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Solar Sustainable Heating, Cooling and Ventilation of a Net Zero Energy House

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Abstract

Present work addresses the heating, cooling and ventilation concerns of the Technical University of Denmark's house, Fold, for Solar Decathlon Europe 2012. Various innovative approaches are investigated, namely, utilization of ground, photo-voltaic/thermal (PV/T) panels and phase change materials (PCM).

The ground heat exchanger acts as the heat sink and heat source for cooling and heating seasons, respectively. Free cooling enables the same cooling effect to be delivered with 8% of the energy consumption of a representative chiller.

The heating and cooling needs of the house are addressed by the embedded pipes which are coupled with the ground. Ventilation is mainly used to control the humidity and to remove sensory and chemical pollution.

PV/T panels enable the house to be a "plus" energy house. PV/T also yields to a solar fraction of 63% and 31% for Madrid and Copenhagen, respectively.

A combination of embedded pipes and PCM was simulated and results show energy savings up to 30%, for cooling season in Madrid, compared to using only embedded pipes. However this option was not realized in the actual house.

Once this house is built, tested and optimized, further possibilities will be investigated in order to apply a similar strategy to the entire building block. This will lead to considerable amount of primary energy savings and consequently avoided greenhouse gas emissions.

Keywords - Solar Decathlon Europe; the FOLD; phase change materials; ground heat exchanger; radiant heating and cooling; photovoltaic/thermal

1. Introduction

Buildings play a key role within the 20/20/20 goals of the European Union because they consume 40% of the energy within the member states [1]. Therefore an urgent and effective transition is necessary in order to reach to the almost "passive house" levels.

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].

A house, other than just providing shelter, should also be able to provide necessary thermal comfort 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 as well with taking advantage of well-known and proven systems and integrating them into the HVAC system and coupling them with relatively less mature technologies.

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.

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

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 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 interior area of 66.2 m² and the conditioned volume is 213 m³. 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 towards 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. South and North glazed façades are inserted later, sealing the joints between glazing frame and house structure. The house is supported on 20 cm to 30 cm concrete blocks.

Prefabricated house elements are made from layers of wooden boards, which in combination with I beams in between forms 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 South and North side 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 for the heating mode. 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 Figure 1 and Table 1:

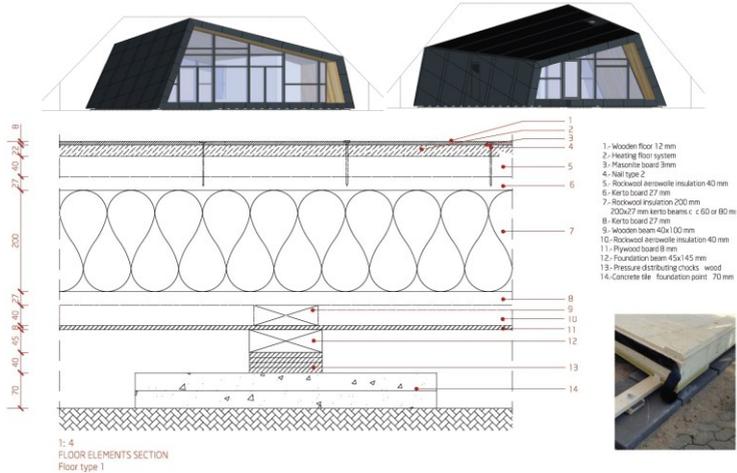


Figure 1: North-East and South-West sides of the house and the structural element [3]

Table 1: House construction details

| External walls | South | North | East | West | Floor | Ceiling |
|-------------------------------|-------|-------|------|------|-------|---------|
| Area [m ²] | - | - | 19.3 | 37.2 | 66.2 | 53 |
| U-value [W/m ² -K] | - | - | 0.09 | 0.09 | 0.09 | 0.09 |
| Windows | South | North | East | West | Floor | Ceiling |
| Area [m ²] | 21.8 | 36.7 | - | - | - | 0.74 |
| U-value [W/m ² -K] | 1.04 | 1.04 | - | - | - | 1.04 |
| Solar transmission | 0.3 | 0.3 | - | - | - | 0.3 |

The house is a fully functioning house therefore it is equipped with different appliances such as: PC, refrigerator/freezer, clothes washer, clothes dryer, dish washer, 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 the introduction.

The initial design conditions required for the house to be fully functioning in two different climates: Denmark (Copenhagen) and Spain (Madrid). Indoor climate requirements were set by the regulations of the competition:

- Temperature limits inside the house: 23.0°C -25.0°C
- Relative humidity in the house: 40%-55%
- Maximum CO₂ concentration in the house: 800 ppm

Even though the design was mainly aimed at keeping the 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 chapter.

To design a heating/cooling and ventilation system, load calculations were performed. Construction of the house is 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 such as, orientation, tilt of the roof and walls, glazing areas etc. this option was not realized in the simulations and in the calculations.

The heating and cooling needs are: ultimate cooling load is 52.0 W/m², average cooling load is 35.2 W/m², ultimate heating load is 45.6 W/m² and average heating load is 26.6 W/m², given the indoor floor area of 66.2 m².

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

Cooling and heating system of the house is water based, with a low temperature heating and high temperature cooling concept. 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.

To increase 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 day to day basis. The equipment is placed in the technical room, which has no direct thermal connection to the inside area.

In order to regulate the air quality in the house, mechanical and natural ventilation systems are installed. The mechanical ventilation consists of 2 supply diffusers to the space and 4 exhausts (kitchen hood, bathroom, toilet and the clothes dryer).

4. HVAC System and Control Concept

The individual operation of the components of the HVAC system and operation of the system as a whole had to be controlled in order to assure optimal performance. This was mainly done on a seasonal basis (heating/cooling) and with more detailed conditions within each season.

Most significant parameters of each component of the HVAC system are presented below:

The ground heat exchanger was designed to be a borehole with a depth of 120 meters, single U-tube configuration and with a diameter of 0.12 m. The inner and outer radii of the heat exchanger pipes were 0.013 m and 0.016 m, respectively. Obtained borehole resistance was 0.1 m-K/W and total resistance to the undisturbed ground (8.3°C and 14.3°C for Copenhagen and Madrid, respectively) was 0.37 m-K/W.

The space heating and space cooling in the house is provided by the pipes that are embedded in the floor and the ceiling. It is a dry radiant system, having piping grid installed under the wooden layer, with an aluminum layer for thermal conductance. Space heating is only obtained by the embedded pipes in the floor and space cooling is obtained by embedded pipes in the ceiling and, if necessary, in the floor. The supply and return flows will be coming from/going into the installed ground heat exchanger. To control water flow and supply temperature a mixing station is installed.

The designed embedded pipe system is given as the following:

- For the ceiling, a foam board system, with aluminum heat conductive device, PEX pipe 12x1.7 mm. In total 6 circuits are designed for the ceiling system, with maximum flow rate in one circuit of 0.07 m³/h.
- For the floor, a chipboard system, with aluminum heat conducting device, PEX pipe 17x2.0 mm. In total 4 circuits are designed for the floor system, with maximum flow rate in one circuit of 0.07 m³/h for the cooling case, and 0.15 m³/h for heating case.

The installed air handling unit, herein AHU, can provide an air flow rate up to 320 m³/h, which is 1.5 ach at 100 Pa. The flow rate fully covers the need for the design flow rate.

AHU has two heat recovery systems: passive (cross flow heat exchanger) and active (reversible heat pump coupled with the DHW tank). Active heat recovery is obtained via a heat pump cycle that changes the evaporator/condenser in the supply air duct to the interior. This is achieved via a 4-way valve in the heat pump cycle. Passive heat recovery system has an efficiency of 88% (sensible heat). Thermal energy of the exhaust air is transported to the supply air. By pass mode is possible.

Mechanical ventilation gives more control over the parameters like temperature, relative humidity and CO₂ levels however due to the use of mechanical fans it consumes a certain amount of energy (40 Wh/m³). This amount of energy can be eliminated when the outside conditions are “feasible” for natural ventilation. Natural ventilation option is possible via two windows in South and North façades and the operable skylight window.

PV/T part also directly interacts with the ground. PV/T part is intended to produce electricity (nominal electrical efficiency is 15.73%), Photo-Voltaic, and produce heat for the Domestic Hot Water and domestic appliances (dishwasher, clothes washer and clothes dryer).

PV/T area (67.8 m²) is divided into Part A (45.4 m²) and Part B (22.4 m²), for different control purposes. Part A is solely intended to charge DHW tank. If there is any flow in Part A this is when there is DHW need and the flow can only be directed to the DHW tank.

On the other hand, Part B serves for both purposes; charging the DHW tank and PV/T cooling. When there is a DHW need, Part B also contributes to the charging of the DHW tank. Initial simulations and calculations showed that the ground (one borehole) is not capable of providing necessary supply temperature to the embedded pipes when house cooling and PV/T cooling are active simultaneously. Therefore PV/T cooling option is only applicable when house doesn't need cooling. There is also a drain-back tank between the PV/T loops and the DHW tank which makes it possible to drain all the water from the PV/T loop, when necessary.

The DHW tank of 180 liters is equipped with two spiral heat exchangers and an electric heater. One of the spiral heat exchangers is connected to the PV/T loops via the drain-back tank and the other one to the active heat recovery system of the ventilation. The top part of the tank (54 liters) is heated by the electric heater (1.5 kW).

5. Dynamic Simulations of the House

In order to evaluate all year round performance of the house, commercially available dynamic building simulation software, TRNSYS [4] was utilized.

Simulations were carried out for Copenhagen and Madrid. Weather files used were; International Weather for Energy Calculations (IWEC) and Spanish Weather for Energy Calculations (SWEC), respectively.

May to September months (both included) were considered as cooling season and rest of the months were considered as heating season. Relative simulation parameters were adjusted accordingly.

Same load profiles for occupants, lighting and equipment were implemented for Copenhagen and Madrid.

Set-points for the temperature (operative) has been defined as $21^{\circ}\text{C}\pm 1\text{ K}$ for heating and $25^{\circ}\text{C}\pm 1\text{ K}$ for cooling season, following [5] so that the operative temperature is within 20°C and 26°C limits. These values refer to the Category 2 of comfort conditions for living spaces in residential buildings in the respective standard.

Also investigation using dynamic building simulation software BSim was made, to evaluate if PCM application in the designed house would bring desired effect of decreasing energy consumption for heating and cooling. In total four cases were simulated, starting with the simplest conventional structure and lastly having a structure fully packed with PCM:

- 50 mm PCM layer in direct contact with indoor space (green column)
- Embedded pipe system in wooden construction (blue column)
- 50 mm PCM layer covered with 10 mm plywood layer (orange column)
- 50 mm PCM layer on the ceiling, covered by 10 mm plywood layer and embedded pipe system in the wooden floor structure (violet column)

Only cooling season was investigated due to limitation of the software. Also results of these simulations are presented in the following chapter.

6. Results

Presented results are from simulations and the respective simulation software is indicated in the parentheses.

Simulation results for the designed ground heat exchanger are presented below:

Table 2: Obtained results for both locations, annually (TRNSYS)

| | Copenhagen | Madrid |
|---------------------------------|------------|--------|
| HP, heat to load [kWh] | 6932.3 | 4351.3 |
| Energy balance, ground [kWh] | -3128.8 | -548.6 |
| Free cooling total [kWh] | 1301.1 | 2042.6 |
| Free cooling to the house [kWh] | 1195.8 | 1661.0 |
| Free cooling to the PV/T [kWh] | 105.3 | 381.6 |

Also long-term behavior of the ground heat exchanger has been investigated, results are presented in the below table and following figure:

Table 3: Initial and average temperatures and heat balance of the ground (TRNSYS)

| | Copenhagen | Madrid |
|----------------------------------|------------|--------|
| Initial ground temperature [°C] | 8.3 | 14.3 |
| Average ground temperature [°C] | 7.8 | 14.2 |
| Heat balance of the ground [MWh] | -28.7 | -2.8 |

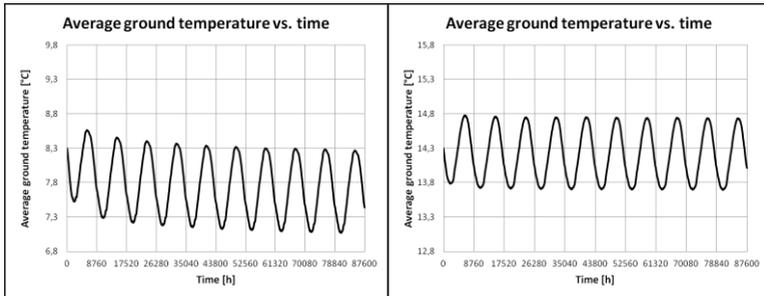


Figure 2: 10 year average ground temperatures for Copenhagen and Madrid (TRNSYS)

Presented results for PV/T system are obtained from simulations:

Table 4: Obtained results for PV/T panels and DHW tank, annually (TRNSYS)

| | Copenhagen | Madrid |
|---------------------------------|------------|---------|
| Electricity production [kWh-el] | 7434.3 | 11392.7 |
| $\eta_{el,A}$ [%] | 15.04 | 14.60 |
| $\eta_{el,B}$ [%] | 15.05 | 14.62 |
| Solar fraction [%] | 30.5 | 62.7 |

In order to evaluate the house on an all year round basis, also simulations have been carried out and the results of the simulations are presented in the following table:

Table 5: Energy consumption by building need (TRNSYS)

| | Copenhagen | Madrid |
|-----------------------------------|------------|--------|
| Heating [kWh/m ²] | 31.6 | 20.7 |
| Cooling [kWh/m ²] | 0.5 | 1.0 |
| Ventilation [kWh/m ²] | 0.7 | 5.2 |
| DHW [kWh/m ²] | 7.3 | 3.8 |

| | | |
|--|-------|-------|
| Rest of the electricity [kWh/m ²] | 5.6 | 4.4 |
| Total electricity consumption [kWh/m ²] | 45.6 | 35.1 |
| Total primary energy consumption [kWh/m ²] | 114.1 | 105.2 |
| Total energy balance (electricity) [kWh/m ²] | 66.7 | 137.0 |

The results of the dynamic simulation for the PCM application in the house are presented in the figure below (cooling season May-September months):

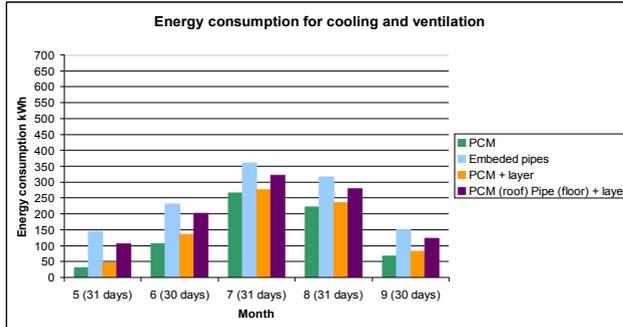


Figure 3: Energy consumption for cooling season in Madrid for different constructions (BSim)

7. Discussion

The evaluations show that the house performs as a “plus-energy house” on an annual basis however it should be kept in mind that the results are aggregated values over a year and the time of energy production and consumption doesn’t necessarily correspond to each other.

For both of the locations, the highest contribution to the energy consumption is from the heating demand. This is mainly due to the North and South glass façades. This effect somewhat offsets the positive effect of the low U-value of the walls.

Embedded pipes in the floor and ceiling are advantageous in achieving the goal of energy efficient heating/cooling, mainly due to the high temperature cooling and low temperature heating concept enabling the natural resources to be coupled/integrated into the HVAC system, in this case being ground heat exchanger.

“Free cooling” is possible to observe for both of the locations, taking Madrid as an example, the same amount of cooling would have been delivered with 848 kWh of electricity compared to 65 kWh of electricity, if it were to be done with the chosen chiller. For the heating case, long-term effects should be considered and kept in mind while realizing this design.

PV/T panels enable the house to be self sufficient and even produce more energy than it consumes on the electrical side and PV/T panels also

contribute significantly to the heat demand for the domestic hot water consumption.

Even though the mechanical ventilation provides better control over the important comfort parameters, natural ventilation possibilities should be exploited until the limits in order to save energy.

The results from the BSim simulation proved that using thermal mass such as PCM decreases energy consumption for the cooling. The highest energy savings using PCM appear in early and late cooling season months, up to 30%. At the peak month energy consumption using PCM is lower, yet only approximately by 20%, compared to conventional water based cooling system. For the testing an early stage concept and possible product was proposed and investigated.

8. Conclusion

The main goal of this study was to design the heating, cooling and ventilation system of DTU's house for the competition, Solar Decathlon Europe 2012 however it was not limited to this extent. Further evaluations were carried out regarding different energy saving and energy efficiency mechanisms.

The competition rules regarding temperature, relative humidity and indoor air quality were on the focal point of the design however an all year round approach was utilized in order to assure that the house and its systems can perform as close as possible to optimum. Keeping these constraints in mind, the components and the HVAC system were designed, simulated and fortunately most of these components were tested and evaluated in full scale once the house was erected in Denmark and later during the competition in Madrid. During the competition period, it was observed that the designed system is capable of meeting the requirements regarding comfort conditions during most of the time [6]. It is worth mentioning that it is always possible to improve and optimize the system and its operation.

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