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Probabilistic performance assessment of a coal-fired power plant

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HIGHLIGHTS

- Power plant equipment is usually oversized to account for input uncertainties.
- Oversized equipment degrades its rated efficiency and increases capital cost.
- A stochastic methodology to assess probabilities of equipment failure was proposed.
- The methodology was proven applicable for design and analysis of the power plants.
- Estimated high reliability indices allow reducing power plant equipment oversizing.

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ABSTRACT

Despite the low-carbon environmental policies, coal is expected to remain a main source of energy in the coming decades. Therefore, efficient and environmentally friendly power systems are required. A design process based on the deterministic models and application of the safety factors leads to the equipment oversizing, hence fall in the efficiency and increase in the capital and operating costs. In this work, applicability of a non-intrusive stochastic methodology to determine the probability of the power plant equipment failure was investigated. This alternative approach to the power plant performance assessment employs approximation methods for the deterministic prediction of the key performance indicators, which are used to estimate reliability indices based on the uncertainty of the input to a process model of the coal-fired power plant. This study revealed that high reliability indices obtained in the analysis would lead to reduced application of conservative safety factors on the plant equipment, which should result in lower capital and operating cost, through a more reliable assessment of its performance state over its service time, and lead to the optimisation of its inspection and maintenance interventions.

1. Introduction

Despite the environmental concern caused by greenhouse gas emissions from the power sector, coal remains a key primary energy resource globally [1,2] and its share in the energy mix has recently increased in countries such as Germany, Spain, China and the United Kingdom, mainly due to the emergence of shale gas [3–5]. Although this trend is inconsistent with the low-carbon scenarios, it is expected to continue as the global coal demand is predicted to increase from 155 EJ to 186 EJ between 2011 and 2018. Additionally, the coal demand in China alone is projected to increase by 24%, from 75 EJ to 93 EJ between 2011 and 2017 [3,6]. Nowadays, the global fleet of the coal-fired power plants operates with an average net thermal efficiency of $33\%_{LHV}$. For this reason, coal-based power generation is responsible for over 70% of the total CO_2 emissions from the power sector [3]. This makes the power sector one of the major contributors towards the global CO_2 emissions [7–11]. It is expected that the substitution of a subcritical unit with a supercritical unit of the same capacity, operating with the net thermal efficiencies of above $40\%_{LHV,}$ would result in a 15% reduction in CO_2 emission [12].

Application of the simulators has been identified as a powerful and cost-effective method in the design and analysis of the advanced power plant processes. Hence, assessment of both coal and gas power plant performance under different loads [13,14], combined power and heat plants configurations [15,16] and CO_2 capture plant retrofits [17,18] is widely conducted using computational process

Abbreviations: FORM, first order reliability method; SORM, second order reliability method; ULS, upper limit state; LLS, lower limit state; SRSM, stochastic response surface method; MPR, multivariate polynomial regression; LSM, least squares method; MCS, Monte Carlo simulation; KPI, key performance indicator.

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Nomenclature

Latin symbols

g	dependent variable
L	allowable (permitted limit) for a given variable
M_u	design matrix
$N_{failure}$	number of failures indicated in Monte Carlo simulation
N_{runs}	number of runs in Monte Carlo simulation
P_f	probability of failure
V	actual value for a given variable
x_k	independent variable in multi-variable system
X	multi-variable vector

Greek symbols

β	reliability index
ϕ^{-1}	inverse of the normal cumulative distribution

modelling tools. However, the deterministic nature of such models does not consider the randomness of the input variables [19], hence does not provide a definitive representation. Moreover, it is a common design practice to oversize the power plant equipment to account for uncertainties in process parameters that result mostly from the fluctuation of the power plant load to meet the market energy demand, but also due to integration of auxiliary systems to the power plant. This is usually achieved by applying the safety factors in design of rotating equipment, heat exchangers, and transformers. These units are typically selected according to sizing guidelines based mainly on field experience, so that material and operability limits are not exceeded. However, such an approach results in a considerable parasitic load on the system as the oversized and under-loaded equipment degrades its rated efficiency, leading not only to higher operating but also capital costs. Furthermore, this may trigger risks such as an increase in vibration stresses or unstable operation [20–22]. Also, some unit operations, such as pulverisers, may become bottlenecks of the process resulting in a limited load [23]. Equipment overheating and a fall in the power production could also be observed if the system is under-sized [20]. Ultimately, such poor design of the power plant equipment and an increased system complexity, among others, are identified as the main causes of failures [24].

In contrast to application of the safety factors, a probabilistic performance assessment approach provides a set of analytical tools which can be used to estimate the probability of failure for particular equipment and systems. These tools systematically consider the impact of the input parameter uncertainty. Frey and Rubin [25] have suggested that stochastic modelling provides a more profound insight into the process performance and may lead to different decisions compared to the deterministic analysis. Their study, where the performance and costs of an advanced technology for SO_2 and NO_x emission control from coal-fired power plant was stochastically analysed, revealed that uncertainties have a considerable effect on the system costs. In their pioneering work, Salmento and Rubin [26] have developed a stochastic modelling framework for the cost analysis of the environmental control systems which allows benchmarking novel technologies, such as integrated gasification combined cycle [27], carbon capture and sequestration [28] or abovementioned SO_2/NO_x emission control technologies with the existing technologies. According to Adhikary et al. [29], only a few studies have been conducted to investigate the reliability of individual pieces of equipment in the coal-fired power plants. In most of these studies, the reliability and availability indices for the power plant were estimated using equipment failure rates and mean times to failure [24,29ã 32]. Guidelines for probabilistic modelling were proposed by Shayan [30] who developed a model that predicts the reliability of the coal milling system. Arora and Kumar [31] performed a stochastic analysis to calculate the availability of the ash handling system in a coal-fired power plant. Gupta and Tewari [32] used a probabilistic modelling in a Markov Birth-Dead process to represent the system operation and used the results obtained to optimise the process availability. These studies have shown that planned maintenance would increase the system availability, hence reliability, however at the expense of increased maintenance cost. Yet, the tools developed and the results obtained can be applied to design of new similar systems.

As no probabilistic assessment of the coal-fired power plant performance has been presented in literature yet, the aim of this work is to provide a systematic methodology that combines a finite number of deterministic numerical simulations of the power plant to approximation methods and Monte Carlo simulation (MCS). This is used to estimate the probabilities that specific thresholds in the system are exceeded in the presence of uncertain system inputs and boundaries. Similar methods have been successfully applied in safety-critical applications of other industries such as nuclear, aviation, manufacturing and offshore [33–36].

2. Coal-fired power plant modelling

2.1. Model description

This study analyses a performance of the supercritical coal-fired power plant located in India with a typical configuration (Fig. 1). The power plant follows the grid electricity demand and operates at its rated gross power output of 660 MW_{el} with a net efficiency of $38.8\%_{HHV}$ at a peak demand. The process model for this system has already been developed in Aspen Plus and its prediction, including the part-load operation, has been validated against the data available in the literature [14]. In general, the model of the power plant consists of three interconnected sub-systems: a supercritical steam boiler, a flue gas emission control system, and a steam cycle.

In the boiler sub-model, pulverized coal prepared in the mills is entrained by the primary air that is a part of the total air used in the coal combustion process. Feedwater enters the boiler via the economiser at nearly 309 bar at a base load and pressure losses are accounted for through a general pressure drop correlation. Live steam leaves the boiler at 537 °C and 242.2 bar and is expanded in the high-pressure turbine, and then returned to the boiler where it is reheated to 565 °C and subsequently expanded in intermediate- and low-pressure turbines, which are coupled to an electric generator. Waste heat from the flue gas leaving the boiler is recovered in an air preheater, before the flue gas enters the emission control system comprising the selective catalytic reduction reactor for NO_x, the electrostatic precipitator for particulate matter, and the flue gas desulphurisation unit for SO_x emission control.

A typical design of the coal-fired power plant includes several steam extractions to the high- and low-pressure feedwater heaters. This aims to increase the net thermal efficiency by increasing the average temperature of heat addition in the boiler. The pressure distribution in the system, which is dependent on the steam generation rate, is represented using the Stodola's ellipse law.

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