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Sustainable heating, cooling and ventilation of a plus-energy house via photovoltaic/thermal panels

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ABSTRACT

Present work addresses the HVAC and energy concerns of the Technical University of Denmark's house, Fold, for the competition Solar Decathlon Europe 2012. Various innovative solutions are investigated; photovoltaic/thermal (PV/T) panels, utilization of ground as a heat source/sink and phase change materials (PCM).

The development of a building integrated photovoltaic/thermal (BIPV/T) system and its performance evaluation compared to a PV installation built of the same photovoltaic cells are also presented. Annual results show that having the combined PV/T system is more beneficial compared to having two separate systems.

PV/T panels enable the house to perform as a plus-energy house. PV/T panels also yield to a solar fraction of 63% and 31% for Madrid and Copenhagen, respectively.

The ground heat exchanger acts as the heat sink/source of the house. Free cooling enables the same cooling effect to be delivered with 8% of the energy consumption of a representative chiller.

The major part of sensible heating and cooling is done via embedded pipes in the floor and ceiling. Ventilation is used to control the humidity and to remove sensory and chemical pollution.

A combination of embedded pipes and PCM was simulated. Results show energy savings up to 30%, for cooling season in Madrid.

1. Introduction

Buildings play a key role within the 20-20-20 goals of the European Union due to the fact that they are responsible for 40% of the energy consumption within the member states [1]. Therefore an urgent and effective transition is necessary in order to reach the almost passive house levels dictated by various standards.

These goals are in parallel directions with the main goals of the competition, Solar Decathlon, where the main goal is to design, build and operate an energetically self-sufficient house that uses solar energy as the only energy source [2].

Technical University of Denmark, herein DTU, joined the competition, Solar Decathlon Europe 2012 with the house "Fold". During the course of this study, an entire HVAC system for a single family house has been designed, simulated and tested.

A house, other than just providing shelter, should also be able to provide necessary and optimal thermal comfort (including indoor air quality) for the occupants however this goal should be achieved with the lowest possible energy consumption. The design of the HVAC system intended to satisfy both of these needs. Innovation was a driving force and this was achieved via taking advantage of well-known and proven systems and integrating them into the HVAC system and coupling them with relatively less mature technologies.

The HVAC system of the house consisted of: ground heat exchanger (GHX), embedded pipes in the floor and in the ceiling, ventilation system (mechanical and natural), domestic hot water (DHW) tank and photovoltaic/thermal (PV/T) panels placed on the roof. The design methodology, further information about the components and main results are presented in the following sections.

2. Design of the house

The project being multi-disciplinary by its nature, some of the design values and parameters were fixed without the possibility

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of alteration. Also some of the design values were fixed due to the commercially available products and their capacities.

The house is a detached, one-storey, single family house with an indoor floor area of 66.2 m^2 and with a conditioned volume of 213 m^3. The design of the house intends to minimize heat gain to the house from the ambient. The house's largest glazing façade is oriented to the North side, with a 19° turn toward West.

The house is constructed from wooden elements. Walls, roof and floor structures are formed by placing prefabricated elements in a sequential order and sealing the joints. North and South glazed façades are inserted later and the joints between glazing frame and house structure are sealed.

Prefabricated house elements are made from layers of wooden boards, which in combination with I beams in between form structural part, and mineral wool insulation. The house is insulated with two types of insulation; 20 cm of conventional mineral wool and 8 cm of compressed mineral wool.

The glazing surfaces in North and South sides of the house are covered by the overhangs which eliminate direct solar radiation to the house during the summer season. For the winter season direct solar radiation enters the house, creating a favorable effect. No active shading systems were installed in the house except for the skylight window.

Inside the house, there is a single space combining kitchen, living room and bedroom areas. Shower and toilet areas are partly separated by partitions. Technical room is completely isolated from the main indoor space, having a separate entrance. Wall between technical room and indoor space is insulated with the same level of insulation as the outside walls. The house, structural element and respective areas can be seen in Fig. 1 and Table 1.

The house is fully functional therefore it is equipped with different appliances such as: PC, refrigerator/freezer, clothes washer, clothes dryer, dishwasher, oven, TV and DVD player. Electrical power of the installed equipment is 1.5 kW.

3. Design methodology of the HVAC system

With the given constraints on the system, an entire HVAC system for the house had to be designed following the ambitions given in Section 1.

To design the heating, cooling and ventilation system, load calculations were performed. Construction of the house was defined by the architectural design team. This design was taken as the basis for load calculations. Even though the idea behind the architectural design of the house was to adjust certain parameters including, orientation, tilt of the roof and walls, glazing areas, etc. this option was not realized in the simulations and in the calculations.

The initial design conditions required for the house to be fully functioning in two different climates: Denmark (Copenhagen) and Spain (Madrid). The resulting heating and cooling needs are as follows: maximum cooling load is 52.0 W/m^2, average cooling load is 35.2 W/m^2, maximum heating load is 45.6 W/m^2 and average heating load is 26.6 W/m^2, given the indoor floor area of 66.2 m^2.

Even though the design was mainly aimed at providing the comfort conditions during the competition period, it had to be assured that the house performs as intended all year round. This was implemented with different set-points in the simulations as explained in the respective section.

The only electrical energy source of the house is solar energy, utilized via photovoltaic panels placed on the entire roof area. The electrical system is designed to be grid-connected with no batteries. Coupled with the photovoltaic panels is the thermal system, which absorbs the heat produced by photovoltaic panels and utilizes it in the DHW tank, making combined photovoltaic/thermal system (PV/T).

Heating and cooling system of the house is water based, with low temperature heating and high temperature cooling principle. Heat source/sink is the ground, utilized via a borehole heat exchanger. Free cooling is obtained during the cooling season without any extra energy consumption other than the circulation pump and ground coupled heat pump is used to achieve the necessary supply temperature to the embedded pipes during the heating season.

As an addition to the space heating and cooling, ground heat exchanger could also be utilized for the PV/T cooling. Yet, initial evaluations showed that this concept was too expensive to be realized, since it requires extra capacity of the ground heat exchanger.

In order to regulate the air quality in the house, mechanical and natural ventilation systems are installed. The mechanical ventilation consists of two supply diffusers to the space and four exhausts (kitchen hood, bathroom, toilet and the clothes dryer).

To increase the building's thermal mass, an option of installing phase change material, herein PCM, into the structure of the building was considered. The model of active cooling using PCM was chosen. Pure PCM material is stored in a metal container. The container is equipped with a piping system, to discharge the heat stored in the material.

The house being high-tech, it stores great amount of machinery and electronic equipment which operate the house. All of these components release heat to the environment. As it is a need to limit heat production in the house, a solution is to isolate all equipment which is not used by the occupants on a daily basis. The equipment is placed in the technical room, which has no direct thermal connection to the inside area.

4. Design methodology of the PV/T system

In order to justify the advantages of combining electrical and thermal part in one element, various investigations were carried out. The main goal was to keep the cell temperature under control and keep the electrical efficiency close to the nominal value and also to utilize the heat that is gained from cooling the cells for the various heating needs of the house (domestic hot water, hot water consuming appliances, but not space heating). Special attention was given to the hydraulic division of PV/T panel, to the practical solution for dismountable joints between panels and to the common design of thermal and electrical parts.

4.1. Test of the thermal part

Parametric analyses were made in order to find out the panel's effectiveness in relation to different configurations of lateral pipes, 6 and 10 per meter (Fig. 2). It can be observed from Fig. 2 that spacing of 100 mm can utilize more solar energy than spacing of 166 mm. The most significant difference appears when the temperature difference between surrounding and PV/T surface is negligible.

Temperature fluctuation across the absorber plate for two different spacing of lateral piping in PV/T panel can also be seen in Fig. 2. The calculation was carried out for solar irradiation of 1000 W/m^2, 25 °C and no wind. The peaks indicate intermediate space between two pipes where the temperature raises the most. It was desired to have as even temperature over the absorber as possible, thus spacing of 100 mm was chosen.

The PV/T panel was tested at an outside testing facility, with a tilt of 67.5° from the horizontal and oriented to the true South, the test setup can be seen in Fig. 3.

The expressions used to calculate the efficiencies are as following:

$$\eta_{\text{Thermal with active cells}} = 0.422 - 5.628 \cdot \frac{\Delta T}{G} \quad (1)$$