at the place of central level and symmetry orientation on the front wall.

Large leakage at the back wall

In order to demonstrate the effect of leakage at the back wall of the furnace the third case is devoted to a situation characteristic of back wall leakage. The set of the diagnostic variables representing this case gives the possibility to detect a characteristic situation imminent for the changes introduced at the back surface:

LEAKAGE(CASE (Intensity (Large) Site (Place (Level (Central) Orientation (Center) Surface (Back))) SENSOR (Reading (Value (High, Medium, Low) Rate (Null)) Position (Side (Front) Location (Row (A_1, A_2, A_3) Column (B_1, B_2, B_3)))))—represented in Fig. 7 with large leakage at the place of central level and central orientation on the back side.

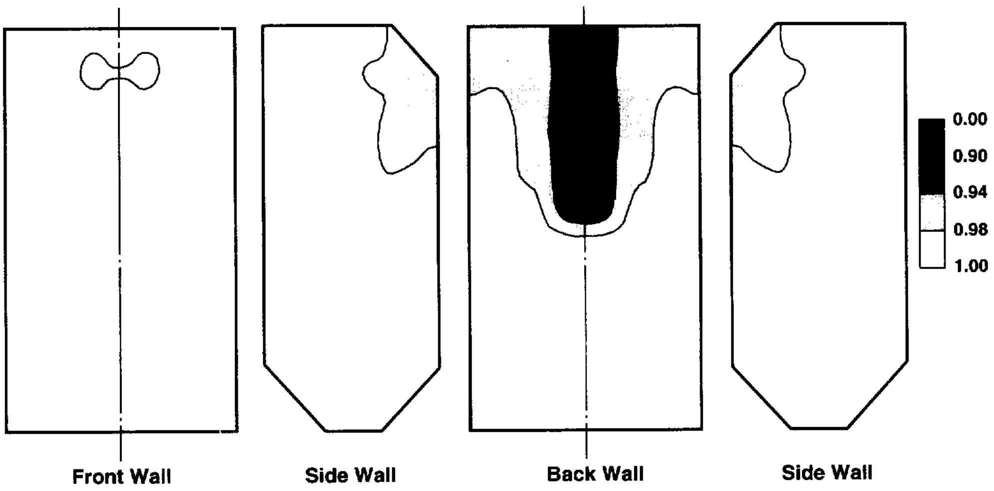

Fig. 7. Distribution of the relative value of the radiation heat flux for leakage at the back surface ($m_1 = 3.815$ kg/s).

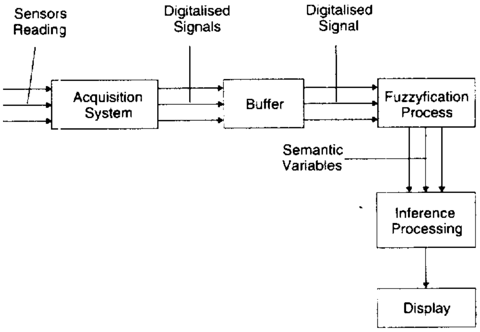

Fig. 8. Schematic of the monitoring system.

The procedure for each case will be repeated in the selected time interval giving the possibility to assess changes from one pattern to the next owing to the temporal development of the leakage in the boiler.

MEASURING AND MONITORING SYSTEM

This part of the paper is devoted to the description of the monitoring system for the radiation heat flux measurement in the boiler furnace. The sensor is based on the transpiration cooling of the porous element of the sensor and temperature difference reading of the incoming gas and gas leaving the sensor [16, 17]. The temperature difference is proportional to the incident radiation heat flux. The measuring system is designed for on-line monitoring of radiation heat flux. Measurement of the radiation heat flux is performed at regular time intervals giving a set of data to be processed by the acquisition system. Sensor positions are determined in accordance with the requirements of the expert system.

Attention is devoted to the signal conditioning in order to meet the requirements of the monitoring system. Figure 8 shows the schematic arrangement of the monitoring system used for signal processing and conditioning for the leakage detection expert system. There are the following elements in the monitoring system: the acquisition element which serves as the buffer for data collection; the validation element aimed to check the range of parameters and its mutual relation to the neighbouring values (its function is to prevent any time or space discontinuity not imminent to the process under consideration); and the trend analyser which processes the signal in order to obtain its time rate change in a different time scale.

CONCLUSIONS

Tube failure in the boiler furnace is an imminent problem of the steam power plant. In this respect, the diagnostic of the leakage development is of great interest for the efficiency assessment of the boiler. A new development in the expert system has opened the venue for its application in the power engineering.

It was shown that the incident radiation heat flux can be used as the diagnostic variable for the detection system. The change in the pattern of the radiation heat flux was demonstrated as the tool for recognition of different situations where the leakage is present. Using a three-dimensional numerical model of the boiler furnace, it was shown that the water leakage introduced at a specific point of the furnace substantially affects the radiation heat flux distribution. Using a number of simulations corresponding to leakage introduced at different places and different mass flow rates, it was possible to generate a number of situations corresponding to individual leakage cases.

The knowledge base of the leakage detection expert system is based on an objective oriented paradigm within the domain of the system. The domain of the system is defined by the selected number of diagnostic variables represented by the relative values of incident heat flux measured at specific locations on the boiler furnace surface. The leakage detection knowledge base uses the incident radiation heat flux distribution pattern in the boiler to describe specific situations.

The inference procedure as a set of procedural processes was demonstrated, leading to the preparation of diagnostic variables used in the diagnostic process. Fuzzification of diagnostic variables converts actual values into semantic values in order to enable the retrieval procedure in accordance with the degree of truth obtained for the respective case.

The demonstrated knowledge based expert system for the leakage detection is based on the knowledge base structure with the LEAKAGE object comprising all potentially developed situations. Classes of objects are defined in accordance with the radiation heat flux pattern representing individual leakage cases. The knowledge base is composed of the facts representing individual leakage situations defined by the CASE and SENSOR structure defined by LEAKAGE objects.

The monitoring system is based on radiation heat flux measurements at specific points in the boiler furnace. Each set of semantic values of diagnostic variables representing the actual situation is retrieved and matched to the individual situation defined by the LEAKAGE object corresponding to the specific case.

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