Passive Solar Floor Heating in Buildings utilizing the Heat from an Integrated Solar Flat Plate Collector

Lazaros Aresti, Paul Christodoulides, Gregoris Panayiotou, Elisavet Theophanous,

Soteris A. Kalogirou and Georgios Florides

Faculty of Engineering and Technology, Cyprus University of Technology
31 Arch. Kyprianou, P. O. Box 50329, 3603 Limassol, Cyprus

Abstract

Floor heating systems provide a comfortable indoor environment because they allow heat to flow slowly in a natural way from the floor upwards. In this way the occupants feel hotter on the feet and cooler on the head enjoying the indoor environment. To this contributes the temperature uniformity over the entire floor. Thermal mass integrated to the floor can act as a thermal reservoir that can store the solar gains of the day and, in this way cover the heating needs of the building under certain climate conditions. In this study we examine the use of the foundation concrete in new buildings as a storing material, where the heat gains of a flat plate collector array on the south wall are driven and accumulated.

As a first step a model building, typically insulated and with walls facing the four cardinal points, was chosen for the study. The south wall area was assumed to be covered with Integrated Solar Flat Plate Collectors and water circulated with a pump between the collectors and the foundation concrete when its temperature exceeded 40°C. A simulation model was built in TRNSYS with the above scenario and hourly results of the collected solar energy and building thermal load were calculated for the climatic conditions of Limassol, Cyprus.

The hourly results of TRNSYS were then used as input for a simulation in COMSOL Multiphysics. The solar energy collected was directed for storing in the foundation concrete. After an initial time priming, the foundation's temperature was raised enough in order to be able to provide the daily heating load of the building. A part of the daily solar energy collected with the collector facade on the south wall, was also directed into the foundation for replenishing the lost energy.

The simulations then were engaged in examining the effect of various parameters, like the thickness of the concrete, the amount of heat available and that which is stored, as well as the controlling technique. The results show that in the climatic conditions of the area considered here, the system chosen can cover completely the heat requirements of the building and provide comfortable conditions for the occupants during winter.

Introduction

Solar energy is a freely available source that can be harvested either for electricity or converted into thermal energy. Thus solar energy is usually turned vastly into electricity, but it is also used for domestic hot water (DHW) applications.

The availability of solar energy to be used as thermal energy comes in contrast with demand. Thermal energy demand is high during the night and early morning in winter, where the maximum available thermal energy is during mid-day. In the whole of summer the thermal energy availability is significantly high, with demand being minimum.

Furthermore, it is noticeable that the efficiency of a Photovoltaic/Thermal (PVT) system ranges within 30%-40%, while that of the Photovoltaics for electricity production ranges within 10%-20% [1]. It is therefore more beneficial to use solar thermal energy than converting it into electricity. This raises the issue of utilizing the solar energy in the buildings, by storing the thermal energy when is available and releasing it by demand when it is required.

Thermal storage can be described by the storage concept and the storage mechanism [2]. The storage concept is distinguished into active and passive, where in the active method there is use of forced convection, and in the passive method gravitational forces are utilized to circulate the fluid of the system [3]. Storage mechanisms on the other hand consist of the sensible, latent and chemical systems. The chemical process uses a chemical reaction where the latent is using phase changing materials (PCM). Although the chemical and the latent systems have proven to be the more advantageous mechanisms [4], the most commonly used is the sensible mechanism where heat is stored as internal energy in the medium being either a liquid or solid [3]. Water, rocks and soil are the most common materials, but also concrete has been tested for short term sensible storage [5]. Concrete, brick and gypsum were studied as sensible thermal storage building materials with results indicating that the convectional 20cm concrete wall provides the most suitable results [6].

In this paper the use of concrete foundations as a passive solar heating in the buildings is examined. The computational modelling was performed into two stages. The first stage is completed using the TRNSYS software to simulate a building with the south facing wall surface covered in solar collectors. With this software, the house load to keep a steady room temperature and the collected heat of the solar collectors were estimated in one hour steps. The second stage was to incorporate those results into the COMSOL Multiphysics software to further examine the use of the buildings concrete foundation as a sensible thermal storage.

Computational Modelling

The model design and the simulation process was carried out by first using TRNSYS software. The building modelled had a rectangular shape with the elongated side facing south and its dimensions were 4m × 8m x 3m (height). The walls considered during the modelling consisted of the following layers: 0.025m of plaster, 0.2m hollow clay brick, 0.05m of extruded polystyrene and 0.025m of plaster on the outer surface. The roof consisted of a layer of 0.025m plaster, 0.15m reinforced concrete with 1% iron and 0.05m of extruded polystyrene. The floor was considered to have no heat losses through the ground. The building also had 24m^2 of solar collectors.

The model consisted of the following components: (i) Type 109 - TMY2 (weather data processing model), (ii) Type 33 – Psychrometrics, (iii) Type 69 - Effective sky temperature for long-wave radiation exchange, (iv) Type 2 - ON/OFF Differential controller, (v) Type 65 - Online graphical plotter, (vi) Type 25 - Printer – TRNSYS - supplied units printed to output file, (vii) Type 56 - Multi-Zone Building, (viii) Type 114 – Pump, (ix) Type 1b - Solar collector.

During the simulation the set temperatures of the heating and cooling modes were 21°C and 27°C respectively, so as to be within the comfort conditions for dwellings. Using the above model, the energy demand for every hour of the day was calculated throughout the winter time. Also the energy collected through the solar collector system was also calculated during the same time. The solar energy was more than enough to heat the model house.

COMSOL Multiphysics v.5.1 software was then used for the computational modelling, which allows the user to employ general equations, but also add and edit equations manually. It also allows the user to create a CAD model, construct the mesh, apply the physical parameters and post process the results under the same user interface. It also has the ability to input multiple physical parameters and conduct parallel processing.

In this paper the CAD model was constructed in 2D under the COMSOL interface, as illustrated in Figure 1. There are four vertical layers; starting from the top there is the tile with a height of 0.01m, followed by the screed with a height of 5cm, the 3rd layer is the main concrete base with variable height (0.5m presented) and finally the pipe section represented with a layer of 0.02m, where water transfers the heat from the storage to the floor area.

Figure 1 2D Geometry of the floor

The material properties used for each layer are shown in Table 1. For the pipe domain, water was selected as a material and the material properties are varied depending on the temperature.

Table 1 Material Properties by layer

Material	**Domain**	**Density (kg m^{-3})**	**Thermal conductivity λ (W m^{-1} K^{-1})**	**Heat capacity at constant pressure c_p (J kg^{-1} K^{-1})**
Tile	1	2100	1.1	837
Screed	2	1200	0.41	840
Concrete	3	2300	1.8	880

The module of Heat Transfer in Solids was selected in COMSOL with the heat distribution over time described by the general heat transfer equation based on the energy balance. Thus, the three dimensional conservation of the transient heat equation for an incompressible fluid used is as follows:

$$\rho c_p \frac{\partial T}{\partial t} + \nabla \cdot q = Q \tag{1}$$

where T is the temperature [K], t is time [s], ρ is the density of the foundation material [kg m^{-3}], c_p is the specific heat capacity of the foundation material at constant pressure [J kg^{-1} K^{-1}], Q is the heat source [W m^{-3}] and q is given by the Fourier's law of heat conduction that describes the relationship between the heat flux vector field and the temperature gradient. To simplify the calculations, Equation 1 is also applied in the pipe domain as a heat source (Q), directly supplying heat from the storage of the collectors.

The data from the TRNSYS were read in COMSOL as interpolations and the house load was applied as a boundary condition on the top surface of the tile domain divided by the area (Q_b) [W m^{-2}]:

$$Q_b = Q_{houseload}(t)/(width \times depth) \tag{2}$$

In this way, the model allows for the loss of heat, contributing thus to the room load. The heat needed for heating the room was supplied by the collectors, stored in a thermal storage unit (not presented in the simulation) and the hourly average of the month was supplied in the pipe domain. In this study case, the average load for January is 222 W h^{-1}.

In order to keep a nearly constant temperature on the house floor, a mathematical parameter was used to represent a thermostat to control the supplied heat and balance the room load, in order to provide the right temperature. A realistic scenario is to read the temperature at the floor and either increase or decrease the input heat to the system. An average line temperature (AveTemp) was introduced in the model at the surface between the tile and the screed (1cm from the top surface), assumed to be constant at 35°C and estimated at every time step (every hour in this scenario). To keep the temperature steady extra heat was supplied in the pipe domain of the floor according to the values shown in Table 2. The General Heat source was calculated with Q_0=Q/V, where V is the volume of the pipe domain.

Table 2 Heat source applied in the pipe domain

Temperature (AveTemp)	**Heat Transfer Rate Q (W)**	**General Heat Source Q_0 (W m^{-3})**	**Steps**
>35.5	0	0	1
34.5<AveTemp<35.5	222	71.04	2
33.5<AveTemp<34.5	222*2	142.08	3
<33.5	222*4.5	319.68	4

Table 2 presents the controlling technique used to maintain a comfortable temperature environment with the floor at 35°C. Several configurations were simulated before ending up in this simple method. Other more complex techniques were tried, but these provided higher fluctuations.

Higher mesh density was used for the top and the bottom lines of the model, where the loads were applied, with lower mesh density in the middle. The mesh for the 0.5m concrete domain consists of 7456 domain elements and 1864 boundary elements, the 1m domain consists of 8010 domain and 1872 boundary elements, and the 1.5m domain consists of 8330 domain and 1876 boundary elements.

Results

Several simulations were performed in order to obtain the optimum scenarios and the best conversion of computational time and memory. Figure 2 presents the Q values from the pipe domain and the house load. The green line in Figure 2 represents the house load (negative as the house requires heat), and the blue line average represents the heat provided to the house. The house load compared with the solar collectors' load is presented in Figure 2, where it is clearly observed that the loads are balanced. The thermostat like configuration can also be distinguished in Figure 2, where there are 4 steps presented as seen and described in table 2. The house load and the solar collectors' loads are presented in Table 3.

Table 3 House load and solar collectors load

	Qcollector (KW)		**Qhouse load (KW)**	**Factor**
	Roof horizontal solar collectors	**Wall vertical solar collectors**		
JANUARY	2770.07	1978.58	165.21	0.08
FEBRUARY	2187.34	1413.02	133.13	0.09
MARCH	7160.76	1332.17	87.74	0.07

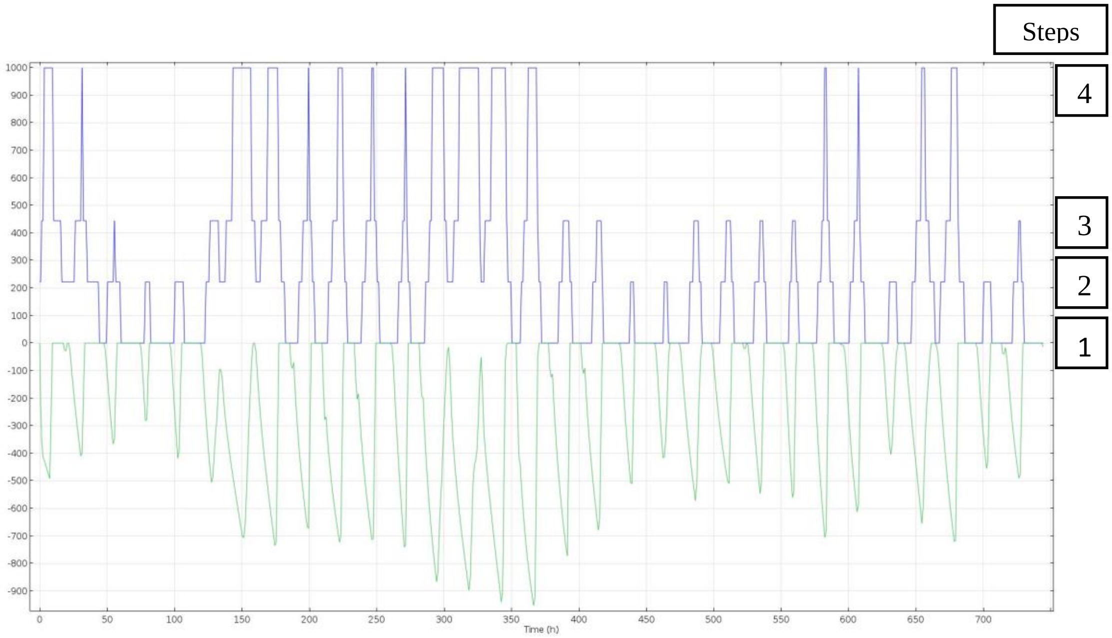

Figure 2 Q values in W, blue line represents the Q values in the pipe domain, green line represents the house load

Different concrete thicknesses have been tested for January in order to examine the stability and control over the temperature that the house floor retains. The four different concrete thicknesses are 0.4m, 0.5m, 1m and 1.5m. In Figure 3 the temperature against time has been plotted for the 0.5m concrete thickness. It is observed that the maximum temperature obtained is 37.125°C with a minimum temperature of 31.317°C. The observed differences of +2.1 and –3.7 are acceptable since the most common types of thermostats have a tolerance of about ±2°C.

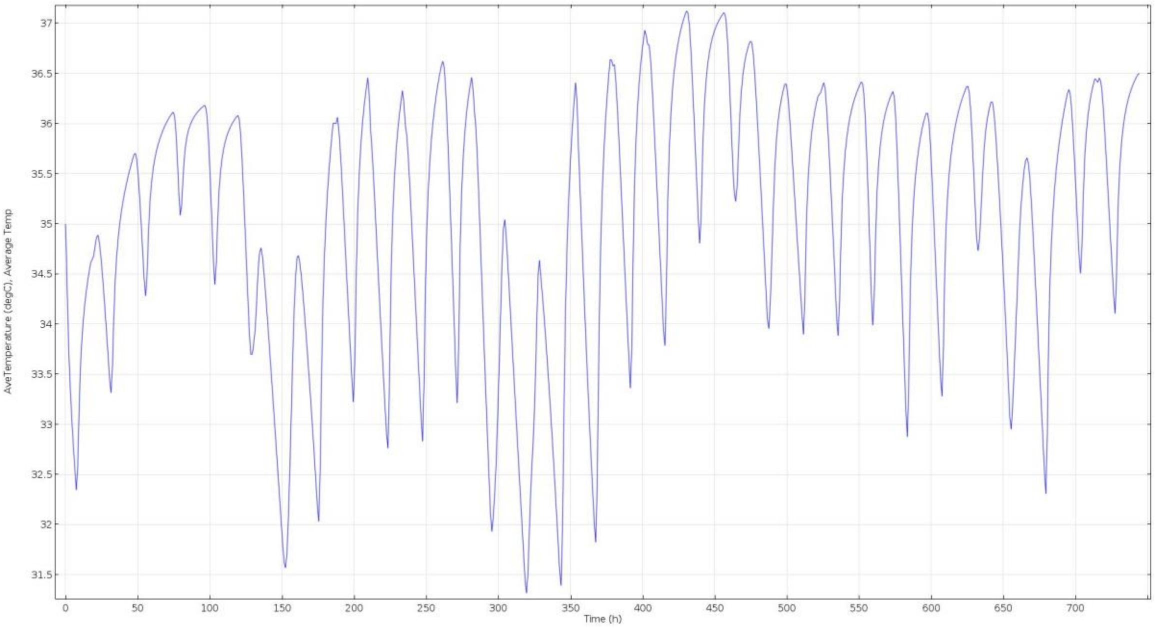

Figure 3 Line Average Temperature at the base of the tile with 0.5m concrete and 35 degrees Celcium inital temperature.

Figure 4 shows the temperature variation for three difference concrete thicknesses: 0.5m,1m and 1.5m. The computational models have kept the same physical configurations except for the meshing. It can clearly be observed that all thicknesses present similar fluctuations for the reason that the models are dependent on the house and the collectors' loads that are kept the same. Additionally, the least variation is noticed in the 0.5m model and the greatest in the 1.5m model. A conclusion can be drawn that for the specific model set up, a concrete height (thickness) of greater than 0.5m leads to a greater temperature variation in the room.

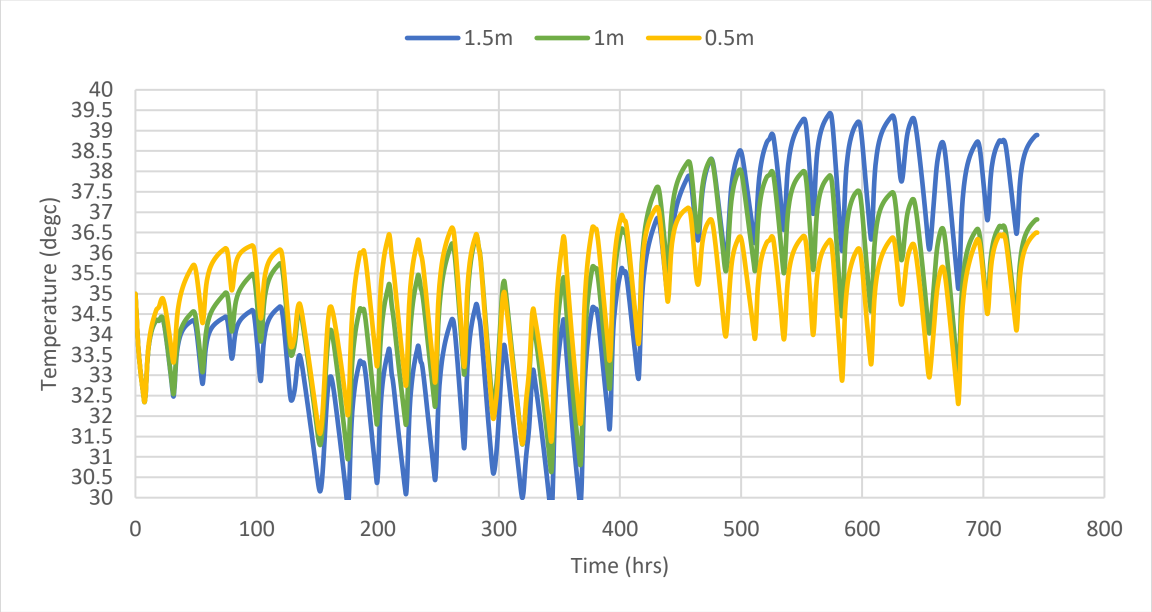

Figure 4 Line average Temperature at the base of the tile at three difference concrete thicknesses (0.5m, 1m and 1.5m) and initial temperature of 35°C

To test if better stability can be achieved, smaller concrete thicknesses were tested with heights of 0.2m, 0.4m and 0.5m, as shown in Figure 5. The three different thicknesses present almost identical results, where the temperature variation in the 0.4m is 5.29°C and for the 0.2m thickness is 5.08°C. It can be safety assumed that the commonly used concrete thickness of 0.5m as a house base layer is able to give good results in the specific model set up.

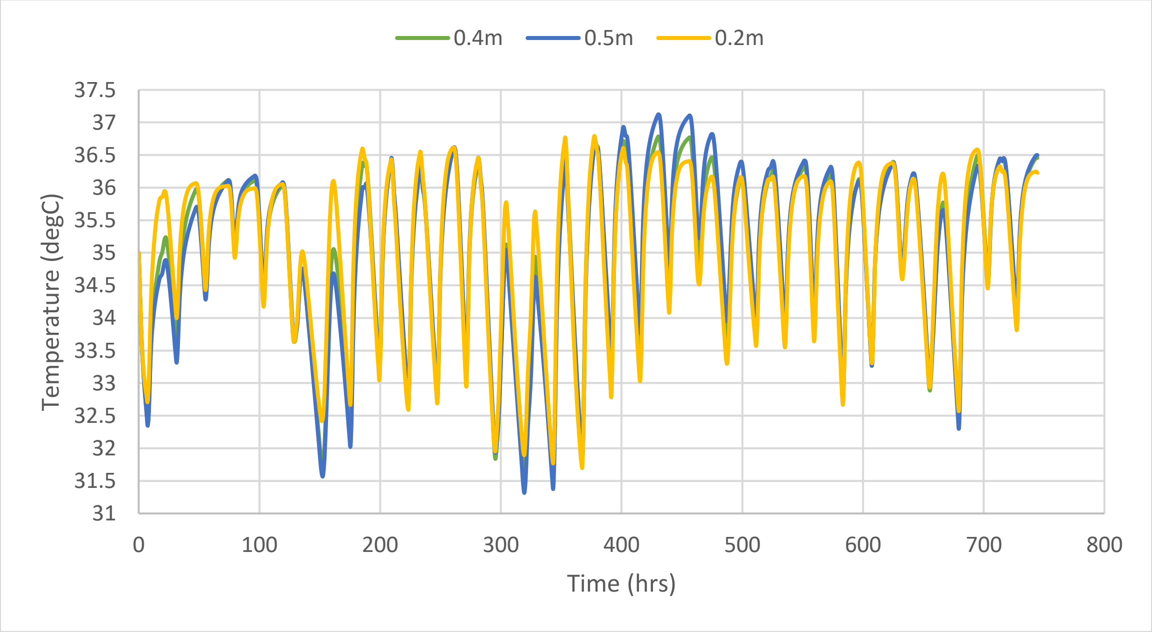

Figure 5 Line average Temperature at the base of the tile at three difference concrete thicknesses (0.2m, 0.4m and 0.5m) and initial temperature of 35°C

Conclusions

A typical house with solar collectors has been modelled and simulated in order to examine where it is feasible to use the house concrete base as a thermal storage unit during sunny days of winter, and depending on the house load requirements to apply heat with natural convection from the house floor.

Two software programs have been used, namely TRNSYS and COMSOL Multiphysics, where the first has been used to simulate and calculate the required house load and the collectors load with the combination of a thermal storage unit, and the latter was used to simulate the heat flow in the concrete base of the house.

The results have shown that the concrete base of a house can be used as a thermal storage unit, and in collaboration with the solar collectors the system can reduce the energy required for the house heating and can offer an alternative possibility for an HVAC system. The results also indicate that an investigation regarding the solar collectors, concrete thickness and thermal storage unit needs to be carried out in advance before a system can be incorporated.

Future research needs to be carried out in order to reduce the fluctuations of the temperature against time, and a way to overcome this is to reduce the time step. This way the thermostat like system will read the temperature difference in a smaller time-step and provide the system with more or less heat, depending on the average temperature. Additionally, different materials for the concrete base can be tested not only computationally, but also experimentally and with the aid of a cluster, the whole year can be examined with the current CFD method.

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