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Performance degradation diagnosis of thermal power plants: A method based on advanced exergy analysis

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ABSTRACT

The performance of energy systems usually degrades gradually away from the best operation conditions during continuous operation. Since the components in an energy system are interconnected with each other, the performance degradation or anomalies occurring in one component can propagate downstream, affecting the performance of other components and even that of the whole system: Any anomaly occurring in a component may cause obvious performance degradation. However, locating the components where anomalies occur in an effective and accurate way is often difficult due to the interactions among components. Therefore, in this paper, we propose a diagnosis method to effectively locate the components with performance degradation, to find the sources over the system which may cause the degradation, thus to prevent the energy systems from anomalies. The proposed diagnosis method is based on the advanced exergy analysis, in which the exergy destruction within each component is split into endogenous and exogenous parts. The endogenous exergy destruction is due to the irreversibility of the component itself, while the exogenous is caused by the inefficiencies of the remaining components. The exogenous exergy destruction is, in fact, the major obstacle to accurately pinpoint the original sources causing the performance degradation. Therefore, the proposed method compares only the endogenous exergy destruction between the reference and degradation conditions for degradation quantification, once the degraded components are identified by an effective internal indicator. The diagnosis method is then applied to a case study of coal-fired power plant, in which the anomalies is introduced to one specific component. It is shown that the proposed method successfully and readily locates, and more importantly, quantifies the degradation.

1. Introduction

Electric power is one of the most crucial secondary energies to drive the society development. In China, thermal power generation, mostly pulverized-coal fired power plants, has dominated the power mix for decades: The shares of installed capacity and electricity generating capacity have reached 69.3% and 78.4% by the end of 2013 [1]. However, the old-fashioned thermal power plants generally suffer from low efficiency and high emission of pollutants and greenhouse gases. In particular, the CO_2 emission from coal-fired power plants currently contributes more than 40% to the total amount of CO_2 emissions in China [2]. Therefore, strict regulations have been imposed on coal-fired power plants in China to improve the thermodynamic and environmental performances in the past ten years. As a result, the average specific coal consumption of coal-fired power plants has been reduced dramatically by 66 g/kW h from 385 g/kW h in 2001 to 319 g/kW h in 2014 [3].

Except for the efficiency improvement, another significant point is to guarantee the reliability of the components and the whole system for continuous, nonstop operation, so that the benefits from the efficiency improvement can be maximized during operation. To evaluate the component reliability, and to identify and locate the malfunctions in the components, frequent energy-saving diagnosis is necessary to monitor the system conditions during operation. More importantly, proper diagnosis can point out the origins (sources), and the features of the operation malfunctions, and can qualify the exact influence of the malfunction on specific components and the overall system. Currently, available diagnosis methods are mostly based on the comparison of energy efficiency or fuel consumption between the current operating state of the

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Nomenclature

HP	high-pressure turbine
IP	intermediate-pressure turbine
LP	low pressure turbine
ACC	air-cooled condenser
H*n*	the *n*th heater
DA	deaerator
h	specific enthalpy, kJ/kg
e	specific exergy, kJ/kg
s	specific entropy, kJ/(kg K)
$\dot{m}$	mass flow rate, kg/s
$\dot{E}$	exergy flow rate, kg/s
$\dot{E}_D$	flow rate of exergy destruction, kg/s
Greek symbols	
α	performance parameter
ζ	internal exergy parameter
ε	exergy efficiency
θ	internal parameter
η	isentropic efficiency
Mathematical symbols	
f	function capturing the endogenous exergy destruction
Subscripts and superscripts	
k	the *k*th component
in	inlet
out	outlet
EN	endogenous
EX	exogenous
REF	reference state
DEG	degradation state

actual system and the "reference" state, which is a condition without any anomalies [4,5]. Several key aspects to make the diagnosis more accurate and effective have been investigated in literature, e.g., acquisition and validation of measured and monitored data to improve the data accuracy and reliability for confident modelling and behaviour characterization of the considered system [6–8], evaluation methods to reveal the fuel consumption and its distribution [9,10], and diagnostic approaches to quantify the thermodynamic inefficiency, to locate operation malfunctions, and to find the causes of specific thermodynamic malfunctions [11].

The performance comparison between the reference and malfunction states is useful for developing strategies to improve the component reliability. However, this comparison generally does not consider the fact that the performance degradation does not occur suddenly at a certain point but accumulates continuously from the reference state all the way to the failure. This continuous variation or degradation of system performance can be caused to by many factors, such as (1) the ambient conditions, e.g., cutting force, friction, environmental temperature and vibration, and (2) the material degradation, e.g., component rust and aging. The deterioration usually accumulates gradually and at certain point the components will lose their original functions, which results in bad performance with a lower energy efficiency. Note that during degradation, the component usually still works but has a larger probability of failure. Therefore, it would be helpful for the targeted maintenance to forecast possible failures, find the origins of malfunctions, and thus prevent considered energy systems from failures.

Since the performance degradation usually is interactively caused by many factors, it becomes difficult to analyze the degradation by using mechanical detection approaches [12]. Thus, additional methods that could accurately and reasonably evaluate the true performance of the considered system and components simply from the process variables under monitoring are necessary. For example, the data reconciliation approach [13], a model-based mathematical method, can be used to estimate the states of components by establishing reliable energy and mass balance of the whole system from the measurements (if with enough redundant measurement points). For its application to malfunction diagnosis, a set of malfunction variables, which best describe the malfunction behavior of the involved components and the system, have to be properly chosen in advance, and in fact, determines largely the diagnosis results. However, it is still not clear which criteria perform the best for selecting the malfunction variables [14]. Another group of commonly-used methodologies is the thermoeconomic methods based on different concepts of exergetic variables [15]. To compare different thermoeconomic diagnosis methods, the TADEUS project [16,17] was initiated and suggested thermoeconomics based on the concept of the unit exergy cost for effectively evaluating the malfunction effects. However, the suggested thermoeconomic method seems often ineffective in identifying the sources of anomalies [18]. This is mainly due to the fact that the conventional exergy-based methods can only identify the components with the largest exergy destruction; however, they cannot distinguish the sources of the exergy destruction [19,20]: whether it is caused by the considered component itself, or due to the irreversibility occurring in the remaining components of the system. From this perspective, a diagnosis approach based on the advanced exergy analysis [19–21] may perform significantly better than those based on conventional exergy-based analysis. In the advanced analysis, the exergy destruction within a component is split into an endogenous part, which is caused by the irreversibility of the component itself, and an exogenous part, which is caused by the irreversibilities of other components. In such a way, the impact of how one component's performance is affected by the remaining components can be revealed. More importantly, the interaction between any two components or any two clusters of components can also be obtained [20,22,23].

In this paper, we propose a diagnosis method based on the advanced exergy analysis for more insights on the performance degradation process. The proposed method is then evaluated by a case study for identifying the anomaly in thermal power plant. The paper is organized as follows: In Section 2, the major theory of exergy analysis (Section 2.1) and advanced exergy analysis (Section 2.2) is introduced. Then, the propagation of the performance degradation is described (Section 2.3). Afterwards, with a variation of the internal parameter (Section 2.4), the diagnosis procedure we propose is illustrated in Section 2.5. Subsequently, a case study is performed to assess the proposed method and results are discussed (Section 3). In Section 4, a comparison with the thermoeconomic method suggested by the TADEUS project is performed to highlights the merits of the proposed method. Finally, the conclusions are drawn in Section 5.

2. Degradation diagnosis

2.1. Conventional exergy analysis

The exergy analysis identifies the location, the magnitude and the sources of thermodynamic inefficiencies in a thermal system