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Early detection and prediction of leaks in fluidized-bed boilers using artificial neural networks

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ABSTRACT

Leaks in fluidized-bed boilers are typically characterized by slow escalation. Early detection and prediction of such faults is an important task that has not been solved in practice yet. The paper reports a series of research and development works related to achieving early detection and prediction of leaks in fluidized-bed boilers using ANN (artificial neural networks). The obtained results were used in pilot implementation of a diagnostics and prediction system covering six blocks of a professional power plant. The diagnostics and prediction task is divided into two stages: early fault detection by virtual sensors and leak isolation using classifiers of fault state. Models of process variables were created by employing a novel two-stage structure of ANN. The resulting efficiency of leak detection is presented. Also provided is an example of 12 faults of a fluidized-bed boiler, achieving detection of 11 faults with at least two days advance prediction of a boiler shutdown. These results are compared with detections obtained by the authors previously with the use of neuro-fuzzy models. Then, the paper reports the ability to distinguish between three classes of leaks by the developed classifier of the fault state. Further possible improvements of this fault classification system are discussed.

1. Introduction

Fluidized-bed boilers [1,2] are currently built and operated in power engineering. They demonstrate many advantages (e.g. lower combustion temperatures and NO_x emission, ease of SO_2 reduction, highly varying quality of fuel). However, they are also put at a risk of leakage-associated faults [1] caused by the eroding activity of the circulating bed. The additional important cause of increased failure rate is the introduction of new environmental regulations regarding renewable energy sources. Due to those regulations, in many countries, energy from fossil fuel power plants is treated as a complement to energy from renewable energy sources (e.g. wind turbines), which have a power output that depends on temporary atmospheric conditions. Power units are working with much greater load variability, resulting in changes in temperatures and pressures. Therefore, those units are exposed to increased precipitation of sediment from water. Those sediments are transported by the working medium and can easily deposit on rough areas of inner surfaces of pipes. This causes further flow disorder and can result in overheating of pipes. Consequently, the problem of early detection of faults is even more important. A considerable number of faults of this type escalate slowly, even up to ten days or so, before they may be detected by the staff of the power plant by conventional means [3–6].

The longer the undetected leak lasts, the bigger the risk of massive damage to the boiler, which means that more money and time is needed to repair it. The estimated cost of repairing massive damage to boilers in 2003 varied from $2 to $10 million per leak [5].

In case of a fault, in addition to the costs related to the repair, significant losses may be experienced due to unplanned shutdowns resulting in unavailability of the energy block due to outage [7]. Fig. 1 presents a summary of the unavailability of two boilers in the years 2006–2013 in a power plant in Poland. The total outage days in the years 2005–2013 for the boiler under consideration are shown in the chart in Fig. 2. The chart illustrates the scale of this problem very well. In the first years of the boiler operation, many combustion chamber faults, such as boiler settings and edges, occur. This results from the ineffectiveness of many of today's commonly applied fault detection methods, which can only detect more extensive faults, thus comprising many components of installation.

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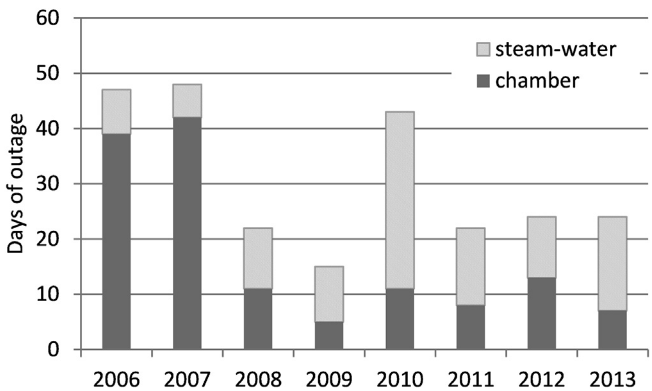

Fig. 1. The total time of outage of two fluidized-bed boilers in the years 2006–2013 in a power plant in Poland. Two main locations of leaks were distinguished: the steam-water system and the combustion chamber.

Currently, the industry puts considerable effort and resources into process optimization, while supervision and abnormal situation management are still waiting for well established, practical solutions. This approach is contrary to the conclusions presented in Ref. [7], where it is estimated that a refinery, after implementation of optimization procedures, can achieve only a 3% performance improvement, while an automated fault diagnosis system can improve performance by 5%. Therefore, it is economically justified to search for methods allowing an early detection and isolation of escalating leaks.

In power engineering, the main methods of early detection of faults, such as leaks of the boilers, almost always rely on some accompanying residual processes such as vibroacoustic emissions and temperature field variations (examples of them can be found in Ref. [8]). The data coming from measurements of such residual processes are then subjected to various complex processing methods, such as expert systems [9], using techniques based on balance signals (such as that used by Ref. [10] with Bayesian networks for boiler fault detection). Finally, many techniques of advanced process analysis include methods using AI (artificial intelligence), upon which the research work reported here is focused.

AI-based methods allow the study of complex nonlinear processes by developing and tuning their numeric models [11–13]. For example, in Ref. [11], ANN (artificial neural networks) were used for modelling ammonia emissions in composting sewage sludge. In Ref. [12], an algorithm using ANN to model an Earth-to-Air Heat Exchanger was presented. Properly trained and verified, ANN can also be used to recognize early faults before they grow and materialize into a critical state. These methods are now extensively used for testing and diagnostic tasks, including early diagnostics and prediction of boiler faults. Being part of a model-based diagnostics system [3,9,10,14,15], they use measurement signals already recorded for purposes of routine running of the plant. Because these signals are gathered for process control, no new special measuring equipment is required for detection of incipient faults. The advantage of this approach is the ability to generate missing (non-measured) process variables using numeric modelling.

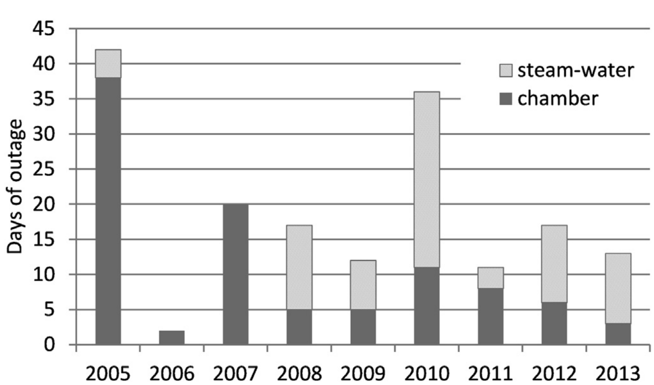

Fig. 2. The total number of outage days in the years 2005–2013 for a considered boiler.

A meticulous study of relations between standard process control variables constitutes the fundamental basis of the methods of leak detection based on AI. It has been proved that the information content of these variables is satisfactory to discover boiler leaks [14,15]. The availability of already collected data in process control systems (e.g. those of DCS (distributed control system) class) makes it possible to develop new process models or fine tune the existing ones. This eliminates the necessity of conducting process experiments in the plant, and significantly reduces development time and costs, as well as the difficulty of implementing a fault detection system. Various ways of processing the already collected data are currently being investigated [14,16–18]. In Ref. [19], a meticulous comparative study of basic data-driven fault diagnosis and process monitoring methods can be found, including an analysis of the PCA (principal components analysis), and a method based on minimum of the PLS (partial least square). In Refs. [6,18] this approach was applied to leak detection in selected sections of the boiler. Such techniques allow analysis based on a smaller number of variables, thus simplifying the development of FDI (fault diagnosis and isolation) systems. In PLS method, the variables are appropriately transposed to make them orthogonal, while preserving information relevant for fault detection.

The most popular AI techniques in the FDI area are based on ANN [20], fuzzy logic [21], including NF (*neuro-fuzzy*) models, and GA (genetic algorithms) [22]. Research is underway on those topics as promising methods of fault detection and process monitoring in different industries, including the power industry. Models of various difficult heat conversion nonlinear processes are developed using fuzzy logic [15,23–25] and ANN [12,13,26–28]. In Refs. [24,25] fuzzy models of a heat exchanger were developed and used for fault detection in a pilot installation. ANN and NF present an advantage over other techniques because they can learn and be trained for diverse tasks. Reports discuss proposed ANN applications to fault detection [29], supervision of internal combustion engines (detection of misfire in turbocharged diesel engines [30]), monitoring engine condition [31], and fault diagnosis by classification of symptoms [32]. Similarly, in Ref. [33], ANN were used to detect leakages in three test fault cases in power plant heaters. In Ref. [34], neural networks were proposed as a part of the virtual boiler diagnostic system based on faulty states pattern recognition. An analysis of heat absorption caused by fouling and slagging during biomass combustion was successfully conducted in Ref. [35]. The conclusion of the last two papers is that ANN are more versatile tools for monitoring than monitoring based on classical analytical models using sets of equations derived from physical process descriptions. ANN are also used extensively for process monitoring [14,15,35–37], accurate prediction of flue gas sulphuric acid dew point [38], and modelling a heat transfer coefficient in the combustion chamber of a CFB (circulating fluidized bed) boiler [13]. Enhancement and optimization of thermal processes using ANN [39] and GA [40] are also researched.

All model-based methods (both black-box style as ANN and classic analytical) must be assessed for their efficiency (i.e. a comparison of model and real process critical variables). To evaluate a residue square error, calculus is usually preferred. More