Energy and Buildings 63 (2013) 138–146

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

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

Investigating the performance of a combined solar system with heat pump for houses

Muhammad Waseem Ahmad[a], Mahroo Eftekhari[a,*], Thomas Steffen[b], Abdulhameed Mambo Danjuma[a]

[a] School of Civil and Building Engineering, Loughborough University, Loughborough, UK
[b] School of Aeronautical, Automotive, Chemical and Materials Engineering, Loughborough University, Loughborough, UK

ARTICLE INFO

Article history:
Received 20 February 2013
Accepted 31 March 2013

Keywords:
Model predictive controller
Heat pump
Conventional control strategies
Load shifting
Solar energy

ABSTRACT

The UK government has committed to generate 20% of the country's energy from renewable sources by 2020. This paper investigates energy reduction in houses by using an innovative solar thermal collector combined with a heat pump system. The dynamic lumped parameter model for a small house is derived and the combined heating system is used to provide the typical hot water and heating requirement. The goal is to maintain thermal comfort inside the house and reduce the amount of electricity consumption used for heating and hot water. This is achieved by reducing the electricity costs through optimising the operation of the heat pump, integrating the available solar energy, and by shifting electricity consumption to the cheaper night time tariff. Models of conventional controller on–off and a multi-variable model predictive control (MPC) are developed and used for several different climatic conditions. The results showed that the model predictive controller performed best by providing better comfort, consuming less electric energy and better use of cheap night time electricity by load shifting and storing heat energy in the heating tank.

1. Introduction

According to the International Energy agency [1] the primary energy use has grown by 40% from 1994 to 2004. Overall there is an average energy and CO_2 increase of 2% and 1.8% each year respectively. The main source of energy consumption in the domestic sector is space heating, which accounted for 60% of the total domestic energy consumption in 2011. Water heating accounted for 18%, lighting 19% and cooking for a 3% [2] of a typical household bills. Currently, the use of solar thermal collectors combined with heat pump systems is becoming popular due to their low electrical cost. A heat pump is mainly used to increase the temperature of hot water generated by the solar collectors. It is acknowledged that the solar heating systems are challenging to control due to the swings in day to day and season to season energy flows and also the varying thermal comfort demands. The control system is an important component of any renewable system and is critical for increasing the performance of such systems.

The long-term performance of a combined solar collector and heat pump system was studied by Huang et al. [3] and was found that its electricity price was cheaper than conventional gas system. The performance of a solar-assisted heat pump water heating system was monitored by Hawlader et al. [4]. They showed that the performance of the system is influenced significantly by collector area, speed of the compressor, and solar irradiation. The performance of a combined solar water heater and heat pump was investigated by Nutaphan et al. [5] using a simulation program. The economical mass of hot water in the storage tank and the refrigerant mass flow for optimum operation of the system were investigated. Predictive control strategies are well known in building control research [6]. An MPC is used for chillers to optimally store the thermal energy in the tanks by using the predictions of the building load and outside weather conditions [7]. In another study a detailed building model is applied for building predictions [8]. Model predictive control has also been used for reducing peak electricity demand in building climate control [9]. Different predictive control strategies for a solar hot water system with non-predictive strategies are compared by Grünenfelder et al. [10]. It is shown in simulation that for a small storage tank, the predictive control saves energy cost when compared with non-predictive strategies. A weather predictor based on observed weather data is used by Henze et al. [11–13]. The system under study uses active and passive building thermal storage systems. Building heating systems using MPC with weather

* Corresponding author at: School of Civil and Building Engineering, Loughborough University, LE11 3TU, UK. Tel.: +44 01509 222606.
E-mail addresses: M.W.Ahmad@lboro.ac.uk (M.W. Ahmad), M.M.eftekhari@lboro.ac.uk (M. Eftekhari), T.Steffen@lboro.ac.uk (T. Steffen), A.D.Mambo@lboro.ac.uk (A.M. Danjuma).

0378-7788/$ – see front matter
http://dx.doi.org/10.1016/j.enbuild.2013.03.055

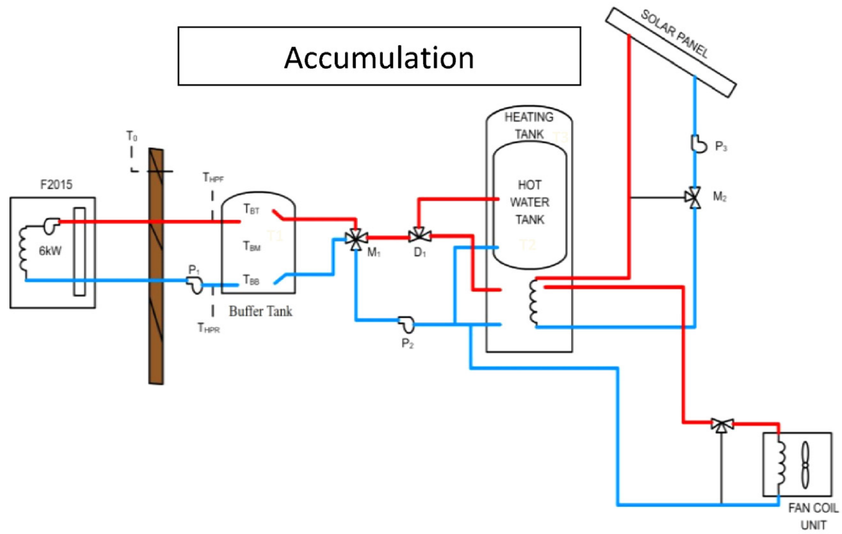

Fig. 1. Solar system combined with heat pump schematic.

prediction have shown to save between 15% and 28% of the energy consumption [14].

This paper will investigate the performance of a combined solar thermal collector and heat pump system. To control the system, a conventional (on–off) and an advanced control system (MPC) are simulated and the energy saving and load shifting of the controllers are compared. Mathematical model of the building and heating system is developed to predict the future behaviour of the whole system according to the outdoor weather conditions and occupancy pattern of the building.

2. Experimental heating system

The full size solar system and the heat pump are installed at the School of Civil and Building Engineering of Loughborough University. It consists of a solar panel, a heat pump and three accumulator tanks. The buffer tank is heated up with the help of a heat pump and when it is required this hot water is transferred into either the heating tank or the hot water tank. The heating tank is also connected to the solar thermal collector. During the night, when electric tariffs are low, the heat pump can be used to heat up all the tanks.

A general schematic diagram of the system is shown in Fig. 1. The heat pump is connected to the buffer tank.

The main components of the system are described below.

2.1. Accumulation system

The accumulation system consists of three tanks. The first tank is the buffer tank for the heat pump, and it has a capacity of 300 l. It is heated by the heat pump, and it can supply hot water to the other two tanks as required. The hot water tank is connected to the buffer tank, it has a capacity of 300l, and it is located inside the heating tank. The heating tank is of 450 l capacity, and it provides hot water to the room fan coil units for heating.

2.2. Solar collector

Solar collectors are used to collect solar radiations and to raise the water temperature of the heating tank. It is the preferred energy source of the system, because it uses only a minimal amount of electricity to power the circulation pump. The solar collector consists of 2 flat plate collectors 2 m^2 in area each, covering a total area of 4 m^2.

2.3. Heat pump

The installed system is a single stage air source heat pump. It is the only way to heat the hot water tank, and it can be used as an auxiliary energy source for the heating tank when necessary. The heat pump is directly connected to the buffer tank. The rated electric power of the heat pump is 6 kW, but the actual power consumption may be lower, and the delivered thermal power is higher due to the additional energy drawn from the heat source.

The single heat pumps are unable to modulate their output power during low load conditions, which could lead to overheating of the fluid loop. In order to solve this problem, the buffer tank is required in between the load loop and the heat pump.

3. Modelling

The system model is important for both the controller design, and for validation. The performance of a model based controller depends to a good part on the accuracy of the plant model. The nonlinear model of the whole system is implemented in Simulink, and a linearised plant model is used to formulate the optimisation problem [15,16].

The building was modelled by considering wall layers as lumped components and considering each layer as a thermal resistor and a thermal capacitor. The tanks are modelled as heat stores with a known thermal capacity. The development of heat pump model was based on curve fitting to manufacturer's data.

3.1. Building

The building under consideration is a two room building; a hall and a bedroom. However the hot water and heating energy consumption is based on a typical house [17]. The hall has a south facing and a window on the south facing window. The dimensions of both the rooms are 4.27 m × 4.57 m and they are 2.44 m high. The schematic layout of the building is shown in Fig. 2.

A typical construction element consists of different layers of different materials. All the external walls and roof are considered of the same basic construction. The model used by Gustafsson [18] is applied here. The Building materials and properties of the external walls, roof and partition wall between hall and bedroom are summarised in Table 1.