Energy and Buildings 116 (2016) 296–306

Contents lists available at ScienceDirect

Energy and Buildings

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

On-site monitoring and dynamic simulation of a low energy house heated by a pellet boiler

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ARTICLE INFO

Article history:
Received 27 October 2015
Received in revised form
25 December 2015
Accepted 1 January 2016
Available online 4 January 2016

Keywords:
Prefabricated low energy house
Pellet boiler
Floor heating system
On-site monitoring
Building simulation
Calibration
Validation
Control strategy

ABSTRACT

Prefabricated low energy houses are becoming increasingly popular thanks to their low cost and high energy performance. Heating systems installed in these houses should be optimally designed and controlled, to ensure thermal comfort for the whole heating season.

This study presents the on-site monitoring and dynamic simulation of a low energy house heated by a pellet boiler via a floor heating system. The house combines a lightweight envelope, a heat distribution system with a high thermal inertia and a biomass-based heat supply. The one-year monitoring campaign allowed to closely investigate the system's response to the heat demand. Moreover, a coupled simulation of the house and its heating and hot water supply system was set-up, calibrated, and validated against measured indoor temperature profiles and energy consumptions. Root mean square deviations between simulated and measured indoor temperature were in the range 0.4–0.8 K, while simulated energy consumptions fulfilled the criteria of the ASHRAE 14-2002 Guideline. As monitoring data evidenced the importance of better managing the high thermal inertia of the floor heating system, two improved control strategies were tested in the simulation environment and evaluated in terms of thermal comfort, pellet consumption and efficiency of the pellet boiler.

1. Introduction

In 2010 the European Union adopted a Directive to reduce the energy consumption of the building sector [1]. At a national level, in Austria, houses having low energy demands can be certified as "low energy houses" and "lowest energy houses" [2]. In particular, prefabricated houses are increasingly popular in Austria, thanks to their low cost and high energy performance. Usually, these lightweight buildings combine a wooden structure with thick insulation layers and highly fenestrated façades which maximize the incoming solar radiation. The environmental performance of prefabricated houses can be further improved by installing heating ventilation and air conditioning (HVAC) systems based on renewable energy sources [3,4]. Solar collectors, heat pumps, biomass boilers and stoves can be combined in several system configurations to completely cover the heat and domestic hot water (DHW) demands. In particular, biomass boilers are widespread in Austria where the population has a high environmental awareness and biomass is a local resource [5,6].

However, it has been observed that high performance houses which approach the zero energy target while maintaining economical convenience might be easily subject to problems of insufficient thermal comfort [7]. Because of the low thermal mass of the lightweight construction, fast temperature gradients may occur in the indoor environment and bring the indoor temperature out of the comfort range. Therefore, HVAC systems must be correctly sized and adequately controlled to meet the building's heat demand and ensure comfortable indoor conditions during the whole heating season. Control strategies should also account for the response time of the heat distribution system, especially in the case of floor heating systems, having a large thermal lag, as pointed out by Chen [8]. In the case of biomass-based heating systems, the system design

Abbreviations: ACH, air changes per hour; DHW, domestic hot water; HVAC, heating ventilation and air conditioning; MBE, mean bias error; RMSD, root mean square deviation.

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http://dx.doi.org/10.1016/j.enbuild.2016.01.001
0378-7788/

Nomenclature

f	cost function used for the calibration [–]
LHV_{pellet}	wet based lower heating value of the pellets [MJ kg^{-1}]
$CV(RMSD)_{GF}$	coefficient of variation of the root mean square deviation for the indoor temperature profile in the ground floor [–]
$CV(RMSD)_{1F}$	coefficient of variation of the root mean square deviation for the indoor temperature profile in the first floor [–]
m_{pellet}	pellet consumption [kg]
$P_{hg,GF}$	internal heat gains in the ground floor [W]
$P_{hg,1F}$	internal heat gains in the first floor [W]
Q_{out}	heat output of the pellet boiler [MJ]
$SF_{GF,summ1}$	shading factor for windows of ground floor (summer, shading not activated) [–]
$SF_{GF,summ2}$	shading factor for windows of ground floor (summer, shading activated) [–]
$SF_{1F,summ}$	shading factor for the windows of the first floor (summer season) [–]
$SF_{GF,winter}$	shading factor for the windows of the ground floor (winter season) [–]
$SF_{1F,winter}$	shading factor for the windows of the first floor (winter season) [–]
T_{mix}	water temperature at the three way mixing valve [°C]
Cap_{GF}	heat capacitance of the zone representing the ground floor [kJ K^{-1}]
Cap_{1F}	Heat capacitance of the zone representing the first floor [kJ K^{-1}]

Greek letters

η_{fuel}	Fuel conversion efficiency [%]

and controls should also ensure that the operating conditions of the pellet boiler are suitable to reach maximum efficiencies and minimum emission factors [9,10].

For these reasons, dynamic building simulation becomes an essential tool for the design of appropriate system solutions that suit the demands of specific buildings [11]. Dynamic simulations can also be used to test different control strategies and improve the management of energy systems in existing buildings, thus reducing their energy consumption. However, the dynamic simulation of an existing building must be correctly set-up and calibrated, to ensure that the model is representative of the building under study. Several calibration methods, proposed in recent studies, have been revised by Coakley et al. [12]. For instance, Koranteng and Mahdavi [13], Tahmasebi et al. [14] and Penna et al. [15] adopted the measured indoor temperature profiles as a reference for the calibration, while Raftery at al. [16], Mustafaraj et al. [17] and Royapoor et al. [18] based their calibrations on monthly energy consumptions, measured by heat and electricity meters. Moreover, single simulation components, whose behaviour is simulated in detail, can be individually calibrated and then integrated into a more complex simulation. This procedure is typical for pellet boilers, usually simulated by means of complex models, which require the calibration of numerous parameters. Persson et al. [19], Haller et al. [20], and Carlon et al. [21] proposed dynamic laboratory tests for the experimental calibration and validation of models suitable to simulate the operation of pellet boilers under transient conditions. Successively, the calibrated boiler models were integrated into the simulation of single family houses. Fiedler et al. [22] and Persson at al. [23] assessed the thermal performance and emission factors of pellet boilers in different system configurations, while Haller [24] investigated the combination of solar collectors, pellet boiler and buffer storage tank. These studies simulate different system configurations equipped with pellet boilers, but they do not compare simulation results and measurement data, therefore it is not clear if the boiler models can accurately simulate the actual boiler operation in field conditions. Moreover, to our knowledge, no simulation studies focusing on pellet boilers operating in prefabricated houses have been published yet. Nevertheless, the simulation of biomass-based heating system for prefabricated houses could be extremely useful to test different system configurations and control strategies which maximize indoor thermal comfort while maintaining a low fuel consumption. Considering that prefabricated houses are industrial products sold to several customers in different countries, the efforts of setting up complex simulations are compensated by the numerous applications in practice. In particular, for houses which combine lightweight envelopes and floor heating systems with high thermal inertia, dynamic simulations can be used to optimize the system response to the changes of the heat demand.

This study presents the on-site monitoring and dynamic simulation of a prefabricated low energy house heated by a 6 kW pellet boiler directly connected to a floor heating system (i.e. system configuration without buffer storage tank). The objective of this study was to experimentally and numerically investigate the performance of a house which combines a lightweight envelope, a heat distribution system with a high thermal inertia and a biomass boiler. The monitoring campaign aimed at closely investigating the system's response to the heating and hot water demand and at characterizing the operation of the pellet boiler in the considered system configuration. Besides, a coupled simulation of the house and its heating and hot water supply system was set up in the TRNSYS simulation suite and successively calibrated and validated against measured profiles of indoor temperature. The objective of the simulation study was not only to assess the energy performance of the house but also to verify if the boiler model adopted for the simulation (i.e. Type 869 [25]) could accurately simulate the boiler operation in field conditions, once integrated in an overall building model. A further aim of the simulation study was to investigate improved control strategies for the heating system, and to compare them in terms of thermal comfort and annual fuel consumption.

2. Case study

The house analyzed in this study is a prefabricated single family house situated in the municipality of Persenbeug-Gottsdorf (48°11′ N, 15°06′ E) in Lower Austria, 220 m above sea level. Thanks to its annual heat demand of 30.1 kWh m^{-2} (calculated with reference to local climatic data, according to ÖNORM H5055 [26]), the building is classified as a "low energy house". The house, manufactured by the company Wolf Systembau Gesellschaft mbH, was monitored in the frame of the BioMaxEff project, a FP7 project aiming at the demonstration of biomass boilers in real life operating conditions [27]. The house was built in 2012 and it is inhabited by two people. The heated volume (561 m^3) comprises the ground floor and the first floor, each one having a 90 m^2 floor area, whereas attic and basement are unheated. The ground floor is the living area of the house, with kitchen and living room, while bedrooms are in the first floor. The heated volume is enclosed in a fully insulated envelope. External walls combine a wooden structure with a 24 cm thick insulation layer, resulting in an overall heat transfer coefficient of 0.14 W m^{-2} K^{-1}. Internal ceilings are insulated by expanded polystyrene and rockwool panels, and have *U*-values in the range 0.15–0.22 W m^{-2} K^{-1}. All windows have triple-glazed panels ensuring overall *U*-values in the range 0.84–0.97 W m^{-2} K^{-1}. The south-oriented façade has a glazed surface of 27 m^2, which