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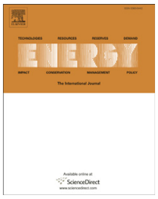

Monitoring energy efficiency of condensing boilers via hybrid first-principle modelling and estimation[☆]

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A B S T R A C T

The operating principle of condensing boilers is based on exploiting heat from flue gases to pre-heat cold water at the inlet of the boiler: by condensing into liquid form, flue gases recover their latent heat of vaporization, leading to 10–12% increased efficiency with respect to traditional boilers. However, monitoring the energy efficiency of condensing boilers is complex due to their nonlinear dynamics: currently, (static) nonlinear efficiency curves of condensing boilers are calculated at quasi-stationary regime and 'a posteriori', i.e. from data collected during chamber tests: therefore, with this static approach, it is possible to monitor the energy efficiency only at *steady-state* regime. In this work we propose a novel model-based monitoring approach for condensing boilers that extends the operating regime for which monitoring is possible: the approach is based on a hybrid dynamic model of the condensing boiler, where state-dependent switching accounts for dynamically changing condensing/non condensing proportions. Monitoring the energy efficiency over the boiler's complete *dynamic regime* is possible via switching estimators designed for the different condensing/non condensing modes. By using real-world boiler efficiency data we show that the proposed approach results in a (dynamic) nonlinear efficiency curve which gives a more complete description of the condensing boilers operation than static nonlinear efficiency curves: in addition, the dynamic curve can be derived 'a priori', i.e. from first principles, or from data collected during normal boiler operation (without requiring special chamber tests).

1. Introduction

Many reports and data confirm that in both Europe and US energy used by buildings accounts for over one third of energy consumption and CO_2 emissions [1]. Among the possible ways to improve energy efficiency in the building sector, developing better control and energy monitoring strategies can result in 10–40% energy savings [2]. The most accurate control and energy monitoring strategies are model-based: this means that mathematical models of the energy and heat transfer dynamics of the building equipment are developed and used to design better operational strategies (for energy-efficient control) or to monitor deviations of the energy consumptions from nominal patterns (for monitoring of energy efficiency). In this work we will focus on monitoring the energy efficiency of condensing boilers, which are becoming a more and more crucial equipment inside heating, ventilating and air conditioning (HVAC) systems: in fact, boiler operation has been estimated in around 85% of the HVAC energy consumption and 67% of the HVAC CO_2 emissions [3]. Nowadays condensing boilers are replacing less energy-efficient traditional boilers [4,5]. The operating principle of condensing boilers is based on exploiting heat from flue gases to pre-heat cold water at the inlet of the boiler. When flue gases condense into liquid form, they recover their latent heat of vaporization (see Fig. 1). The condensing mode can result in as much as 10–12% increase in efficiency with respect to traditional boilers. For the condensing mode to be activated, return water temperature at the boiler inlet should be low and below the dew temperature of the flue gas: when this condition is not maintained, the boiler will operate in the traditional non-condensing mode [6].

External conditions and ageing (wearing of materials, isolation,

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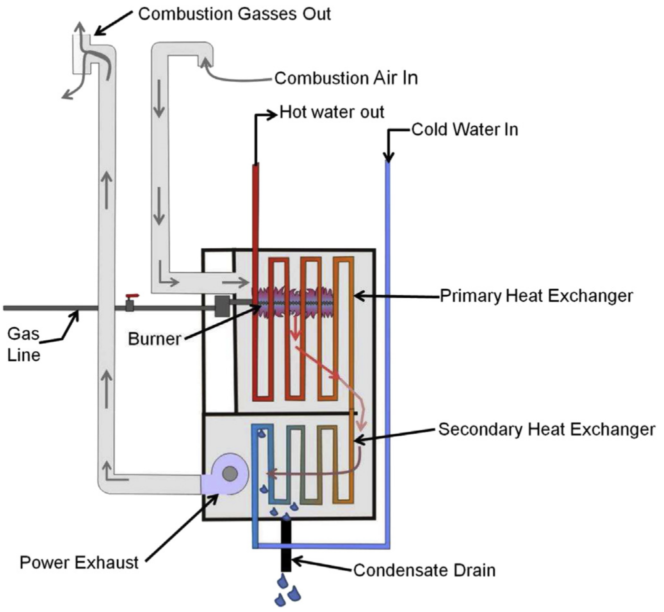

Fig. 1. Condensing boiler, retrieved from Ref. [7].

limescale, etc.) will lead to major deviations from the nominal energy efficiency of condensing boilers, thus calling for a constant monitoring of efficiency. Due to their bimodal (condensing/non-condensing) behavior, model-based monitoring of condensing boilers is more complex than model-based monitoring of traditional boilers: this is due to the complexity in modelling boiler dynamics over their entire operating range. Currently, the efficiency of condensing boilers is calculated via nonlinear efficiency curves, which are derived ‘a posteriori’, i.e. from data collected during special tests in adiabatic chambers, performed by the manufacturer at static or quasi-stationary regime (the interested reader can consult the technical libraries of many boiler manufacturers). However, static boiler operation in adiabatic chambers can be very different than dynamic boiler operation in buildings [8]. In other words, the range of validity of models derived from experimental tests is limited to the domain of the experimental data, which is the main limitation of the current state of the art [9]: therefore, it not appropriate to use the efficiency curve derived from static data to design monitoring strategies for dynamic regimes. New model-based monitoring methods are needed, which should be derived ‘a priori’, i.e. involving parameters derived from physical considerations, or from data collected during dynamic operation without requiring special chamber tests. By capturing the dynamic operation of condensing boilers instead of the static one, energy efficiency could then be monitored in the entire range of condensing boiler operation. Achieving this goal is at the core of the presented work, which overcomes the state of the art as summarized in the next section.

1.1. *Related work*

Mathematical models of boilers are meant to estimate the boiler efficiency as a function of certain design parameters. For traditional boilers several dynamic models have been developed, e.g. first-principle models [10,11], fuzzy models [12], Markovian jump models [13], and nonlinear models [14]. However, the situation for condensing boilers is less rich: static models of condensing boilers are dominating literature: in Refs. [15,16] the static efficiency is computed or measured as a function of the return water temperature, while in Ref. [17] the static seasonal efficiency of condensing boilers is normalized with respect to efficiency at full load. Static models are also used to calculate flue gas exit temperature and condensation rate of water vapor as a function of return water temperature: in Ref. [18] a payback period for retrofitting a conventional boiler into a condensing boiler is calculated based on static combustion and heat transfer calculations; in Ref. [19] a static model of a condensing heater is developed to evaluate the impact of relative humidity on the efficiency; Ref. [20] derives static charts for boiler combustion efficiency according to different natural gas blends characteristics parameters. On the other end of the spectrum are models based on computational fluid dynamic [21] that, due to their complexity, can be used to study new materials, but they cannot be used for real-time monitoring or control purposes [22].

The simplest way to describe some dynamical behavior of condensing boilers is the lumped element model [23], whose main limitation is assuming that the heat exchange occurs in a single point: this does not allow to differentiate between the wet exchange of condensing mode and the dry exchange of non-condensing mode. For this reason, a more common approach is to couple the lumped element model with a nonlinear efficiency curve [24]: unfortunately, as the nonlinear efficiency curve is obtained from steady-state operation, there is no guarantee that the same efficiency curve is valid also in dynamic regime: actually, the boiler efficiency during transient behavior is typically lower than at steady state [8]. The approach in Ref. [25] proposes a set of equations based on steady-state operation and two point heat exchange which describe the main physical processes inherent to the boiler sub-components; in Ref. [26] the heat transfer between the flue gases and the water is calculated by the classical ε-NTU method and a fixed distribution of dry/wet heat exchange; in Ref. [27] the dynamic behavior of the model is obtained by extending the nonlinear efficiency curve (obtained) from steady-state data with thermal mass considerations; in Ref. [28], an analytical heat transfer model in a secondary heat exchanger was proposed to calculate the heat transferred from flue gas to cooling water and the condensation rate of water vapor in the flue gas. Unfortunately, by relying on the lumped element model idea, all these approaches neglect that the heat transfer in condensing boilers is spatially distributed and time dependent: the proportion of dry/wet exchange in condensing boilers change dynamically in space and time. Furthermore, in most works mentioned above, heat transfer is considered only through water and gas, while a more complex and realistic heat exchange model should include the heat transfer via the extended surface and the tube wall. Despite the numerous modelling approaches which have been listed, we can clearly identify a series of shortcomings in existing condensing boiler models:

- Heat transfer dynamics are oversimplified to a static nonlinear efficiency curve. The efficiency curve is calculated by installers and specifiers of condensing boilers, *at steady-state* (e.g. in special adiabatic rooms). Therefore, current models are not able to capture the true heat transfer dynamics.
- The bimodal condensing/non-condensing behavior is oversimplified with two heat exchangers, one for dry and one for wet heat exchange, always in a *fixed proportion*. A model is required that can capture dynamical changes in space and time of dry/wet heat exchange.

With this work we will bridge these gaps and arrive to a novel monitoring approach. First, we exploit some preliminary ideas by the authors [29] to develop a model with state-dependent switching triggered by the temperature of the combustion gas: the switching mechanism is able to describe highly dynamic