Energy Conversion and Management 136 (2017) 329–339

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Real-time monitoring energy efficiency and performance degradation of condensing boilers

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ARTICLE INFO

Article history:
Received 16 September 2016
Received in revised form 6 January 2017
Accepted 6 January 2017
Available online 19 January 2017

Keywords:
Condensing boilers
Real-time performance monitoring
Mass flow virtual sensor
Fault detection and diagnosis

ABSTRACT

Condensing boilers achieve higher efficiency than traditional boilers by using waste heat in flue gases to preheat cold return water entering the boiler. Water vapor produced during combustion is condensed into liquid form, thus recovering its latent heat of vaporization, leading to around 10–12% increased efficiency. Many countries have encouraged the use of condensing boilers with financial incentives. It is thus important to develop software tools to assess the correct functioning of the boiler and eventually detect problems. Current monitoring tools are based on boiler static maps and on large sets of historical data, and are unable to assess timely loss of performance due to degradation of the efficiency curve or water leakages. This work develops a set of fault detection and diagnosis tools for dynamic energy efficiency monitoring and assessment in condensing boilers, i.e. performance degradation and faults can be detected using real-time measurements: this real-time feature is particularly relevant because of the limited amount of data that can be stored by state-of-the-art building energy management systems. The monitoring tools are organized as follows: a bimodal parameter estimator to detect deviations of the efficiency of the boiler from nominal values in both condensing and noncondensing mode; a virtual sensor for the estimation of the water mass flow rate; filters to detect actuator and sensor faults, possibly due to control and sensing problems. Most importantly, structural properties for detection and isolation of actuators and sensing faults are given: these properties are crucial to understand which faults can be diagnosed given the available measurements. The effectiveness of these tools is verified via extensive simulations.

1. Introduction

Building energy use, mainly driven by heating, ventilating and air conditioning (HVAC) equipment, is responsible for over a third of Europe and US global energy consumption and CO_2 emissions which are supposed to heavily contribute to climate change [1]. In order to achieve higher energy efficiency levels, a range of technical solutions must not only help building professionals in selecting and installing the most suitable heating systems, but also constantly monitor them, using fault detection and diagnosis tools [2]. Monitoring techniques give the possibility, when properly developed, to improve energy efficiency, decrease running costs and reduce emissions [3].

While most of the techniques used in fault detection and diagnosis for building automation purposes are based on steady-state reasoning (i.e. dynamic heat transfer behavior is often neglected), the purpose of this work is to explore the possibility of *including dynamical models for fault detection and diagnosis purposes*. It has to be underlined that current state-of-the-art monitoring tools are based of static maps of the equipment, and in order to assess loss of performance it is necessary to have large sets of historical data to be used to benchmark performance of different period in the life time of the equipment. It is thus of practical importance to develop tools that can use data in real-life and possibly detect performance changes timely: this can potentially be achieved by developing monitoring tools based on dynamic models of the HVAC equipment. Including dynamical models in monitoring is crucial to distinguish, in real-time HVAC system operation, among the following possibilities for loss of performance:

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http://dx.doi.org/10.1016/j.enconman.2017.01.016
0196-8904/

(a) Different working points.
(b) Incipient faults (parameter drift).
(c) Faults in the controller.

The focus of this work is on the condensing boiler case, because this kind of equipment is becoming more and more adopted. The relevance of the condensing boiler case arises from the fact that, with respect to the total HVAC operation, boilers are estimated to contribute to 85% of the energy consumption and 67% of the CO_2 emissions [4]. The temperature of the flue gas exiting a traditional boiler is usually high, so that a great amount of heat is lost to the environment. Condensing boilers aim at recovering sensible and latent heat of the flue gas by adding a condensing heat exchanger (see Fig. 1). The condensing heat exchanger uses the return water as the cooling medium. When the return temperatures from the heating system is sufficiently low (below the dew temperature of the flue gas) the latent heat of water vapor in the flue gas can be recovered, so as to achieve significantly higher efficiency than traditional boilers. The key point is maintaining a high difference between supply and return temperature. When this condition is not maintained, the boiler will operate in a non condensing mode [5]. Due to its typical bimodal behavior (condensing, noncondensing mode), fault detection and diagnosis in condensing boilers is challenging and still not fully explored. To the best of the authors' knowledge, no dynamic monitoring tools have been developed specifically for condensing boilers: most static fault detection techniques for condensing boilers are based on checking the difference between the supply water temperature set-point and the actual supply water temperature[1] [6].

It is relevant to consider the dynamics of the boiler (as opposed to steady-state static behavior) because dynamics can take into account transient behavior in the temperature profile. Dynamic behavior is crucial since the condensing boiler presents all the aforementioned three possibilities (a)–(c) for loss of performance (which should be distinguished from each other for a proper diagnosis of the problem):

(a) *Different working points*: the boiler has a nonlinear efficiency curve (depending on the boiler power and/or the return water temperature). The efficiency curve is often described with a (piecewise) polynomial curve in these variables.
(b) *Incipient faults (parameter drift)*: incrustation and corrosion cause slowly decreasing degradation of performance, whose trend is important to identify, so as to take appropriate maintenance actions.
(c) *Faults in the controller*: the boiler includes a burner controller regulating the supply temperature: for example, the burner might stop functioning or function at reduced power. If not working properly, such faults must be timely and correctly diagnosed.

1.1. Related work

Condensing boilers are equipped with two heat exchangers, a primary (dry) heat exchanger and a secondary (wet) heat exchanger. An optimal design of heat exchangers can lead to heating efficiency of about 90% when using the optimal designed heat exchangers. Compared to a conventional Bunsen-type boilers, the heating efficiency can be improved of about 10% [7]. Special preburners (that mix and preburn air and gas) can also increase efficiency and reduce emissions [8]. The development of new types of boilers with higher efficiency and lower emissions is an active area of research, e.g. exhaust gas recirculation-condensed water recirculation-waste heat recovery condensing boilers (EGR-CWR-WHR CB) [9], with an efficiency of almost 94%. Traditional natural gas fired boiler can be retrofitted into condensing boilers as soon as the return temperature, which varies with the seasonal ambient temperature, is lower than the dew temperature of the flue gas during most of a heating season [10]. Condensing boilers can be adopted not only for residential applications, but they are becoming widespread in process industry [11] and district heating systems [12].

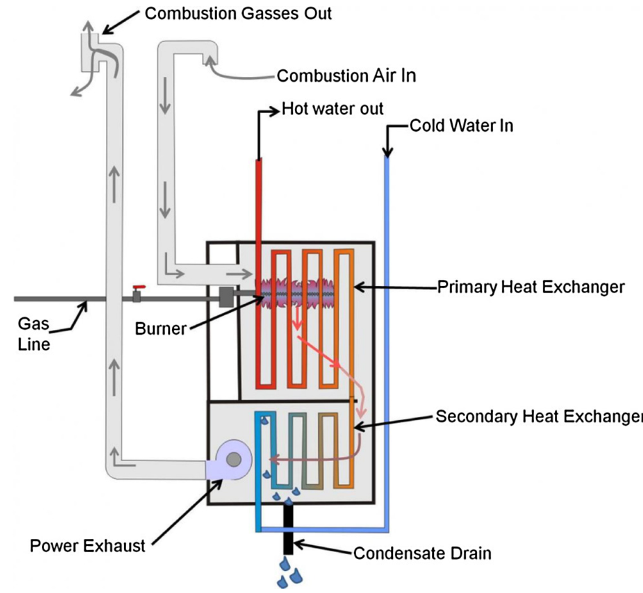

Fig. 1. Condensing boiler (source: U.S. Department of Energy).

The development of analytical boiler models is at the base of optimal boiler design and monitoring [13]: in [14] a simple model was developed to predict that the seasonal efficiency of condensing boilers based on the efficiency at full load evaluated at return water mean temperature. In [15] a heat and mass transfer analytical model of a condensing heat exchanger system was developed so as to predict the heat transferred from flue gas to cooling water and the condensation rate of water vapor in the flue gas. The main purpose of these models is to predict the boiler efficiency according to certain design parameters choices. In fact, the use of these models allows the computation of relevant variables like flue gas exit temperature, supply water temperature, water vapor mole fraction, and condensation rate of water vapor [16]. However, to the best of the authors' knowledge these models have never been used for real-time dynamic fault detection and diagnosis purposes. Furthermore, when considering condensing boilers, an important issue is related to the dynamic estimation of non accessible quantities like mass flows: sensors to measure mass flow can be quite elaborate and expensive [17], and are available in almost no commercial boiler). Monitoring mass flow rate is an important part of monitoring tools, because it allows to detect degradation due to limescale deposit in boiler pipes, or leakages [18]. In order to advance the state of the art, this work is the first one, to the best of the authors' knowledge exploiting boiler dynamics for the design of advanced virtual sensing and fault detection and diagnosis tools. The tools are organized as follows: a bimodal parameter estimator to detect deviations of the efficiency of the boiler from nominal values in both condensing and noncondensing mode; a virtual sensor for the estimation of the water mass flow rate; filters to detect actuator and sensor faults, possibly due to control and sensing problems.

[1] A typical static technique is based on checking whether a desired temperature set point is reached at steady state. This static technique might result in false alarms if transient behavior occurring during operation, maintenance actions or replacement of boiler with a new one, is not taken into account.