Applied Energy 138 (2015) 505–516

Contents lists available at ScienceDirect

Applied Energy

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

Experimental validation of a thermodynamic boiler model under steady state and dynamic conditions

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HIGHLIGHTS

- Laboratory tests on two commercially available pellet boilers.
- Steady state and a dynamic load cycle tests.
- Pellet boiler model calibration based on data registered in stationary operation.
- Boiler model validation with reference to both stationary and dynamic operation.
- Validated model suitable for coupled simulation of building and heating system.

ARTICLE INFO

Article history:
Received 2 July 2014
Received in revised form 6 October 2014
Accepted 7 October 2014
Available online 19 November 2014

Keywords:
Pellet boiler
Dynamic test method
Building energy simulation
HVAC boiler model
Model validation

ABSTRACT

Nowadays dynamic building simulation is an essential tool for the design of heating systems for residential buildings. The simulation of buildings heated by biomass systems, first of all needs detailed boiler models, capable of simulating the boiler both as a stand-alone appliance and as a system component. This paper presents the calibration and validation of a boiler model by means of laboratory tests. The chosen model, i.e. TRNSYS "Type 869", has been validated for two commercially available pellet boilers of 6 and 12 kW nominal capacities. Two test methods have been applied: the first is a steady state test at nominal load and the second is a load cycle test including stationary operation at different loads as well as transient operation. The load cycle test is representative of the boiler operation in the field and characterises the boiler's stationary and dynamic behaviour. The model had been calibrated based on laboratory data registered during stationary operation at different loads and afterwards it was validated by simulating both the stationary and the dynamic tests. Selected parameters for the validation were the heat transfer rates to water and the water temperature profiles inside the boiler and at the boiler outlet. Modelling results showed better agreement with experimental data during stationary operation rather than during dynamic operation. Heat transfer rates to water were predicted with a maximum deviation of 10% during the stationary operation, and a maximum deviation of 30% during the dynamic load cycle. However, for both operational regimes the fuel consumption was predicted within a 10% deviation from the experimental values.

1. Introduction

The recent EU policies encourage energy efficiency in heating systems and promote the use of energy from renewable sources [1,2]. In this framework small scale biomass combustion devices (boilers and stoves) are currently considered a promising technology to supply heating and domestic hot water for the residential sector in Europe [3,4]. Because of the ongoing renovations of the residential building stock and because of the increasing popularity of low-energy and passive houses, the demand is gradually shifting to small scale heating devices. Boilers are the core of hydronic central heating and domestic hot water supply systems. Hot water leaving the boiler is delivered to one or more space heating circuits and to the hot water storage tank. The technology of biomass boilers is already well-established, with efficiencies reaching 90% and low emission factors [5]. Heat production can also be

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http://dx.doi.org/10.1016/j.apenergy.2014.10.031
0306-2619/

Nomenclature

$c_{p,fg}$ specific heat capacity of the dry flue gases (kJ kg^{-1} K^{-1})
$c_{p,vap}$ specific heat capacity of water vapour (kJ kg^{-1} K^{-1})
$c_{p,w}$ specific heat capacity of water (kJ kg^{-1} K^{-1})
C_{therm} thermal capacitance of the boiler (kJ K^{-1})
dT_{nom}, $dT_{hx,wat}$ parameters for the determination of the flue gas temperature (K)
$fac_{A,lam}$, $fac_{B,lam}$ parameters for the determination of the excess air ratio (–)
HHV higher heating value of the fuel (kJ kg^{-1})
$\dot{m}_{fg}$ mass flow rate of dry flue gases (kg h^{-1})
$\dot{m}_{fuel,dry}$ mass flow rate of dry fuel (kg h^{-1})
$\dot{m}_{CO,fg}$ mass flow rate of CO in the flue gases (kg h^{-1})
$\dot{m}_w$ water mass flow rate (kg h^{-1})
$\dot{m}_{w,fg}$ mass flow rate of water vapour in the flue gases (kg h^{-1})
$\dot{m}_{w,nom}$ water mass flow rate at nominal load (kg h^{-1})
P_{el} electricity absorbed by the boiler (W)
$P_{el,MAX}$ electricity absorbed by the boiler, at nominal load (W)
$P_{el,MIN}$ electricity absorbed by the boiler, at minimum load (W)
$P_{el,OFF}$ electricity absorbed by the boiler, in stand-by mode (W)
P_{min} minimum firing thermal output of the burner (W)
P_{max} maximum firing thermal output of the burner (W)
P_{nom} nominal thermal output of the boiler (W)
P_{start} firing output of the burner during start-up phase (W)
$\dot{Q}_{air}$ heat transferred from the boiler's body to the forced draught air (W)
$\dot{Q}_{amb}$ heat transferred from the boiler's body to the environment (W)
$\dot{Q}_{ash}$ heat loss to the unburnt constituents in the residues (W)
$\dot{Q}_{bc,camb}$ heat transferred from the combustion chamber to the environment (W)
$\dot{Q}_{envelope}$ heat transferred from the boiler's envelope to the environment (W)
$\dot{Q}_{fg,chem}$ chemical heat loss in the flue gases (W)
$\dot{Q}_{fg,lat}$ latent heat loss in the flue gases (W)
$\dot{Q}_{fg,sens}$ sensible heat loss in the flue gases (W)
$\dot{Q}_{fuel}$ energy input of the fuel, based on its higher heating value (W)
$\dot{Q}^{GCV}_{fuel,nom}$ energy input of the fuel at nominal load (W)
$\dot{Q}_{hx}$ heat transferred from flue gases to water (W)
$\dot{Q}_{Mtherm}$ heat stored in the boiler's body (W)
$\dot{Q}_{wout}$ heat transferred to the water (W)
T_{boiler} boiler's temperature (°C)
T_{fg} outlet temperature of the flue gases (°C)
T_{room} room temperature (°C)
$T_{w,in}$ water return temperature (°C)
$T_{w,out}$ water outlet temperature (°C)
t time (h)
UA_{amb} heat transfer coefficient to the environment (W K^{-1})
$UA_{amb,ON}$ heat transfer coefficient to the environment, during burner operation (W K^{-1})
$UA_{amb,OFF}$ heat transfer coefficient to the environment, during standby (W K^{-1})
Vol_{wat} volume of water inside the boiler (m^3)
W_{el} electricity consumption during start-up phase (Wh)

Greek letters
λ excess air ratio (–)
τ duration of test sequence (h)
$\Delta H_{vap,w}$ latent heat of vaporisation of water (kJ kg^{-1})
$\Delta H_{CO,comb}$ standard enthalpy of combustion of carbon monoxide (kJ kg^{-1})

supported by solar collectors or heat pumps, thus forming a hybrid system [6,7].

Dynamic building simulation is an essential tool for the reliable design of appropriate system solutions that suit the demands of specific buildings, since it is capable to describe the dynamic interactions among building, energy systems, occupants and outdoor environment. The analysis of the building, coupled with its heating system, provides key information for choosing, sizing and controlling the system's components in order to ensure comfort conditions in the house for the whole heating season. Previous studies [7–9] investigated the installation of combined solar and pellet heating system in single-family houses. The authors modelled and compared different system configurations and found improved control strategies to increase system efficiencies. The simulation of a heating system equipped with a biomass boiler needs a detailed boiler model, capable of describing the boiler both as a stand-alone appliance and as a component of the house's heating system. Nonetheless, detailed models require a large number of parameters whose imprecise definition can undermine the reliability of simulation results. Hence, the model must be calibrated to represent the specific boiler, both under steady state and dynamic conditions.

Currently, in many countries, regulations and related technical standards characterise the behaviour of biomass boilers only in steady state conditions for few load factors, thus making it difficult to calibrate dynamic simulation models. For example, efficiencies and emission factors of biomass boilers commercially available in the EU are currently assessed by means of standard laboratory tests [10–13]. Test methods comprise steady state operation at full and partial load (i.e. 30% of the nominal load) but no dynamic tests have been standardised yet. Dynamic tests in cycling operation have been performed on various types of boilers and stoves, in order to characterise the start-up and stop sequences as well as the burner's cycling operation [12–15]. In a recent work of Glembin et al. [16], gas and oil boilers were tested under cycling operation and load transitions. Another type of dynamic test is represented by dynamic load cycles, which reproduce the time variable heating and domestic hot water demand of a house, so that, even if the test is carried out in the laboratory, it is representative of the actual boiler operation in the field [17–20]. In the last decade, new dynamic test methods have been developed in order to test the combination of system components (i.e. boilers, heat pumps, solar collectors and hot water storage tanks) in different configurations, thus allowing to reproduce the complete heating and hot water supply system at the test bench [21–25].

Only few studies have formally dealt with the validation of simulation models under unsteady state conditions. For instance, Persson et al. [26] presented the validation of a thermodynamic model, suitable for pellet stoves and boilers, under steady state conditions and during dynamic tests in which the boilers underwent "on/off" cycles or heating up and cooling down curves [27].

To our knowledge, no data about the validation of a boiler model under dynamic tests, which reproduce in detail the field operation of the boiler in single family houses, are available in the literature yet.

This paper presents the experimental validation of a boiler model, suitable for dynamic building simulations, for two commercially available pellet boilers, whose nominal capacities are 6 and 12 kW. The boilers have been simulated in the TRNSYS simulation suite. TRNSYS is a software used for the dynamic simulation of systems, in particular for buildings and energy systems [28]. The