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KNOWLEDGE BASED SYSTEM FOR FOULING ASSESSMENT OF POWER PLANT BOILER

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ABSTRACT

The paper presents the design of an expert system for fouling assessment in power plant boilers. It is an on-line expert system based on selected criteria for the fouling assessment. Using criteria for fouling assessment based on " clean" and "not-clean" radiation heat flux measurements, the diagnostic variables are defined for the boiler heat transfer surfaces. The development of a prototype knowledge-based system for fouling assessment in power plant boiler comprise integration of the elements including knowledge base, inference procedure and prototype configuration.

Diagnostic variables are organised by the knowledge representation method in cases. The cases are obtained by 3D model of the boiler furnace and representing individual situations expected in boiler. The inference procedure is the set of procedural rules to be followed in the processing of diagnostic variables for the retrieval of diagnostic cases. This procedure implies fuzzification of actual variables and their conversion into a linguistic variable with the respective membership function. The sets of linguistic variables representing all fields in the boiler furnace are selected by the minimum values of membership functions. The selection of the case with the maximum values of the membership function among the cases under consideration will lead to the diagnostic case.

Demonstration of the prototype knowledge-based system for fouling assessment was performed on the Sines power plant. It is a 300 MW coal fired power plant. 12 fields are used with 3 on each side of boiler.

1 INTRODUCTION

Expert system application in diagnostic of fouling process in the power plant boiler has proved to be a useful tool in treating complex relations between the diagnostic variables. In this respect, it was demonstrated that (Afgan, et al, 1997) the knowledge-based system using a fuzzy logic procedure in the inference engine leads to the efficient and reliable tool for the assessment of fouling in the power plant boiler.

The fouling process in boiler furnace has been recognised as the main cause for the efficiency degradation in coal fired boiler. There have been a number of studies devoted to the investigation of the effect of different parameters on fouling process (Bryers 1996, Wall et al, 1993). It is known that the design of boiler furnace is strongly dependent on several inlet parameters reflecting change in the quality of fuel, humidity of air, burner function, boiler load and to less extend to the change of other parameters of the system. Even, there have been successful achievements in the prevention of fouling process in boiler furnace, there is a need to investigate options which might contribute to the control of fouling process in order to achieve higher efficiency of power plant system.

There have been several attempts to use modern information technology to improve the diagnostic methods of boiler operating conditions (Stirikovich 1986, Divakaruni et al, 1991, Valverde et al, 1991). In particular, attention has been focused to the development of the concept of an expert system for fouling assessment in the boiler furnace (Afgan et al 1996, Afgan and Carvalho 1996), efficiency assessment (Afgan and Carvalho 1993) and lifetime assessment (Afgan et al 1991).

The fouling assessment expert system design is based on the on-line monitoring of characteristic parameters of the boiler furnace reflecting its surface fouling condition. (Afgan et al 1993). It is immanent to the surface fouling condition in boiler the change of incident and received heat flux to the boiler furnace surfaces. It has been proved that the ratio of incident heat flux to received heat flux is the measure of fouling layer thickness on the boiler heat transfer surface (Carvalho and Coelho, 1990).

2 CRITERIONS FOR FOULING ASSESEMENT

The ratio of incident heat flux to received heat flux is proportional to the fouling layer thickness on the heat transfer surface. It is known, that the heat generated in boiler furnace is mainly transferred to working fluid by radiation heat transfer. For a clean tube the heat received by tube can be defined as " clean" heat flux (Radovanovic and Afgan 1994).

$$q = \sigma_0 \varepsilon_0 \left(T_g^4 - T_w^4 \right) \quad (1)$$

The fouling deposit layer on the boiler tube surface effects the heat transfer from flue gases to tube. From the assumption that the emissivity of "clean" and "not-clean' surfaces are not substantially different, follows that the ratio of "not-clean" surface heat flux and "clean" surface heat flux is

$$\frac{q_{notclean}}{q_{clean}} = \frac{T_{gn}^4 - T_{wn}^4}{T_{gc}^4 - T_{wc}^4} \quad (2)$$

By the analysis of expression for "clean" to "not-clean" heat flux ratio, it follows under assumption, there is no difference between the emissivity and temperature of tube surface without and with deposit, that

$$\frac{q_{notclean}}{q_{clean}} = f(\delta_d) \quad (3)$$

Also, it can be proved that, for the limited range of the deposit material physical and chemical properties, it could be adapted

$$\varphi = \frac{q_{notclean}}{q_{clean}} \approx K_0 * \delta_d \tag{4}$$

The fouling deposit rate is defined by the deposit thickness time change. From the investigation of deposit thickness time change several models have recognised different mechanisms for the description of the fouling process. In this respect for the fouling process in a boiler furnace it is adapted that

$$\delta_d = \delta_0 \left[1 - \exp(-kt)\right] \tag{5}$$

It can be proved under these assumptions that

$$k = A \frac{d}{dt} \ln \left[1 - \frac{D_0}{\delta_0} \left(\frac{q_{notclean}}{q_{clean}} \right) \right] \tag{6}$$

is defining the fouling rate for a specific fouling process. This expression for fouling rate is used as the second criterion for a fouling assessment diagnostic. It gives the possibility to differentiate individual fouling processes by their mechanism.

3 KNOWLEDGE BASED SYSTEM (KBS) PROTOTYPE DEVELOPMENT

The concept of knowledge-based system for the fouling assessment in power plant boiler is based on the evaluation and monitoring of ratio of "clean" and " notclean" heat flux as a diagnostic variables. In this respect, numbers of locations on boiler furnace are selected for the heat flux measurement. Using this concept for fouling assessment the prototype of KBS comprise elements required to perform its function. The prototype of KBS for boiler fouling assessment includes following elements: knowledge base, inference procedure and prototype configuration.

3.1 Knowledge Base Design

The state of boiler furnace as regards the fouling assessment is defined with the fouling criteria. This will imply that the state of boiler furnace is defined with a number of heat flux sensors, distributed on the control fields of the boiler furnace surface. The control fields are instrumented with sensors to measure respective "clean" and "not-clean" radiation heat flux as specified by the criterions for fouling assessment. Each side of boiler furnace has three instrumented fields at the same level. In total there are 12 control fields with respective sensor readings assigned as the diagnostic variables. Figure 1 shows distribution of control fields on the boiler furnace.

Each diagnostic variable representing control field is defined by position, location and reading of sensors. In order to present expected situations in the boiler with diagnostic variables, the knowledge representation method is used. In order to accommodate the knowledge presentation adequate for the retrieval procedure, the object-oriented presentation is used. This will comprise reading of all diagnostic variables, describing the specific fouling situations of boiler furnace that will be considered as the potential diagnostic cases. Recently there are number of the mathematical models of the boiler operation (Carvalho and Coelho 1990, Coelho and Carvalho 1993). For the development of expert system prototype the 3D boiler numerical model is used to generate diagnostic cases for the assessment of the actual situation in the boiler furnace. The cases obtained by numerical evaluation of different situations will represent the knowledge of the specific domain to be organised in form of knowledge base.

The knowledge base is organised to meet requirement for knowledge representation. The prototype of KBS knowledge base for the fouling assessment is based on the object-oriented structure with the definition of object FAESKB (Fouling Assessment Expert System Knowledge Base). The object class FAESKB is composed of subclasses SENSOR and FOULING.

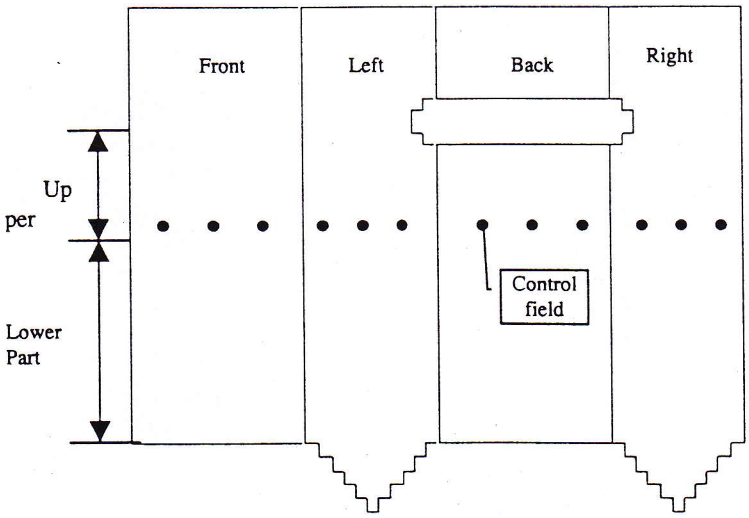

Figure 1 Position of control field in boiler.

It should be noticed that the object FAESKB is a semantic expression of the state of boiler furnace described by the elements of object structure. Subclasses SENSOR and FOULING are having sub-subclasses. The SENSOR has sub-subclasses: Position and Reading. The sub-subclass Reading has sub-sub-subclasses Value and Rate. The value used in the description of situations are Low, Medium and High corresponding to the specific range of numerical values of actual variables. The set of instantiated values for all sub-sub-subclasses will represent the FAESKB objects. Each situation in the boiler furnace is defined by the objects FAESKB. It can be noticed that the subclass FOULING has the sub-subclasses Place and Intensity. The sub-subclass Place has the sub-sub-classes: Surface and Half .The sub-sub-subclass Surface has a value Front, Back, Side1, Side2. Also, the sub-sub-subclass HALF has values: up and down. The sub-subclass Intensity comprise three values: I = No_fouling, II = Low_fouling and III = High_fouling. With instantiating respective sub-subclasses with the assigned values, it will be possible to define the situations corresponding to the domain of system.

3.2 The Inference Procedure

Measurement of actual value of diagnostic variables is the first step in the inference procedure for the fouling assessment in a boiler furnace. Reading actual values will result in the set of values reflecting a specific situation in the boiler furnace. Actual values are normalised by the reading corresponding to nominal state of the system.

Since in the knowledge base diagnostic variables are defined by semantic values L (Low), M (Medium) and H (High), it is necessary to convert all numerical reading of actual values in the respective semantic values. In order to obtain semantic values of diagnostic variables the fuzzification of actual values was introduced (Jamshidi 1997, Zadeh 1965). The fuzzification of diagnostic variable is a process to determine the degree of truth for actual value of diagnostic variable. In order to perform this process the membership function is selected for each semantic variable. The membership function is applied to the actual value in order to determine the degree of truth of the diagnostic variables semantic values

For this purpose it is assumed that the membership functions for diagnostic variables are in form

$$\mu(\varphi, L, M) = \begin{cases} 1 & \varphi < L \\ 1 - \left(\dfrac{\varphi - M}{M - L}\right) & L < \varphi < M \\ 1 & \varphi > M \end{cases} \qquad (7)$$

$$\mu(\varphi, L, M, H) = \begin{cases} 0 & \varphi < L \\ 1 - \left(\dfrac{M - \varphi}{M - L}\right) & L < \varphi < M \\ 1 - \left(\dfrac{H - \varphi}{H - M}\right) & M < \varphi < H \\ 0 & \varphi > H \end{cases} \qquad (8)$$

$$\mu(\varphi, M, H) = \begin{cases} 0 & \varphi < M \\ 1 - \left(\dfrac{\varphi - M}{H - M}\right) & M < \varphi < H \\ 1 & \varphi > H \end{cases} \qquad (9)$$

Figure 3 shows fuzzification of the diagnostic variables with respective membership functions.

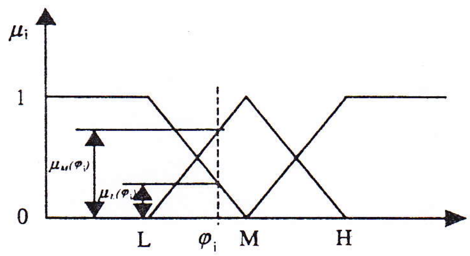

Figure 3 Fuzzification of Diagnostic Variables

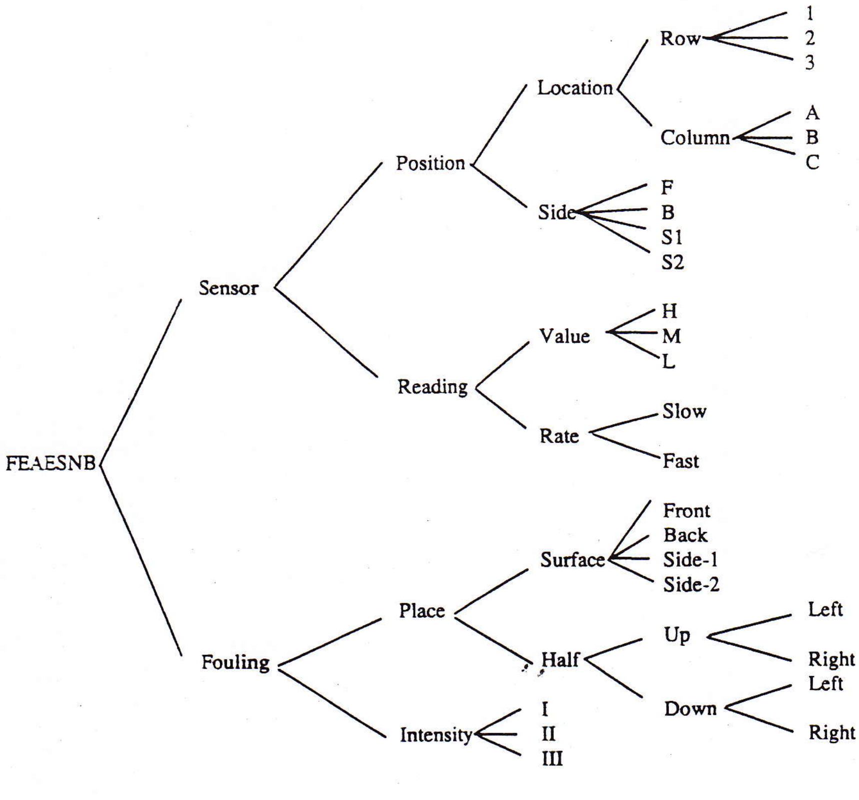

Figure 2 FAESKB Object Structure

The linguistic variables are defined with following constrains

High $> \mu = 1.05$

Medium $1.05 < \mu < 0.85$

Low $< \mu = 0.85$

The selected numerical values are determined by the optimisation of number of the cases to be obtained from 'the available data.

Once the semantic value and the degree of truth of actual value are established for each diagnostic variable, the retrieval procedure can be initiated. This implies the determination of cases that are stored in a knowledge base and related to the specific fouling assessment of system (Daniels and Rissland 1995, Kolonder 1993)

All diagnostic cases are defined by three linguistic values. The fuzzification process will lead to the definition of linguistic values and degree of truth for every diagnostic variable. So, every reading of diagnostic variables will be represented with respective semantic value and corresponding degree of truth. The cases representing actual situations in the boiler are described with the intersection of fuzzy sets representing individual variables. In this respect the intersection of fuzzy sets will comprise the group of diagnostic cases to be used in the retrieval procedure. Formally this means that the intersection of fuzzy sets is defined as

$$\Phi_i = \{\varphi_n, \mu_n(\varphi)\} \qquad n = 1, 2, 3, ..., 12 \qquad (10)$$

The intersection of fuzzy sets will represent diagnostic cases. It is obvious that there will be a number of cases that may represent the potential diagnostic cases. This will lead to the diagnostic set being defined as

$$\mu_i^j(\Phi_i) = \min\{[\mu(\Phi_1)],[\mu(\Phi_2)],[\mu(\Phi_3)]...[\mu(\Phi_{12})]\} \qquad (11)$$

So, the inference process is to define the cases with minimum degree of truth for all diagnostic variables. The cases with a minimum degree of truth are representing intersection of fuzzy sets of diagnostic variables and the cases with " and" operator in fuzzy rules, in the form

If Φ_1 and Φ_2 and Φ_3 and ... Φ_{12} than Fouling

Since in the knowledge base is designed in form of object-oriented scheme representing known situations, the inference procedure is based on the set of rules. Each rule will comprise ascendant and consequence part leading to the retrieval of the diagnostic cases. The ascendant part of the rule is the set of semantic variables accompanied with respective degree of truth and with "and" operator between clauses reflecting the subclass SENSOR. The consequence parts of the rules are related to the specific situations defined in the knowledge base domain as the subclass FOULING.

This will enable us to obtain the validity of rule consequences. Namely, there will be a number of rules in the knowledge base satisfying premises part of the rules, with the differences in minimum operator. The result will lead to the aggregation of all consequences by using maximum operator. This will give us possibility to obtain the rule with the maximum degree of truth that will represent the diagnostic case specified by the definition of consequence part of the rule.

Formally, this can be presented in form

$$\mu_r^{con}(\mu) = \max\{\mu_i^j\} \qquad (12)$$

Using a minimum operator as the representation of intersection of 12 diagnostic variables will lead to 4096 rules with the minimum values of the membership function describing respective cases. In order to retrieve those cases that are in compliance with the knowledge base cases, only cases that are among 4096 and at the same time in the expert system knowledge base will be taken into consideration for the further analysis. Ranking all those cases by the value of membership function the list of the potential diagnostic cases will be obtained. The first on this list will correspond to the most probable diagnostic cases.

On the consequence side of the rules there are diagnostic cases corresponding to the different situations. Every situation is assigned to the fouling site and fouling intensity. The consequence part of the rule will be displaced as the diagnostic outcome of the fouling assessment procedure.

Once the diagnostic outcome is defined, it will be possible to determine the fouling rate at respective fields. Also, the thermal efficiency of diagnostic field and its effect to the total efficiency of boiler furnace will be defined.

3.3 Configuration of the Knowledge-based System

The configuration of knowledge-based system comprise: acquisition element, variable reading and conditioning, storage buffer of actual values, knowledge base, inference procedure including fuzzification of diagnostic variables, retrieval of diagnostic situations and assessment of boiler furnace state and display of the fouling assessment readout. Figure 4 shows schematic presentation of knowledge-based system design.

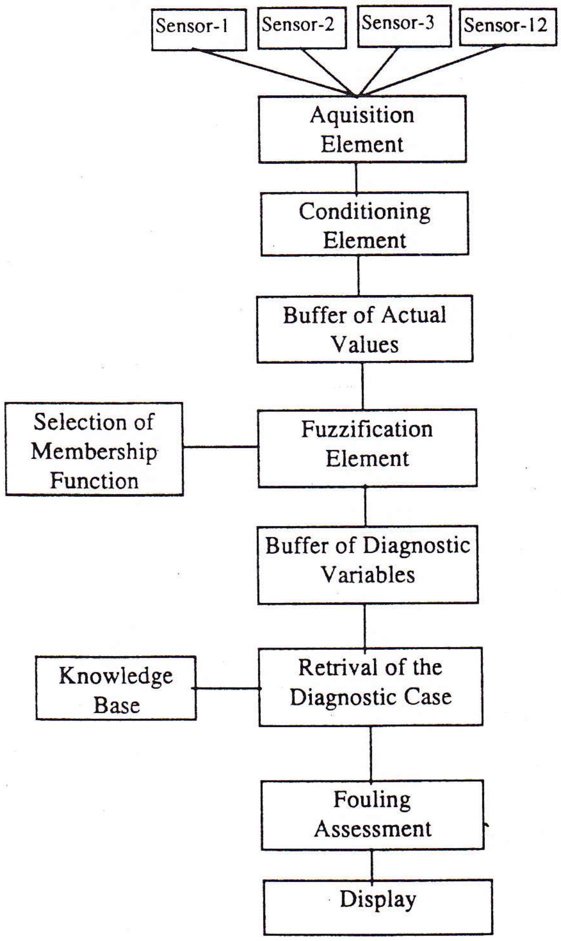

Figure 4 -The Organisational Chart of Diagnostic Procedure

4 PROTOTYPE DEMONSTRATION

4.1 Boiler Characteristics

The prototype KBS demonstration for the boiler fouling assessment is performed on the coal fired power plant boiler of 300MW at power plant in Sines. The boiler furnace is shown on Figure 5 (Coimbra et al 1994). The boiler furnace has 20 swirl burners positioned at the front side of the boiler.

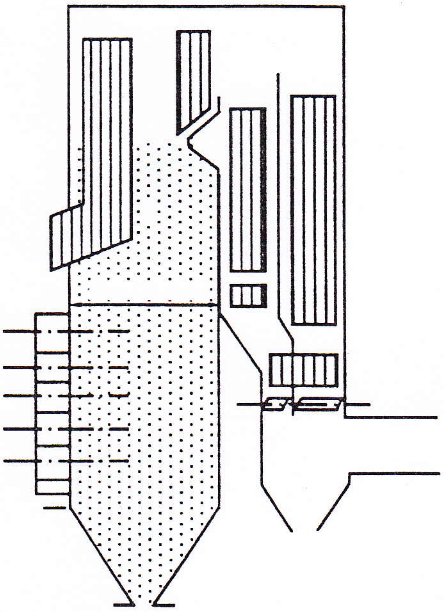

Figure 5 -Schematic presentation of boiler

4.2 Three Dimensional Heat Transfer Model

The three-dimensional model of utility boilers is based on the numerical solution of governing conservation equations in combustion chamber including super-heater platens. The flow field and heat release distribution used in the 3D heat transfer model are taken from the full CFD simulation of fluid flow, combustion and heat transfer in the boiler. Special emphasis was given to the heat flux distribution on boiler walls with different local fouling conditions, while keeping the fluid flow field and heat release distribution unchanged. The radiative heat transfer is modeled using the discrete ordinate method. Heat transfer calculations is based on Cartesian grid of 12x13x34 with 5031 active control volumes.

The absorption coefficient of gas-particles mixture is calculated by an empirical correlation (Luo et al 1991) which has the form:

$$K_{gas}=0.28EXP(-T_{gas}/1135) \qquad (18)$$

It was assumed that the particle absorption coefficient and particle scattering coefficient are 0.30 and 0.13, respectively.

The emissivity for "clean" and fouling walls is kept constant 0.6. For "clean" wall, the wall temperature is prescribed as 620K, while the wall temperature of fouling area is calculated by an energy balance:

$$Q_{absorbed} = (T_{fouling} - T_{wall}) / (\delta/k) \qquad (19)$$

The heat resistance of the fouling layer for boiler walls at the normal operation condition is in the range of 1 to 5 m2K/KW (Wall et al 1993)

The front, back and two side-walls of the boiler are divided in the Fields with a different heat resistance assigned to each Field representing the fouling conditions on the specific parts of the boiler wall. Zero heat resistance represents "clean" wall.

4.3 Prototype Knowledge Base

The prototype knowledge base for the KBS for the boiler fouling assessment is designed as the object-oriented structure with the object FAESKB. For the instantiation of the object following sensors are installed, namely, the "clean" radiation heat flux sensors (Afgan and Leontiev 1995, Martinis et al 1994) and "not-clean" radiation heat flux sensor (Brajuskovic et al 1991, Brajuskovic and Afgan 1991). There are three sensors on each side of the boiler.

In order to define diagnostic cases to be used for the diagnostic of boiler furnace, a number of situations are anticipated. The boiler furnace is divided into Fields. It is assumed that the diagnostic cases will represent the fouling process is taking place on the specific Field as defined by subclass FOULING. For each Field, it is anticipated three values of thermal resistance, namely I $= k/\delta = 3$, II $= k/\delta = 6$, III $= k/\delta = 9$. Also, combination of two neighbouring Fields is represented in the list of cases. Table 1 define the cases for the fouling in the Front surface of boiler.

TABLE 1 Design of Cases with fouling on Front Surface

Case	Surfaces				Halves		Intensity		
	F	B	S_1	S_2	U	D	I	II	III
1'	x	-	-	-	x	-	X	-	-
2'	x	-	-	-	-	x	X	-	-
3'	x	-	-	-	x	-	-	x	-
4'	x	-	-	-	-	x	-	x	-
5'	x	-	-	-	x	-	-	-	x
6'	x	-	-	-	-	x	-	-	x

TABLE 2 Design of Cases with Fouling on Front and Side Surface

Case	Surfaces				Halves		Intensity		
	F	B	S1	S2	U	D	I	II	III
1''	X	-	X	-	x	-	X	-	-
2''	X	-	X	-	-	x	X	-	-
3''	x	-	X	-	x	-	-	x	-
4''	X	-	X	-	-	x	-	x	-
5''	x	-	X	-	x	-	-	-	x
6''	x	-	X	-	-	x	-	-	x

Having in mind that cases as for the Front surface may appear for other three surfaces the total number of cases for the single area fouling will be 18.

Beside the cases with the fouling taking place only on the single Field it was taken into consideration the cases where the fouling is present on the two neighbouring Fields in horizontal levels. Table 2 shows the design of the cases for the two Field having the same and different intensity of the fouling.

As it can be noticed that only cases with the same intensity of the neighbouring Fields are taken into a consideration. Under this assumption the total number of the cases with two areas fouling will be 12

There are also cases where the fouling process will take place on the total level furnace fouling. These cases are presented in the Table 3.

TABLE 3 Design of the Cases with Level Fouling

Case	Surfaces				Halves		Intensity		
	F	B	S1	S2	U	D	I	II	III
1'''	x	x	X	-	x	-	X	-	-
2'''	x	x	X	-	x		-	x	-
3'''	x	x	X	-	x	-	-	-	X
4'''	x	x	X	-	-	x	x	-	-
5'''	x	x	X	-	-	x	-	x	-
6'''	x	x	X	-	-	x	-	-	X

The total number of the cases to be taken into a consideration in the fouling assessment retrieval will be 42. For all of these cases the 3-D code with the boiler numerical model has be used to produce the data for knowledge base.

Results obtained for some of the specified cases obtained by 3-D heat transfer model code are presented on Figure 6 and Figure 7. The data obtained for no fouling case to be used as the standard case. Figure 6 present data for heat fluxes ration for the Case 2''

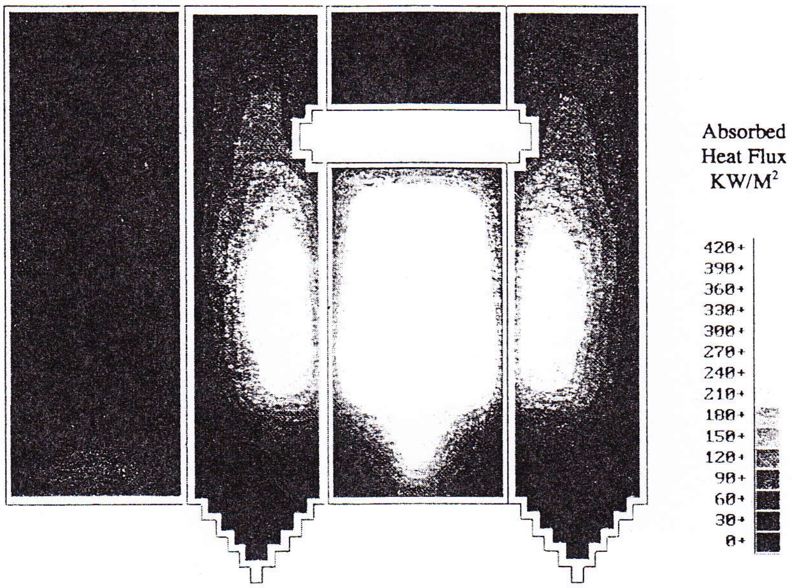

Figure 6 - Heat Transfer Flux Distribution for Nominal Regimes

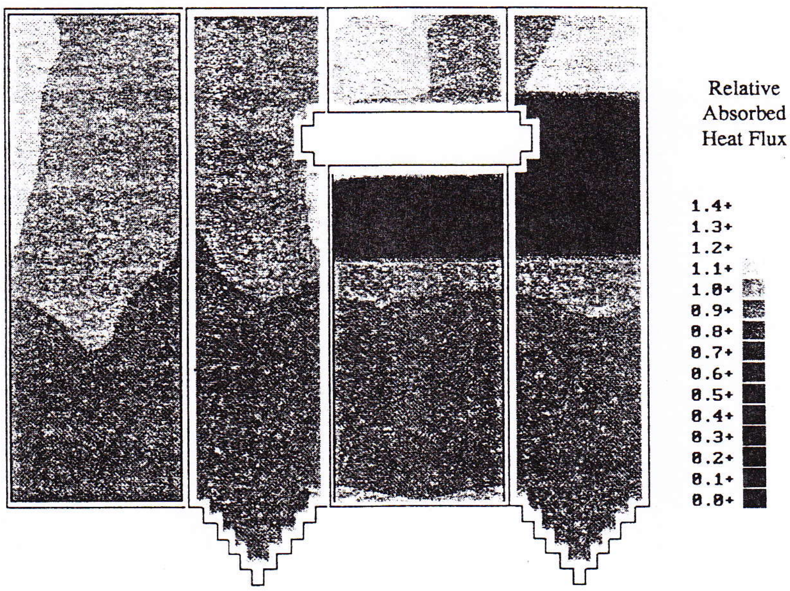

Figure 7 - Heat Flux Ratio Distribution for Case 20

4.4 Prototype Diagnostic Processing

The diagnostic procedure for the prototype knowledge-based system for the fouling assessment comprise, several steps leading to the determination of the case representing outcome of assessment procedure. The processing of on-line reading of diagnostic variables sensors requires the software and hardware support of system. The retrieval of the diagnostic cases requires adequate software procedure including fuzzy processing and respective reasoning strategy (Duic and Afgan 1997). Finally, the knowledge -based system is equipped with the respective display capability. Having this in mind, the prototype diagnostic process is composed of the following elements, namely: monitoring module, case reasoning module and display module.

For demonstration purpose, it was assumed that the reading of diagnostic variables actual values after conditioning are given in Table 4 .The values of actual values of diagnostic variables are selected as the arbitrary set of values to be used in the diagnostic process. In this respect the set of diagnostic variables is composed of 12 sensors reading within the range of expected values.

TABLE 4 Set of Demonstration Values

φ_1	φ_2	φ_3	φ_5	φ_5	φ_6
1.0217	1.0098	1.0023	1.0001	1.0033	1.0148
φ_7	φ_8	φ_9	φ_{10}	φ_{11}	φ_{12}
0.7093	0.6838	0.6904	0.8299	0.7561	0.7447

The first step in the demonstration procedure is conversion of actual diagnostic variables in the linguistic variables including definition of linguistic variables and the degree of truth for each variable. This will give the sets of fuzzy variables in the linguistic form with corresponding degree of membership. Total number of diagnostic cases to be defined with linguistic variables corresponding to actual data is $2^{12} = 4096$. Only cases presented in the knowledge base will be taken for further consideration in the retrieval procedure. The next step is ranking all cases with the minimum values of the degree of membership function. Table 5 shows cases selected by the minimum values the degree of membership function.

TABLE 5 List of the diagnostic cases

Surface	Half	Intensity
Back+Side	UP	Light Fouling

The case with the maximum of K_{min} values represents the diagnostic case and defines the uncertainty of the selected case.

The assigned object FAESNB for Case 1'' is

Case 1'' $K_{min} = 0.60$

This case represents the assessment of the fouling situation in boiler furnace obtained by the expert system for the fouling assessment of the boiler furnace.

The graphical presentation of diagnostic case Figure 7, and the data sheet with results obtained by calculation of data reflecting the assessment of boiler furnace state. Figure 8 presents display of the diagnostic procedure as it is shown to the operator of the plant.

Since the fouling process is in principle a slow process so the time period for the successive assessment of the fouling process in the boilers should not exceed one hour.

5 CONCLUSIONS

The prototype knowledge-based system for fouling assessment is demonstrated as a tool for the diagnostic of fouling process in the boiler furnace. The concept of KBS is derived form the physical interpretation of fouling process in the boiler. By the use of diagnostic variables defined as the ratio of "clean" and "not-clean" radiation heat flux, it was developed the concept of knowledge presentation relevant for the assessment of fouling process in the boiler furnace.

The knowledge base of expert system is designed as the object-oriented structure. The object FAESKB class was formed with respective sub-classes and sub-sub-classes in order to present knowledge related to the position and reading of sensors. Rule based structure is used to present the individual cases to be used as the knowledge generated by the 3-D boiler furnace model. Diagnostic cases are presented in the knowledge base.

The retrieval processing is based on the case evaluation. The processing of diagnostic variables included the fuzzification procedure to form a fuzzy set of diagnostic variables and to determine the degree of truth for each variable. The actual values of diagnostic variables are converted in the group of fuzzy sets representing the potential diagnostic cases. Using fuzzy clustering of diagnostic variables potential cases are selected as the candidates for assessment results.

Time

Date	Hour
July 8,1997	13 h 45 min

Fouling Assessment

Surface	Half	Intensity
Back +side2	UP	III

Efficiency

Nominal Efficiency	Present Efficiency	Forecast
100% (Base)	97.50% (relative to base)	

Economy

Nominal Cost cents/kWh	Present Cost Cents/kWh	Forecast	Estimated Cleaning Cost
100% (Base)	101.2% (relative to base)		

Figure 8. Display of the Diagnostic Case Assessment

The display of knowledge-based system for the fouling assessment is divided in two options, namely: for operators and for management. The operator display will contain the information of diagnostic cases in form defined by the object FAESKB. The management display will include data derived from the determination of boiler efficiency change and the forecast of its further development.

The demonstrated version of the prototype of KBS for fouling assessment has proved feasibility of the system and its possibility to be used as the tool for fouling assessment in the power plant boilers.

6 ACKNOWLEDGEMENTS

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7 NOMENCLATURE

k - fouling rate constant

K_0,D_0 - correlation constant defined by equation (4)

P - probability

Q - absorbed heat flux by fouling wall

T_g,T_w - gas and wall temperature , respectively

δ - deposit thickness

ε - emissivity of the tube surface and flue gases , respectively

μ - membership function

φ - actual value of diagnostic variable

Φ - fuzzy set of diagnostic variable

δ/k - heat resistance of fouling layer

7.1 Subscripts

g - gas

w - wall

gn -gas "notclean"

gc - gas "clean"

wn - wall " notclean"

wc - wall "clean"

8 REFERENCES

1. Afgan, N. H, Bloch, A. G., Radovanovic, P. M., Zhurovlev, Yu. and Gorb, E.I., 1991,Boiler Expert System, ICHMT Forum on Expert System and Mathematical Modelling of Energy System, Erlangen
2. Afgan, N. H. and Carvalho, M. G., 1996, An Expert System for Controlling Process in a Power- Station Boiler Furnace, Thermal Engineering, Vol.43, pp.514-523
3. Afgan, N. H. and Carvalho, M. G., 1993, Concept of Boiler Efficiency Assessment Expert System, Second Int. Conference: Combustion Technologies for a Clean Environment, Lisbon
4. Afgan, N. H., Carvalho, M. G. and Coelho, P. J., 1996, Concept of Expert System for Boiler Fouling Assessment, Applied Thermal Engineering, Vol.16, No.10, pp. 836-844
5. Afgan, N. H., Carvalho, M. G., Radovanovic, P. M. and Bloch, A. G., 1993, Design Concept of Boiler Expert System, ICHMT International Symposium on Heat and Mass Transfer in Energy System and Environmental Effects, Cancun
6. Afgan, N. H., He, X. G., Carvalho, M. G. and Azavedo, J. L. T., 1997, Prototype of Knowledge-based System for Boiler Fouling Assessment at Power Plant Sines, Proceeding of 4th International Conference on Clean Air Technologies, Lisbon.
7. Afgan, N. H. and Leontiev, A. I., 1995, Hemispherical Radiation Heat Flux Measurement, Heat Recovery System
8. Brajuskovic, B., and Afgan, N. H., 1991, A Heat Fluxmeter for Deposit Monitoring System: II. Clean Heat Fluxmeter Characteristics, Int. Journal of Heat and Mass Transfer, Vol. 34, pp. 2303-2315
9. Brajuskovic, B., Matovic, M. and Afgan, N. H., 1991, A Heat Fluxmeter for Deposit Monitoring System: I. Ash Deposit Prevention, Int. Journal of Heat and Mass Transfer, Vol. 34, pp. 2291-2301
10. Bryers, R. W., 1996, Fireside Slagging, Fouling and High Temperature Corrosion of Heat-Transfer Surface due to Impurities in Steam-raising Fuel, Prog. Energy Combustion Sciences, Vol.22, pp. 29-120
11. Carvalho, M. G. and Coelho, P. J., 1990, Numerical Prediction of an Oil-Fired Water Tube Boiler, Engineering Computation,7,(3), pp.227-234
12. Coelho, P. J., and Carvalho, M. G., 1993, Application of a Domain Decomposition Technique to the Mathematical Modelling of a Utility Boiler, International Journal for Numerical Methods in Engineering, 36, pp.3401-3419
13. Coimbra, C. F. M., Azevedo, J. L. T. and Carvalho, M. G., 1994, 3-D numerical model for predicting NO_x emission from an industrial pulverized coal combustor, Fuel Vol.73, NO.7.
14. Divakaruni, S. M., Koklik, G., Sopocy, D. M. and Frigner, D., 1991, Review of Fossil Plant R and D Project Prioritisation for AI Application., Expert System Application for Electric Power Industry, Hem. Pub. Corp., Washington
15. Duic, N. and Afgan, N. H., 1997, FAR Code, private communication
16. Daniels, J. J. and Rissland, E. L., 1995, A Retrieval-based Approach to Intelligent Information Retrieval, The Proceedings 18th Annual SIGIR Conference 1995
17. Jamshidi, M., 1997, Large-scale Systems: Modelling, Control and Fuzzy Logic,(to be published)
18. Kolonder, J. L., 1993, Case-based Reasoning, Morgan Kaufmann,
19. Luo, X. -L, Boyd, R. K. and Kent, J. H., 1991, Journal of the Institute of Energy.
20. Martinis, N., Carvalho, M. G., Afgan, N. H. and Leontiev, A. I., 1994, A New Method for Radiation Heat flux Measurement, 10th International Heat Transfer Conference, Brighton.
21. Radovanovic, P. and Afgan, N. H., 1994, Boiler Furnace Efficiency Monitoring due to the Heat transfer Surface Fouling Process, 10th International Heat Transfer Conference, Brighton
22. Stirikovich, M. A., 1986, Prospect for Utilisation of Organic Fuel with Regard to Ecological and Social Factor, Fuelling the 21st Century, Hem. Pub. Corp.
23. Valverde, L. J., Stephan, A., Gohl, M., Armor, A. F., Schebel, J. R. and Divakaruni, S. M., 1991, Fossil Power Plant Application of Expert System: An EPRI Perspective Expert System Application for Electric Power Industry, Hem. Pub. Corp., Washington
24. Wall, T. F., Bhattachariya, S. P., Zhang, D. K., Gupta, R. P. and He, X., 1993, The Properties and Thermal Effects of Ash Deposits in Coal-fired Furnaces, Progress in Energy Combustion Sciences, Vol.19, pp. 487-504
25. Zadeh, L. A., 1965, Fuzzy Sets, Information Control 8, pp.338-353