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Research paper

Grey-box modeling of a low pressure electric boiler for domestic hot water system

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HIGHLIGHTS

- The physics-based model of the stratified electric boiler is developed.
- Experimental setup is presented to measure the data.
- Measured data is used for parameter estimation and model validation.
- Physics-based model is implemented in Simulink® and its parameters are estimated.
- Model's performance is evaluated analytically and compared to the measured data.

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ABSTRACT

Due to the increasing cost of electricity and its variable price structure throughout the day, it is of interest to shift the loads to off-peak hours. In this work, the grey-box model of a domestic hot water electric boiler is presented. The developed model is useful for the development of new supervisory controller to help offset the boiler heating load to off peak hours in a smart grid environment. The boiler used in this research is an integral part of the domestic hot water system and residential Heating, Ventilating and Air-Conditioning (HVAC) systems in many Swiss homes. The water stored in the boiler is not well mixed and thus the temperature varies along the height of the boiler. The cold water is entering in the boiler from the bottom and the hot water is drawn at the top. This results in a temperature gradient along the height of the boiler which needs to be predicted to accurately simulate the temperature dynamics of the boiler. The boiler was divided into eight stratified virtual layers and physics-based model was developed by writing the heat balance equation for each layer. Experimental setup consisting of boiler, sensors and data logger was prepared at the Institute of Aerosol and Sensor Technology (IAST), University of Applied Sciences and Arts Northwestern Switzerland (FHNW) to measure the training and test data for the model including the temperature of each layer, ambient temperature, boiler's power consumption and flow rate of water entering into the boiler. The parameters of the physics-based model were estimated from the measured data thus converting it into a grey-box model. The model performance was visually compared to the measured data and was also evaluated analytically using several metrics showing the high accuracy of the developed model.

1. Introduction

Federal Office for the Environment (FOEN) of Switzerland reported that in 2013 over 80% of the residential energy was consumed by the heating systems including hot water [1]. During the peak energy demand periods the cost of generating and distributing electricity is higher than off-peak periods, so the primary loads (e.g. boiler, heat pump and chiller) should remain switched off and vice versa to reduce the operating cost of these systems [2–4]. However, an accurate control is required to avoid the shortage of hot water resulting in the operation of the boiler during peak hours. Most of the domestic hot water is provided by either electric or gas water heaters due to their low installation cost

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but on the other hand these domestic hot water heaters have low energy utilization efficiency [5]. Therefore smart control system is needed to reduce the operating cost of these systems.

The models are generally classified as data-driven, grey-box and physics-based [6]. A detailed review of modeling methods for HVAC systems was reported in Ref. [7]. Physics-based models are also known as white-box, forward or analytical first principal models. These models are derived under few or no assumptions using the detailed knowledge of underlying physics and engineering principles of the process. They require significant effort to develop and calibrate but do not require the system input–output data measurement for model development. Physics-based models have good generalization capabilities but suffer from the lower accuracy compared to data-driven models [6]. Data-driven models (black-box models or inverse models) on the other hand fit a linear or nonlinear mathematical function to the measured input–output data of a system and do not require the understanding of the physics of the process. They are easier to develop compared to the physics-based models and have high accuracy as well but their accuracy decreases as the test data deviates from the training conditions. Grey-box models use the physics-based model as the mathematical structure and the measured data of the inputs and output of the system to estimate its parameters. Since, physics-based models have high generalization capabilities whereas data-driven models have high accuracy, grey-box models therefore have both the benefits i.e., high generalization capabilities and high accuracy [8].

In order to simulate the HVAC systems in MATLAB Simulink® several toolboxes have been developed such as Conventional And Renewable eNergy Optimization Toolbox (CARNOT) [9], SIMulator of Building And Devices (SIMBAD) toolbox [10], International Building Physics Toolbox (IBPT) [11], ASTECCA toolkit [12,13] and Heat, Air and Moisture (HAM) tools [14,15]. Along with journal and conference proceedings, American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) has published several handbooks for HVAC system fundamentals [6], equipment details [16], and applications [17]. Haller et al. [18] reported a mathematical model to simulate different boilers using oil, natural gas and biomass. Flynn and O'Malley [19] analyzed a drum boiler using Simulink®. Jiang et al. [20] proposed a model and different control schemes for an electric boiler integrated with a wind generator. Klaassen et al. [21] presented a control strategy for demand-side management of electric boilers. Xu et al. [22] compared the results of a partial differential equation (PDE) based model for a residential electric water heater with one-mass and two-mass composite models.

2. Contributions of the research

Though a significant effort has been made for the modeling of the boilers, the grey-box modeling approach presented in this paper has not been reported in the recent literature to the best of the authors' knowledge. The purpose of this research work is to develop an accurate boiler model that precisely captures the temperature dynamics of the water inside the boiler's tank. The physics-based model was developed by writing energy balance on each layer and the measured data was used to estimate the parameters of the model thus converting it into grey-box model. The developed model has good generalization capability and high accuracy. It is useful for the development of control systems and implementation of supervisory control strategies to reduce energy consumption during peak price periods.

The remaining part of the paper is organized as follows: Section 3 provides the description of the experimental setup including the data acquisition system and sensors. The physics-based model is derived in section 4. The model implementation in MATLAB Simulink® is described in section 5. Section 6 outlines the parameter estimation procedure and results of the model compared to the actual measurements. Finally the conclusions and acknowledgments are presented.

3. Experimental setup

The experimental setup consists of a low pressure hot water boiler, temperature sensors, measuring instruments and data logging devices was used. The following subsections provide the details about the experimental setup in detail.

3.1. Boiler

A domestic boiler manufactured by Domotec AG is chosen because it is representative of the most boilers installed in single family households of Switzerland. The height of the boiler is 160 cm and its diameter is 60 cm. Fig. 1(a) shows the electric boiler used in this research. The boiler has one heating element with the rated power consumption of 3 kW situated near the bottom of the boiler. Total capacity of the water tank is 300 L. The water inlet is near the bottom of the boiler and the outlet is on its top. The boiler remains always full of water and holds the line pressure. That means as the hot water flows out the cold water flows in. To deal with over pressure, a safety pressure valve is also installed near the inlet.

3.2. Sensors

To effectively capture the temperature changes inside the boiler, its total height was divided into eight equal layers and a temperature sensor was installed in the middle of each layer in physical contact with the inner wall of the boiler's tank. The black straps on the boiler in Fig. 1(a) show the position of eight installed temperature sensors. The distance between the two neighboring sensors is 20 cm. The top layer near the water outlet is named as *Layer*−1 or L_1 and the bottom layer near the water inlet is named as *Layer*−8 or L_8. In addition, the flow rate of the water, ambient temperature and power consumed by the electric heating element was also measured. All the sensors were wired to the data logger as shown in Fig. 1(b). The sampling time of data acquisition was set as 10 s which was sufficient to capture the temperature dynamics of the boiler and provided the high resolution data for parameter estimation and validation. The power consumed by the boiler's electric heating element was measured using the A2000 wattmeter (manufacturer: Gossen Metrawatt) shown in Fig. 1(c).

3.3. Data logger

The complete wiring diagram of the experimental setup is shown in Fig. 2. Compact data logger GL200A midi LOGGER (manufacturer: GRAPHTEC Corporation) with 10 inputs was used to store the data on a USB flash drive in a comma separated value (.csv) format. Out of the 10 inputs, the first input was connected to the wattmeter, next 8 inputs were connected to 8 different LM35 high precision water layer temperature sensors and the last input was connected to the room temperature sensor.

3.4. Pre-processing of the data

The raw data was imported into MATLAB® and converted into corresponding temperature and power units. The temperature sensors produce a voltage signal within the range of 0 V–1 V which was converted to the degrees Celsius using the slope of the data i.e.,