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A novel plugged tube detection and identification approach for final super heater in thermal power plant using principal component analysis

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ABSTRACT

During startup or normal operations, tube monitoring systems for steam boilers can considerably improve efficiency and reliability in thermal power plants (TPPs). Although several attempts have been made to detect and locate boiler tube leaks, what seems to be lacking is the study for tube plugging, one of the fundamental causes of the leaks and other tube failures. Scale and deposit formations on inner surfaces of tubes cause the tubes to be plugged. Although the formations can be suppressed and removed by chemical treatments for boiler water and steam blowing during startup procedures, it is still difficult to monitor and prevent tube plugging during startup or normal operations. In this paper, a novel plugged tube detection and identification approach is proposed for final super heater (FSH) tube banks. Principal component analysis is applied to tube temperature data for plugging detection and identification. The data are collected from thermocouples installed on the FSH outlet header section. To identify plugged tubes, contribution analysis and the characteristics of plugged tube temperatures are employed. To verify the performance of the proposed method, tube temperature data from an 870 MW supercritical coal-fired TPP are used. The experiment results show that the proposed method can successfully detect and identify plugged tubes. The proposed method can help to decide how many times steam blowing should be performed, whether startup procedures should be delayed or stopped, and which tubes should be maintained. Furthermore, severe tube failures can be prevented by avoiding damage from overheating due to tube plugging.

1. Introduction

Due to increasing load demands and high variations, power plants are confronted with strict requirements for efficiency and reliability; these can be fulfilled by preventing boiler tube failures in advance. In the chemical, refinery, and power industries, steam boilers are critical units for transforming water into steam. Approximately 60% of boiler outages are caused by tube failures [1] that may occur because of overheating, erosion by soot-blowing steam or ash particles, and waterside and fireside corrosion [2,3].

Tube leakage is the most common failure type in thermal power plants (TPPs). Although make-up water systems can temporarily control pinhole leaks, the leaks should be corrected during scheduled shutdowns. The leaks eventually lead to secondary damage (e.g., tube explosions) if not handled properly. Detecting the leaks accurately and reliably is indispensable for establishing proper shutdown procedures, reducing repair time, and minimizing financial losses related to maintenance and labor costs [4].

One of the reasons for tube blockages and leaks is scales and deposits formed on inner surfaces of boiler tubes [5,6]; corrosion products introduced into boilers with feedwater (FW) and contaminants in makeup water or condensate water lead to the formation of scales and sediments. As the FW evaporates, the scales and deposits adhere to heating surfaces on tube insides. If not eliminated, they decrease boiler thermal efficiency and eventually lead to severe tube failures. To prevent the formations in advance,

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boiler water should be purified and treated thoroughly. Using chemical additives, pH and oxygen concentrations are regulated to suppress scale formations and corrosion. During startup operations, steam blowing is also performed several times to clean the inner surfaces of super heater (SH) and reheater (RH). Despite the difficulty in cleaning the inside of SH and RH due to their geometric shapes, the steam blowing removes the scales and deposits effectively. Keeping the tube insides clean can improve boiler efficiency, raise steam purity, and reduce maintenance, repair and replacement costs.

In recent decades, several studies have been proposed for tube leakage detection and location. For example, Afgan et al. [7] described the development of an expert system for tube leakage detection based on selected diagnostic variables obtained by radiation heat flux measurements. In Ref. [8], a model-based least-squares algorithm with a time-varying forgetting factor was developed for leak detection in boiler steam-water systems. Sun et al. [9] proposed a leakage detection method that combines a new data preprocessing technique and a fault detection scheme with dynamic principal component analysis (PCA). Widarsson and Dotzauer [10] used an early warning method based on Bayesian network and mass-balances on both steam and combustion sides to detect tube leaks in a recovery boiler. An et al. [1] used maximum likelihood and phase transformation estimators to localize boiler leakages based on a four-element acoustic array and a set of hyperbolic equations. Zhang et al. [4] used a three-dimensional space-location algorithm based on an acoustic array to localize water-cooling wall tube leaks in a 600 MW coal-fired boiler. Rostek et al. [11] reported an artificial neural network based method to detect and predict tube leaks in fluidized-bed boilers.

The research mentioned above has several limitations, although the methods can detect and localize boiler tube leaks effectively. First, the above methods did not consider tube plugging, one of the most common causes of tube leaks and other tube failures. In this paper, the term “plugging” does not mean to stop the flow of tube insides by some intentional ways; the term means that the flow is interrupted because the tubes are partially plugged by scales and/or foreign materials. When the fluctuation range of the load is large, the main steam temperature and pressure change frequently, and the amount of sediment inside the tubes rises gradually [11]. The sediment is easily deposited in rough areas inside the tubes, and impedes the smooth flow of working fluids; these may cause serious damage to boiler tubes from local overheating. Secondly, no studies have ever tried to monitor tube conditions during startup. Tube corrosion and stress-rupture from short-term overheating often occurs in startup mode [12]. Therefore, tube-condition monitoring during startup contributes to the prevention of tube failures significantly.

PCA is the most popular multivariate statistical technique that can handle high-dimensional, noisy, and correlated data efficiently, and thus, has been widely used for data compression [13], denoising [14,15], feature extraction [16], pattern classification [17] and face recognition [18–20]. In PCA, data samples in correlated original space are projected into a new uncorrelated and reduced space, while retaining the original information as much as possible. PCA has also been successfully applied to fault detection and diagnosis in various industries [21–25] where process data are complex and highly correlated. The main advantages of PCA-based methods can be briefly summarized as follows. For one thing, only historical data are needed, without any prior physical knowledge about the target systems. Furthermore, robust performance can be achieved, since only the main parts that drive the target systems are considered and unnecessary parts, such as random noise and uncontrollable disturbances, are disregarded by dimensionality reduction. One final point is that analysis with practical computation and time effort is possible, because analysis complexity is reduced.

In this paper, we propose a novel plugged tube detection and identification approach for final super heater (FSH) tube banks in startup mode. Plugged tube detection corresponds to determine whether tube plugging has occurred in the target tube banks; and if tube plugging is detected, plugged tube identification is performed to find the plugged tubes. In the proposed approach, to detect and identify plugged tubes, PCA is applied to tube temperature data from thermocouples installed on the FSH outlet header section. In the early stages of startup, a plugged tube temperature is lower than normal; on the other hand, after starting the inflow of superheated steam into a high-pressure (HP) turbine (i.e., after synchronization), plugged tube temperature is higher than normal [26]. The proposed PCA-based method identifies plugged tubes using 1) the characteristics of plugged tube temperatures and 2) the results of contribution analysis for the time interval where tube plugging was detected.

The steam temperature from FSH is controlled by firing rate, FW flow, and multi-stage attemperators. To avoid failures of SH, RH and turbines due to extremely high metal temperature, it is indispensable to control the steam temperature precisely [5,6]. Although there are control installations for superheated steam temperature, the temperature may show abnormal fluctuations because of several factors [27,28]. The temperature can be lower than preset temperature due to insufficient excess air and/or fouling formed on outer surfaces of FSH; slag attached to outer surfaces of waterwall and too much excess air increase the steam temperature. The uneven temperature of flue gas passing through FSH influences on the steam temperature of each tube.

The most significant factor affecting the superheated steam temperature is the cleanliness of the tube outer surfaces. Ash particles from coal combustion form into slag (or fouling) at the outer surfaces of waterwall (or SH and/or RH). The slag decreases heat flow rate from fireside to waterside; the temperature of flue gas passing through FSH increases so that the superheated steam temperature increases. The fouling decreases heat flux absorbed by the main steam; it makes the temperature of the steam lower than rated value. In Subsection 6.3, we discuss the effects of slag, fouling and excess air on the proper operation of the proposed method.

To verify the performance, the proposed approach is applied to tube temperature data collected from an FSH tube bank in an 870 MW supercritical coal-fired TPP. Experimental results show that the proposed method can effectively detect and identify plugged tubes. The proposed approach can support decision-making processes directly related to boiler efficiency and reliability, such as adjusting the number of steam blowing, deciding whether to stop or delay startup procedures, and determining the tubes to be maintained. Furthermore, severe tube failures (e.g., tube leakage and explosions) can be avoided by reducing damage from local and short-term overheating due to tube plugging.

The remainder of this paper is organized as follows. Section 2 describes the once-through boiler (OTB), the FSH tube banks in the target TPP, and the behavior of tube temperatures measured by thermocouples in startup mode. Sections 3 and 4 explain the PCA-based plugged tube detection and identification method. Section 5 presents the experimental results, and Section 6 presents the discussion about: the advantages of PCA-based method over limit checking (also known as threshold checking), the installation costs of thermocouples and their financial benefits, the effects of slag, fouling and excess air on the operations of the proposed method, and decision supports by the proposed method during startup or normal operations. Finally, we give our conclusions in Section 7.