A Knowledge-Based Prototype for Detecting Working Fluid Losses in a Utility Boiler

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Abstract: - Early detection of working fluid losses in a utility boiler contributes to the increase of the reliable boiler operation through timely planning and preparation for the boiler shutdown. Since the detection problem corresponds to the problems that are successfully solved by using knowledge-based systems, the system for detecting working fluid losses is built as a knowledge-based system. The prototype for detecting steam leakage uses the ratios of the current heat fluxes and the flux nominal values (fluxes without leakage) in the spatially distributed measuring points on the boiler sides as the starting data for setting up the hypothesis about the leakage existence. The paper presents the prototype strategy in detail and illustrates the strategy with several examples.

Key - Words: - Boiler Failures, Working Fluid Loss Detection, Pattern Recognition Problem, Knowledge-Based Prototypes.

1 Introduction

The reliable operation of a utility boiler depends upon the correctness of the boiler's tube system. The rupture of a tube produces the losses of the steam working fluid. As a final result, the rupture of a tube requires the boiler to be shut down and repaired. This type of failures is very frequent when thermal power plants are considered. A study made for the "Nikola Tesla" thermal power plant and the period from 1980 to 1990 shows that 66 % of all the boiler failures was the failures of the tube system [7]. Thus, early detection of working fluid losses would contribute to the increase of the boiler's reliability. It would enable the operator of the boiler to prepare the boiler shutdown timely. Taking into account this fact, it is obvious that there is a need to develop a system for detecting working fluid losses in a utility boiler

The development of the system for detecting working fluid losses is based upon the physical variables specific for the processes of a boiler.

Those are heat fluxes, temperature, steam pressure and similar. The appropriate instruments of a boiler measure these variables and supply the necessary values. We can group these instruments into two classes: standard and additional. Standard instruments are those built in from the first moment of the boiler's operation. Additional instruments are built in afterwards to monitor the boiler processes more completely. The additional instruments important for detecting working fluid losses are heat flux sensors built in the defined, spatially distributed points on the boiler sides [1], [9]. If the nominal values of heat fluxes measured when there is no working fluid leakage in a boiler are known, then the ratios between the current and nominal fluxes can be used as the leakage detection parameters. The occurrence of the working fluid losses produces the decrease of the heat flux values in its neighborhood in comparison with the nominal values. The flux ratio equal to one corresponds to the nominal situation without leakage and the ratio less than one would correspond to the occurrence of leakage [1].

2 Problem Characteristics

The problem of detecting working fluid losses in a utility boiler has the following characteristics:

- it requires the specialized knowledge gathered from past experience,
- it includes symbolic reasoning (the precise numeric values are not of the crucial importance for reasoning but the ranges of values and the boundary values that can be presented by symbols),
- it uses the data that can be incomplete and uncertain (e.g. some of the instruments can fail or partially degrade during the operation),
- it includes the inexact reasoning (the solution can have several lines of reasoning that produce different conclusions; in general, we trust these lines differently),
- it produces the solution more in the form of a recommendation than in the form of an exact answer,
- it is well-focused and stable (it covers the narrow domain of the boiler monitoring and it uses the defined and known starting data),
- its complexity is reasonable and thus it is solvable in the sense of defining the main steps, and
- it has some value (the solution can save the cost of maintaining a boiler).

All the enumerated characteristics correspond to the characteristics of a problem that can be successfully solved by using a knowledge-based system [3], [10]. Because of this, the system for detecting working fluid losses is built as a knowledge-based system.

Knowledge-based systems are successfully applied to the domain of power systems. According to the investigation made upon the sample of 2500 knowledge-based systems in 1992, 6% of this sample is related to the domain of power systems [3]. To illustrate the knowledge-based system application to the domain of power systems we mention the system for monitoring coal quality [4], the more general system that controls a thermal power plant [11] and the fuzzy expert system shell that diagnoses disturbances of a fossil power plant [2].

Knowledge-based systems are suitable to solve the following types of problems: interpretation, monitoring, diagnosis, prescription, prediction, control, planning, design and instruction [6]. Many real problems are the mixture of several typical problems at the same time. The problems of interpretation, monitoring, diagnosis, prescription and control are important for the problem of detecting working fluid losses.

3 General Strategy

The flowchart of the general strategy of detecting working fluid losses in a utility boiler is shown in Fig. 1. It corresponds to a strategy very often used to solve diagnostic problems [3]:

- set up the hypothesis based upon the starting data in the first step and
- prove the hypothesis in the second step.





In our case of detecting working fluid losses, we try to set up the hypothesis about the working fluid leakage existence based upon a number of data in the first step (Fig. 1). Heat flux deviations from the nominal values of fluxes, measured in the spatially distributed points in a boiler are the starting data used in the first step. If the hypothesis is set up, the hypothesis should be supported with some additional data in the next step (box 2 in Fig.1). If the statement that there is no leakage is set, it should be proved too, in the next step (box 3 in Fig.1). In the case of detecting working fluid losses the additional data for proving the hypothesis are sounds and vibrations measured with the appropriate instruments assigned to the sides of a boiler and the data collected with the standard boiler instruments. The last step of the strategy gives the final conclusions about the occurrence of working fluid losses based upon all the available data:

- losses detected or
- no losses.

In the case of the first possible conclusion it is necessary to further explain the detected losses by specifying in detail their locations and intensities.

4 Prototype Strategy

Knowledge-based systems are developed through evolution, i.e. by elaborating a prototype incrementally [3]. A prototype presents the reduced system version with the reduced capabilities of solving the problem. In our case the prototype is devoted to the general strategy shown in Fig. 1 and the elaboration of the first task:

• setting up the hypothesis about the existence of working fluid losses.

The starting data used to set up the hypothesis about the existence of working fluid losses in the prototype are the ratios of the current and nominal values of heat fluxes measured in the spatially distributed points on the boiler sides. The sensitivity analysis performed in detail in [1] shows that these starting data have enough discrimination capabilities to distinct the standard boiler operation from its operation with working fluid losses. The mathematical model of a boiler furnace that gives the distribution of heat fluxes in various points of the boiler is used in the analysis. The model is further extended with a section that simulates particular cases of the tube leakage sources described by their locations and intensities. The simulation results show that heat fluxes of the points on the boiler sides deviate from the nominal values when a particular leakage source is introduced. The points with deviations form a regular geometric figure with central or axial symmetry. More points and the bigger figure correspond to a stronger leakage source and the center of the figure corresponds to the location of the leakage source. The data on

the ratios of heat fluxes that are gathered experimentally with the appropriate instruments during the standard boiler operation confirm the results of the analysis.

Taking into account the fact that the existence of working fluid losses can be presented in the form of a geometric figure, setting up the hypothesis about working fluid losses can be treated as a pattern recognition problem. With this approach to the problem solution accepted, it is necessary to find the appropriate nominal characteristic figures for leakage sources first [5]. Then it is enough to test if a geometric figure formed on the basis of the current values of heat fluxes in the measuring points matches one of the nominal figures in order to set up the hypothesis about the existence of working fluid losses.

In the simplest approach to the pattern recognition problem it is necessary to classify all the possible patterns into the previously defined classes represented by the appropriate templates [5]. A current pattern is then compared with all the templates according to a defined criterion of matching in order to find out the most similar template and its class. This approach relies upon classification. The main problems of this approach concern the representation of templates and the criterion of matching.

The general overview of the strategy of setting up the hypothesis about the existence of working fluid losses in a utility boiler is shown in Fig. 2. In order to apply this strategy it is necessary to code the ratios of heat fluxes with numbers 0 or 1 first. The number 0 corresponds to the ratio of heat fluxes when there is no deviation. The number 1 corresponds to the ratio of fluxes when there are some deviations. These numbers form the starting data for the prototype analysis. Then the sum of these numbers from all the measuring points on the boiler sides becomes the main indicator of the working fluid losses detection. In the case when the sum is greater than 0, working fluid leakage exists. If the numbers connected with the particular boiler sides are considered, the leakage sources can be localized on the boiler sides. The leakage analysis focused on the boiler sides (box A in Fig. 2) is presented in Fig. 3.

The leakage analysis shown in Fig. 3 corresponds to the simplest approach of solving the pattern recognition problem. The points with heat flux deviations are recognized and grouped

to form a geometric figure. These points are neighbors among all the points on one boiler side. The templates of leakage sources - nominal figures are represented with rectangles and their variations. The dimension of a nominal figure is proportional to the leakage intensity. The geometric figure is framed with a summary rectangle. These rectangles – frames are helpful when the geometric figure has to be classified. The dimension of the frame drawn around the geometric figure reduces the number of all the possible nominal figures – leakage templates to the number of the most plausible ones with which the geometric figure is compared (box B in Fig. 3).



In order to find the leakage sources on boiler sides and to describe them in detail, the analysis of geometric figures is performed (box B in Fig. 3 and Fig. 4). The criterion of matching the current geometric figure and a possible nominal figure is the number of the points that distinguish the two compared figures divided by the number of points of the nominal figure. The geometric figure is compared with the nominal figure in terms of the points that are missed from the nominal figure and the points that are added to the geometric figure. Then the number of the missed points and the number of the added points are considered. Thus the criterion of matching has two parts:



Figure 3 The prototype strategy - the leakage analysis on a side

- the quotient of the number of the missed points and the number of all the points in the nominal figure, and
- the quotient of the number of the added points and the number of all the points in the nominal figure.

To generate the final result about the leakage sources the sum of the absolute values of the two quotients is made and shown as a percentage -R (Fig. 4). The nominal figures that have the final result less than 100% are the only candidates for

leakage sources. Finally, the nominal figure with the least value of R is selected among the candidates. This nominal figure describes in detail the corresponding leakage source on a boiler side:

- the center of the figure defines the source location and
- the figure itself (its dimension) defines the source intensity.

In the most cases there is only one, the best nominal figure for the current geometric figure according to the criterion of matching. In general there can be several such nominal figures. If there is only one, the best nominal figure then our belief in the leakage source description is the most. If there are several such figures, the prototype generates several conclusions about the leakage sources. Then our belief in these conclusions is less firm and depends upon the number of conclusions.

The prototype strategy shown in Fig. 2, Fig. 3 and Fig. 4 is the second version of the strategy. The first version was less general. It was able to define only one leakage source on a side and to interpret only one side of a boiler. In addition, the criterion of matching treats the missed points of the nominal figures only.



Figure 4 The prototype strategy - the analysis of the specified figure

The prototype strategy is illustrated with a boiler example equipped with thirty-six instruments for measuring heat fluxes. Each of the four boiler sides has nine instruments in this example. The positions of the instruments on one side are given in Fig. 5. The locations of the measuring points define the centers of so called control fields on the boiler sides. A control field on a side is specified by a level and a column. There are three levels of control fields: up, middle and down. In addition, there are three columns of control fields: left, central and right. It is assumed that the boiler example has the characteristic leakage sources with three degrees of intensity: small, medium and high. The further assumption is that the characteristic leakage sources are positioned on the locations that are equal to the locations of the measuring points. Thus, the control fields are used in the leakage source description according to locations. The different characteristic leakage sources with different degrees of intensity give the nominal figures shown in Fig. 6. They meet the condition that they are regular figures with central or axial symmetry. All the nominal figures correspond to rectangles and their variations. The dimensions of rectangles are m x n with m, n = 1,2,3. A square is treated as a special cases of rectangles with m = n. A point is treated as a special case of rectangles with m = n = 1. A line is treated as a special case of rectangles with m = 1 and n = 2 and vice versa.

0	0	0
0	0	0
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Figure 5 The positions of the measuring points on a side

Figure 7 presents two examples of geometric figures for which the leakage source intensity interpretations are given. The prototype forms a single conclusion for the geometric figure from Fig. 7a: there are two leakage sources with small intensity. The prototype forms two possible conclusions for the geometric figure from Fig. 7b:

- the leakage source with medium intensity (Fig. 7b) and
- the leakage source with high intensity (Fig. 7c).

The final result of the criterion of matching for both the conclusions are the same: 33%.

5 Prototype

The first step to be performed in building the prototype for detecting working fluid losses in a

utility boiler is to define in detail the type of the target knowledge-based system. In other words, it necessary to define the knowledge is representation and the inference mechanism of the prototype. Since this detection problem can be considered as a classification problem and that classification problems are typically solved by using rule-based systems [3], rules are adopted as the form to represent knowledge. In addition, forward chaining is adopted as the inference mechanism. Forward chaining directly follows the way of detecting working fluid losses: detection starts from the coded ratios of heat fluxes and comes towards the conclusion about the leakage sources. The additional argument that supports the rule-based approach with forward chaining is the fact that this approach was used mostly in solving the problems relevant for detecting working fluid losses: interpretation, prescription monitoring, and control [3].





The other look at the prototype strategy presented in Fig. 2, Fig. 3 and Fig. 4 uncovers a

number of the domain objects like geometric figures, nominal figures and frames. The detailed analysis of the prototype strategy and these objects direct us towards the selection of objects (frames [3]) as the knowledge representation of the prototype, and the respective inference mechanism of inheritance and message passing.

The selection of the knowledge representation and the inference mechanism of the prototype determines the selection of the appropriate tool for the prototype development: Kappa-PC [8]. This tool supports rule-based programming with forward and backward chaining and objectoriented programming. Thus it is a hybrid tool with two different knowledge representations suitable for detecting working fluid losses.

The prototype for detecting working fluid losses in a utility boiler is implemented according to the strategy given in Fig. 2, Fig. 3 and Fig. 4 and by using the tool Kappa-PC. It has three standard sections of a knowledge-based system [10], [3]: knowledge base, inference mechanism and interface. The rules that implement the prototype strategy and the interrelated objects with their attributes and methods form the knowledge base. The menu-grouped commands form the user interface. The tool itself supports inference mechanism of forward and the backward chaining, inheritance and message passing.

6 Conclusion

The prototype for detecting working fluid losses in a utility boiler forms the hypothesis about the existence of working fluid leakage based upon the ratios of heat fluxes measured in the spatially distributed points on the boiler sides. The hypothesis specifies the leakage sources in terms of intensity and location. The location of a leakage source is described by a side and a control field. Boilers to which the prototype is applicable have to be equipped with the appropriate instruments for measuring heat fluxes.

The prototype is implemented as a knowledgebased system. It belongs to the class of systems that improve reliability of thermal power plants like those in [4], [11] and [2]. The consistency and the logic of the knowledge base have just been tested. The next step is to demonstrate the prototype to the end-users. The aim of the demonstration is to validate the prototype and then further elaborate it towards the complete system.

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