Innovative Fabric Integrated Thermal Storage Systems and Applications

Ahmed Elsayed, Andrew Shea, Nicolas Kelly, John Allison

***Abstract*—**In northern European climates, domestic space heating and hot water represents a significant proportion of total primary total primary energy use and meeting these demands from a national electricity grid network supplied by renewable energy sources provides an opportunity for a significant reduction in EU CO_2 emissions. However, in order to adapt to the intermittent nature of renewable energy generation and to avoid co-incident peak electricity usage from consumers that may exceed current capacity, the demand for heat must be decoupled from its generation. Storage of heat within the fabric of dwellings for use some hours, or days, later provides a route to complete decoupling of demand from supply and facilitates the greatly increased use of renewable energy generation into a local or national electricity network. The integration of thermal energy storage into the building fabric for retrieval at a later time requires much evaluation of the many competing thermal, physical, and practical considerations such as the profile and magnitude of heat demand, the duration of storage, charging and discharging rate, storage media, space allocation, etc. In this paper, the authors report investigations of thermal storage in building fabric using concrete material and present an evaluation of several factors that impact upon performance including heating pipe layout, heating fluid flow velocity, storage geometry, thermo-physical material properties, and also present an investigation of alternative storage materials and alternative heat transfer fluids. Reducing the heating pipe spacing from 200 mm to 100 mm enhances the stored energy by 25% and high-performance Vacuum Insulation results in heat loss flux of less than 3 W/m^2, compared to 22 W/m^2 for the more conventional EPS insulation. Dense concrete achieved the greatest storage capacity, relative to medium and light-weight alternatives, although a material thickness of 100 mm required more than 5 hours to charge fully. Layers of 25 mm and 50 mm thickness can be charged in 2 hours, or less, facilitating a fast response that could, aggregated across multiple dwellings, provide significant and valuable reduction in demand from grid-generated electricity in expected periods of high demand and potentially eliminate the need for additional new generating capacity from conventional sources such as gas, coal, or nuclear.

***Keywords*—**Fabric integrated thermal storage, FITS, demand side management, energy storage, load shifting, renewable energy integration.

I. Introduction

RISING energy prices and a desire to reduce the level of carbon dioxide emissions due to building conditioning systems and to incorporate a greater proportion of renewable energy sources into the electricity generating fuel mix provide the motivation to direct research and development effort towards the utilization of energy storage techniques. Thermo-active buildings take many forms but, in our case, a heat transfer fluid is heated, for example, via electric resistance (joule heating) or heat-pump technology, and is then circulated within a building structure to charge an energy store for retrieval of the thermal energy at a later time for application as winter-time space heating or hot water generation. The working principle of this system is based on accumulation (temporary storage) of heat or cold (energy) in the thermal mass of the building [1].

Previous studies have investigated a range of solid, air, and liquid-based storage solutions including water storage tanks buried below the building structure [2]; pebble beds of alumina and cored bricks [3]; and air-heated concrete columns [4], [5]. Concrete as a storage material has several advantages including low cost, high heat storage coefficient, it can be formed into regular and irregular shapes, and can be easily extended for increased capacity [6]. Much of the existing literature investigates the use of concrete at high temperatures with the heat transfer fluid in the temperature range of 250 °C to 400 °C [6], [7]; with these applications being predominately in the field of power generation. Ozrahat [5] tested concrete heat storage in the temperature range of 120 °C to 160 °C for application in buildings, however, whilst reducing the required volume of storage material, such high temperatures present a number of issues including relatively higher standing losses and, where stores are not intended to directly heat the building, there is difficulty in isolating the thermal store from the occupied environment. Where stores are intended to be charged from fluid heated by electrical heating, i.e. heat pumps or immersion heaters, such temperatures are incompatible.

In this paper, we present an investigation of the parameters that influence the storage performance of an underfloor concrete storage slab sandwiched between insulation layers. The practical intention of the store is to absorb heat from the heat transfer fluid heated from electrical sources, for example, in times of low electricity demand across a power network or reduced tariff, and to store thermal energy for later use as space heating and/or domestic how water. The study investigates the effect of concrete thermophysical properties i.e. thickness of material, density, thermal conductivity, and heat capacity, to reflect the common types of material generally described as light weight, medium weight and heavy weight. Additionally, the heating tube pitch, transfer media, and the effect of insulation material are evaluated.

II. Model Validation

Conjugate heat is the main physical process for heat transfer

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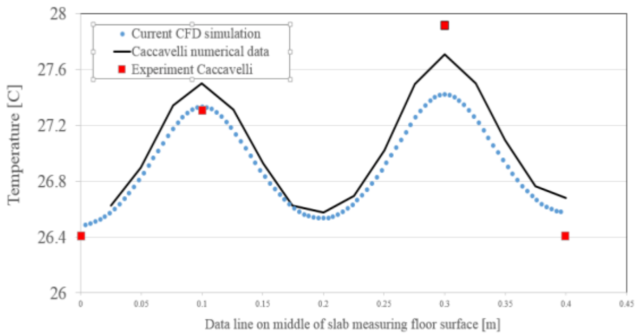
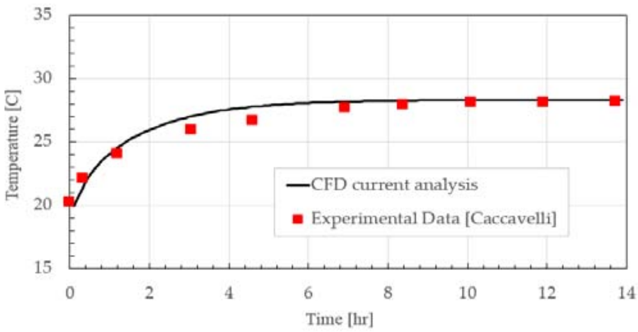
between a hot fluid/solid slab or between two solid layers. Ansys Fluent 17 [8] has been utilized in the current analysis where data in [9], [10] have been used for validation. Fig. 1 shows good agreement for both for steady-state floor heating and transient analysis.

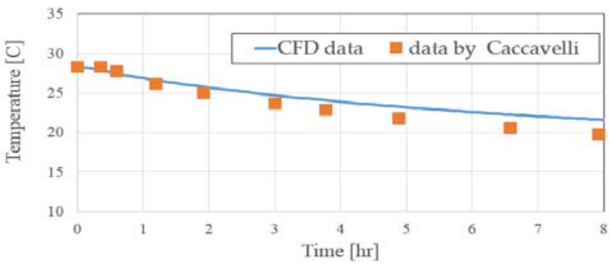
In the simulation, the room temperature was set to 19 ˚C and the hot water flow velocity was 0.3932 m/s for a 12 mm inner pipe diameter of PEX-AL-PEX material, with an outer diameter of 16 mm.



(a) Steady state heated floor validation



(b) Transient model validation, heating system active



(c) Transient model validation, heating system inactive

Fig. 1 Steady and Transient Model validation

III. Discussion and Findings

In order to investigate the effect of different parameters on the performance of the concrete storage medium a slab area of 1.2 m x 0.6 m was used. Tube pitches of 100 mm, 150 mm, and 200 mm were evaluated. The material properties utilized in the current analysis are summarized in Table I.

TABLE I
Thermophysical Properties of Materials Used in Simulation

Material	Density [kg/m^3]	Specific heat [J/kg.K]	Thermal conductivity [W/m.K]
EPS Insulation	60	1300	0.033
Heavy Concrete	2000	840	1.3
PEX-AL-PEX Pipe	901	1800	0.45
Water flow velocity 0.7 m/s and viscosity of 0.0007 Pa/s			

A. Effect of Heating Pipe Arrangement

The 100 mm pitch provides a more rapid heating response (Fig. 2) due to the longer tube pass and more uniform heat distribution as presented in the CFD analysis (Fig. 3).

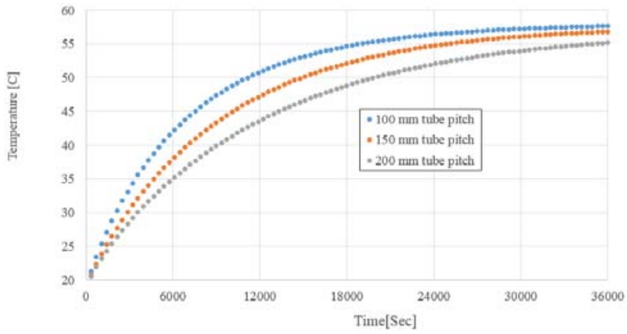
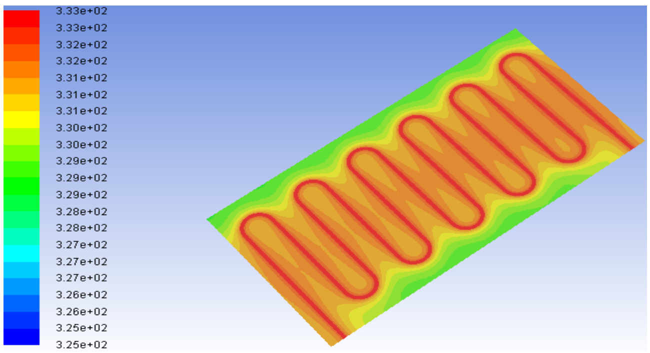
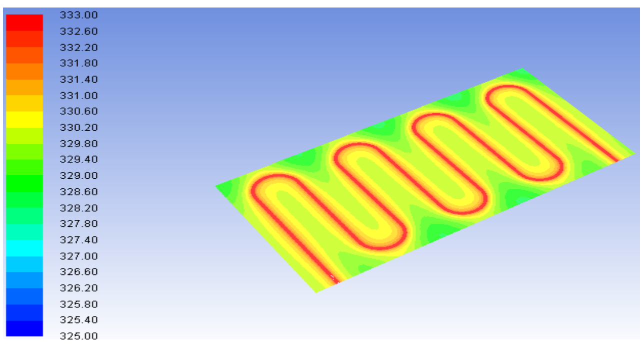


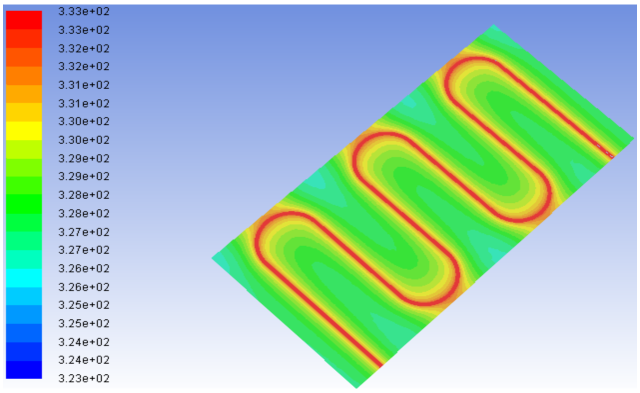
Fig. 2 Transient average temperature of concrete Slab with different loop designs



(a) 100 mm pitch



(b) 150 mm



(c) 200 mm

Fig. 3 Mid-section concrete slab temperature distribution

The amount of energy stored per m^2 is dependent on the charging time and type of loop design; the 100 mm pitch shows a greater amount of energy stored if the charging times are less than 2 hrs. The difference between different arrangements becomes less significant at high storage times, as indicated in Fig. 4. For a 5 hr storage time for 4 m x 4 m floor area one could expect 88,000 KJ. This could be equated to a hot water mass flow of 0.2 kg/s with 10 K temperature difference for 2.9 hrs, which could be utilized by a space heating system, or at temperature difference of 35 K, the storage system could supply, for example, domestic hot water, for 0.84 hr.

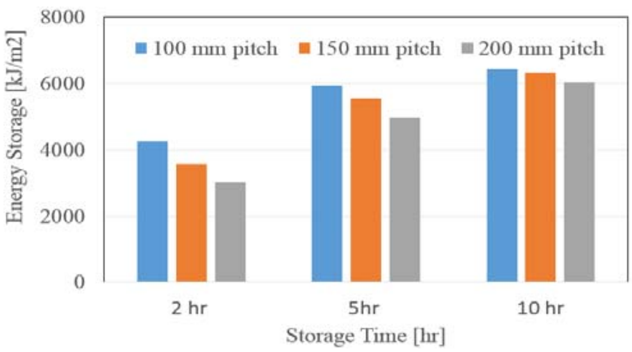


Fig. 4 Energy stored per m^2 of floor area for different heating pipe layouts

B. Comparing the Effect of Flow Velocity

Evaluation of the results of the average temperature of the concrete slab over a 10 hr heating period (Fig. 5) reveal that the concrete slab thermal resistance dominates the control of heat transfer, since concrete has low thermal diffusivity and relatively thick slab. Convective heat transfer enhancement due to the increase in flow rate has only a modest effect on the slab temperature; all flow conditions are turbulent. The results agree with test results of Rao [11], wherein tests on a concrete module revealed similarly small differences in temperatures with time for velocities ranging from 0.25 m/s to 0.5 m/s.

C. Comparing Different Concrete Materials

Three definitions of dry concrete were selected from [12] namely, heavy, medium, and light-weight. Results indicate (Fig. 6) that heavy-weight concrete, due its relatively high thermal conductivity, results in a slab that is more responsive to the heat transfer fluid. Additionally, the high density of the heavy-weight concrete confers greater energy storage for the same slab temperature. A consequence also of the change in material thermophysical properties is that the heavy-weight slab has the highest floor surface temperature (Fig. 7).

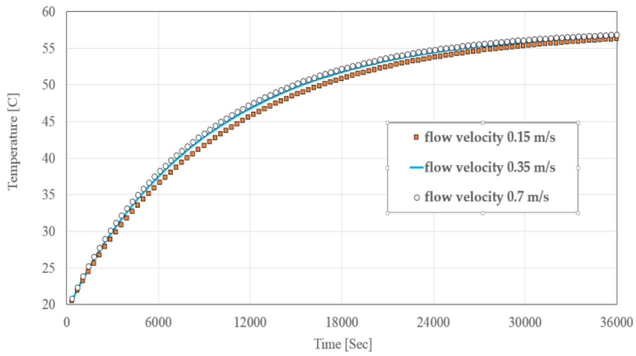


Fig. 5 Concrete slab temperature at different hot water flow velocities

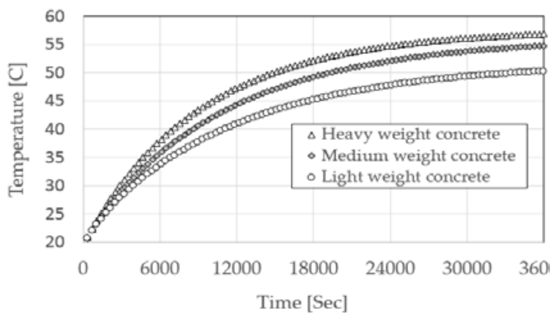


Fig. 6 Average slab temperature for different concrete definitions

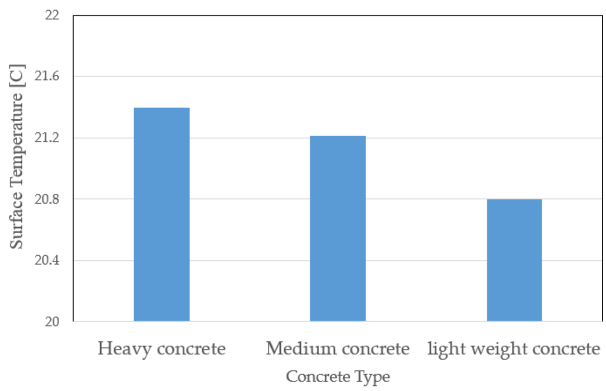


Fig. 7 Surface temperature of Floor for different concretes

D. Effect of Concrete Slab Thickness

Thinning the concrete storage slab helps in the speed of response to thermal loads; there is little effective difference between the 25 mm slabs and 50 mm slabs, however the 100 mm slab has a more noticeable delay in response to the applied heat, as presented in Fig. 8.

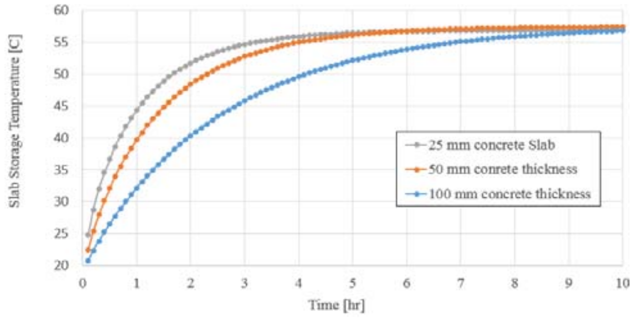


Fig. 8 The transient temperature distribution for different slab thicknesses

In Fig. 9, the energy stored per m^2 for different concrete slabs is presented. Approximately 2 hours of charge is sufficient for both the 25 mm and 50 mm slabs as little change is observed with the extended charging periods of 5 hrs and 10 hrs. In the case of the 100 mm slab, around 5 hrs is required to approach the maximum charging capacity.

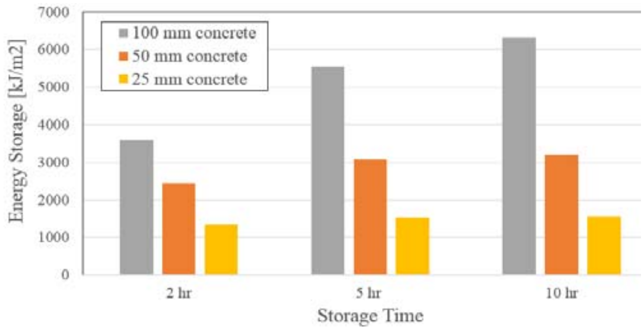


Fig. 9 Different concrete thickness heights energy stored

E. Evaluating the Effect of Using Nanofluid Al_2O_3 as the Heat Transfer Fluid

Nanofluids are reported to be most effective in the case of a laminar flow regime. Their enhancement becomes insignificant in a turbulent flow regime [13], especially with high flow velocities such as the 0.7 m/s employed in our current configuration. When comparing different nanofluids, it would seem prudent to clearly state if the comparison was evaluated at same flow velocity or Reynolds number; often nanofluids have higher viscosity and higher density than conventional alternatives. Such intra-regime behaviour could quickly be predicted using Dittus-Boelter turbulent correlations, where the effect of Reynolds and Prandtl numbers would identify if the fluid heat transfer could be enhanced or not.

TABLE II
COMPARISON OF THE EFFECT OF DIFFERENT HEAT TRANSFER FLUIDS ON THE CONCRETE SLAB TEMPERATURE

Heat transfer fluid	Heating time/slab temperature [˚C]	
Heating time	5 hr	10 hr
Pure water	52.13	56.81
Nanofluid (5%Al_2O_3)	52.17	56.83
Glycol (55%) [14]	51.59	56.57

F. Natural Alternatives for Concrete

Concrete production is an energy demanding process and some alternatives may be worthy candidates for evaluation and could improve whole-life carbon impacts associated with their production and use. Limestone has similar performance to concrete slabs but, another alternative, Quartzite, is more responsive to thermal loads (Fig. 10) due to its high thermal conductivity 4 W/m.K [15]. In the case of materials that have cracks due to the repeated cycles of cooling and heating, wet sand mixed with conductive fluids are suggested for low temperature storage operating conditions [16].

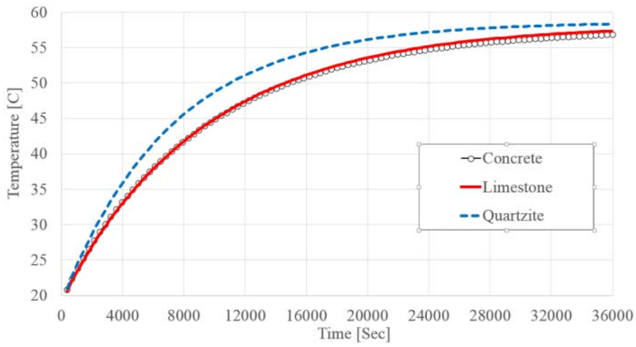


Fig. 10 Performance of storage matrix with different natural materials

G. Effect of Thermal Insulation Material

There is a wide range of insulating materials that would improve the performance of the storage matrix. Table III summarizes the thermal performance of the heat storage slab with a range of insulation materials, namely, EPS, PUR, Cork and Vacuum Insulated Panels (VIP). PUR exhibits slightly better thermal performance, than EPS and Cork, as the floor temperature is lower while still maintaining the concrete at higher temperature of 57.09°C, after 10 hrs of heating. The VIP is highly effective due to very low thermal conductivity (0.00375 W/m.K).

TABLE III
EFFECT OF DIFFERENT INSULATION MATERIALS

After 10 hr	Concrete Temp [C]	Floor Temp [C]	losses to room [W/m^2]
EPS	56.81	21.40	22.88
PUR	57.09	20.84	17.86
Cork	56.47	22.05	28.79
VIP	57.80	19.09	2.16

Results indicate that the insulating layer helps improve uniformity of the floor surface temperature, where heat in the slab is forced to spread in the axial direction maintaining a uniformity of temperature over the floor, as shown in Fig. 11.

H. Effect of Floor Insulation Thickness

Thicknesses of 100 mm, 75 mm and 50 mm of EPS were investigated. It was observed that reduced insulation thickness increases the heat transfer from the concrete slab to the room, as expected. For a room 4 m x 4 m, this would equate to a heating input of 366 W in the case of the 50 mm slab, and consequently, increased surface temperatures and reduced concrete slab temperature, as shown in Table IV.

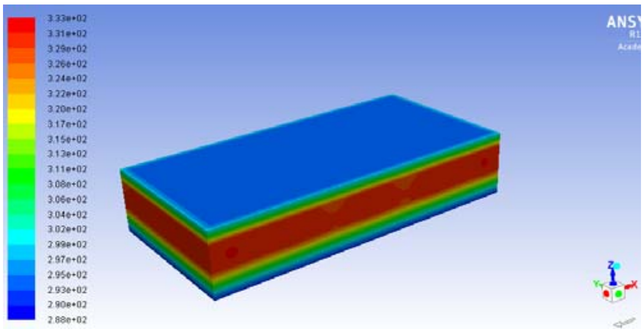


Fig. 11 Temperature distribution for 150 mm tube pitch, 0.7 m/s flow, concrete thickness 100 mm and bottom and top insulations of 100 and 50 mm, respectively

TABLE IV
EFFECT OF VARYING FLOOR INSULATION THICKNESS

After 10 hr	Concrete slab temp. [C]	Heat to room [W/m^2]	Average floor surface temp. [C]
100 mm	57.33	11.94	20.18
75 mm	57.17	15.77	20.60
50 mm	56.81	22.88	21.40

IV. CONCLUSION

Reducing heating pipe spacing from 200 mm to 100 mm enhances the stored energy by 25%. Whilst standard and advanced insulation materials both provide good isolation of the thermal store from the occupied room environment, the Vacuum Insulation results in heat loss flux of less than 3 W/m^2, compared to 22 W/m^2 for the more conventional EPS insulation solution. The combination of relatively high thermal conductivity and large volumetric heat capacity ensure that dense concrete achieves the greatest storage capacity, relative to medium or lightweight alternatives, although a material thickness of 100 mm required more than 5 hours to charge fully. Layers of 25 mm and 50 mm thickness can be charged in 2 hours or less, which provides opportunities for more responsive systems that can, aggregated across multiple dwellings, provide valuable capacity for demand side energy management.

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