Energy Conversion and Management 87 (2014) 1248–1260

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Dynamic model of a natural water circulation boiler suitable for on-line monitoring of fossil/alternative fuel plants

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ARTICLE INFO

Article history:
Available online 9 July 2014

Keywords:
Natural circulation boiler
Nonlinear dynamic model
Physical modeling
On-line monitoring
Process disturbance analysis

ABSTRACT

The environmental protection policies and legal obligations motivate process industries to implement new low-emission and high-efficiency technologies. For the purpose of production process optimization and related control system design it is worthwhile to first build an appropriate process model. Apart from favorable execution speed, accuracy, and reliability features, the model also needs to be straightforward and only include the physical and design characteristics of the overall plant and its individual components, instead of relying on empirical relationships. To this end, this paper presents a nonlinear dynamic model of the single-drum natural-circulation steam boiler evaporator circuit, based exclusively on the fundamental physical laws of conservation of mass, energy and momentum, wherein the reliance upon empirical relationships has been entirely avoided. The presented boiler system modeling approach is based on the analysis of the physical phenomena within the boiler drum, as well as within downcomer and furnace tubes, and it also takes into account the boiler system design-specific features such as cyclone steam separators, thus facilitating the derivation of a fully-physical process model. Due to the straightforwardness of the derived process model, it should also be useful for the analysis of similar steam boiler facilities, requiring only adjustments of key operational and design parameters such as operating pressure, temperature, steam capacity and characteristics of ancillary equipment such as pumps. To illustrate the model effectiveness, it has been employed in the analysis of the phenomena occurring in different parts of the particular boiler system for the case of realistic disturbance event, wherein the model inputs are based on the field data from the boiler on-board data collection system (DCS). It is anticipated that the proposed physical boiler model should also be easily adapted for the case of boiler systems utilizing alternative fuels, thus aiding in the optimization of the dedicated control and supervision systems.

1. Introduction

Reliable operation of any boiler system is a key factor for the safety of plant personnel and consistent energy supply. For example, by observing the behavior of single-drum water-tube boilers with natural circulation, the highly-dynamic operation of the boiler-based production facility, coupled with sudden changes of process parameters, dynamic variables and inadequate water level control, may often result in a notable drum water level disturbances [1]. These disturbances, coupled with external loads, may account for a large number of unplanned plant shutdowns [2]. Hence, thorough boiler modeling represents one of key factors for operational performance assessment [3]. This is particularly important for systems that are separated from the distribution network (isolated or islanded power systems) because consumer's energy demand would need to be met continuously without the possibility of external power backup. Finally, accurate boiler modeling may be crucial to minimizing the energy loss/exergy destruction [4] and related boiler system payback analyses [5]. Accordingly, considerable research efforts have been dedicated to developing accurate boiler models for the purpose of internal boiler state monitoring and overall control system optimization for a wide range of boiler internal designs and fields of application, as outlined in [6] and references therein.

In order to obtain a comprehensive picture of overall boiler operation and steam generation process, a precise model formulation based on the basic physical laws of conservation of mass and energy should be employed [7], which may also be expanded by the boiler media (water and steam) momentum conservation equations [8]. Indeed, the physical modeling approaches

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http://dx.doi.org/10.1016/j.enconman.2014.06.059
0196-8904/

frequently employ energy balance analysis [9], taking also into consideration the specific enthalpy of the boiler system [10] in order to derive a simplified process model. The aforementioned approaches have resulted in several models of varying levels of complexity, such as the dynamic simulator of water-tube boiler system [7], a lumped-parameter model of boiler water level dynamics [11], and a boiler model combining physical and empirical relationships [12]. Parameter estimation of physical boiler process models can be based on the suitably chosen Kalman estimator [13] used for off-line identification based on previously recorded boiler experimental data. Instead of a fully-physical boiler model, a hybrid model can be used [14], combining energy balance equations for the analytical part of the model, and a neural network-based artificial intelligence system for the empirical modeling of those quantities which are difficult to measure. Neural network systems have been also applied for: (i) emulation of simplified dynamic behavior of a boiler system [15], (ii) on-line boiler efficiency estimation based on averaged process measurements [16], and (iii) on-line boiler diagnostics [17] with neural network-based data processing and pattern recognition alongside a more complex boiler CFD model [18]. The boiler control system design, on the other hand, typically requires a non-parametric process model, such as: (i) linear ARX and ARMAX time-series discrete-time model [19], (ii) a linear time-invariant state-space model [20] for the design of a robust H_∞ controller or state estimator for boiler monitoring purposes [21], and (iii) nonlinear ARX (NARX) boiler model in the form of a fuzzy neural network (FNN) [22]. The model parameter estimation in the above cases is based on appropriate test signals applied in the vicinity of the boiler operating point, and suitable process model identification techniques. Model validation may either be performed through comparative simulation tests against other models [11], including comparison with data from the literature [8], or against experimental data as suggested in [6,23]. Naturally, the latter approach may be considered as a kind of an ultimate model assessment, especially if in-field application is considered.

Still, in order to cover all the aspects of steam generation process within the boiler, and to facilitate high accuracy of the boiler model performance (i.e. the ability to faithfully track highly-dynamic internal boiler phenomena over a wide range of operating conditions) it is vital to build a fully physically-based boiler model taking into account the boiler system internal structure and boundary conditions [8], and basic physical laws of conservation of mass, energy and boiler media (steam + water) momentum. The utilization of empirical relationships, such as proposed in [6], should be avoided because they may not be universally applicable to any type of boiler facility, whereas a physically-based modeling approach would be easily applied to any boiler facility of the similar type. Thus, only the boiler system parameters (e.g. drum dimensions, fuel type, and similar) would have to be adjusted in order to facilitate faithful emulation of actual boiler system behavior. To this end, this paper analyzes a steam generator with a single drum and natural recirculation, wherein the steam generator drum design is of the frequently used type, whose integral part is the steam separation system based on cyclone steam separators. The goal of this work is to derive a fully-physical lumped-parameter steam generator (boiler) process model based on fundamental physical laws, while at the same time avoiding any reliance on empirical relationships between model dynamic variables (in contrast to boiler modeling approaches proposed in [6,14]). The subject matter presented herein is based on the operation of a plant used for the production of superheated steam, as a part of the larger power production facility. The paper analyzes the dynamics of the boiler system while taking into account pressure and enthalpy changes within the drum, as well as the dynamics of the downcomer and furnace tubes, and validates the model against the experimental data obtained from the dedicated data collection system (DCS). The resulting straightforward model is suitable for the analysis of different boiler system dynamic effects, and on-line monitoring and estimation of key boiler dynamic variables. Since the model is also not limited by the fuel type, it could be well-suited for steady-state analyses aimed for economic assessment through energy balance analysis for both the traditional (fossil fuel) and alternative fuel boiler systems [24], which have become increasingly attractive in recent years [25], especially in the context of cogeneration plants [26]. The simulation model has been developed and implemented within MATLAB/Simulink software environment [27].

The paper is organized as follows. Section 2 briefly describes the boiler facility in question, including the boiler drum water level control system. This is followed by detailed derivation of the boiler system model in Section 3, based on the fundamental physical laws of conservation applied to each of the boiler subsystems. Thus obtained boiler system model is summarized in Section 4 in a compact model form suitable for simulation model building. Section 5 presents the comparative results of boiler system simulation and field test experimental data for the case of abrupt disturbance transient along with detailed analysis of the observed event. Concluding remarks are given in Section 6.

2. Facility description

2.1. Boiler specification

The considered boiler system with nominal operating pressure and temperature of 80 bar/510 °C and a total power output of 84 MW is an integral part of a larger power plant, and is used as the main source of steam for the operation of 30 MW condensing turbine with two controlled extractions and additional heating power supply for an oil refinery production facility. Fig. 1 shows the simplified schematic representation of a boiler with natural water circulation. The pump delivers the feed-water under the pressure of about 120 bar with the capacity of 40–105 t/h. The pump flow is controlled by a control valve commanded by the water level controller. After passing through two economizers and heating to a temperature of approximately 265 °C, the feed-water enters the boiler drum. Apart from the feed-water, a two-phase medium (water + steam) is returned to the drum from the recirculation circuit riser tubes. Most of the water exiting the drum comes through the downcomer, with a rather small ratio of approximately 2% being passed through the desalting (desalinization) tubes, while the produced steam exits the drum and enters the superheaters before finally being transported towards the consumers. Since the boiler with natural circulation is discussed in this paper, the circulation in evaporator part of the boiler occurs due to density differences of the medium in downcomer and furnace pipes.

Inside the boiler drum, a dynamic balance of water and steam mass and energy accumulation processes is being continuously maintained. Accumulation of mass and energy is caused by: (i) different and variable flow of input and output medium, (ii) energy losses due to drum walls-medium heat exchange. Drum water output and the return of two-phase medium to the drum are variables depending on the processes in the boiler. Desalting water valve opening typically does not change or changes rarely once it has been adjusted, so that its mass flow can be regarded as constant, or it can be determined from the known valve position.

2.2. Boiler control system overview

The simplified schematic representation of inlet and outlet flows of medium into main parts of a boiler, including simplified system of water level control inside a drum, is shown in Fig. 2. The proposed