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Thermal behaviour of an active slab: experimental study for TABs applications

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Abstract

The building sector presents considerable potential to have its energy consumption reduced. An alternative of current great interest is taking profit of the thermal inertia of the same structure of the building, through embedded pipes, for storing thermal energy generated when costs are lower and/or efficiency is higher, named "Thermal Activated Building Systems" (TABS). Energy accumulated is then dissipated when demand raises, seeking to ensure stable indoor comfort conditions while reducing the consumption of conventionally generated energy. The behaviour of these systems is determined by a number of operating parameters to be defined to ensure it operates in an optimal way, taking into consideration criteria such as heat flux dissipated, times of charge and discharge of the structure, position of the active slab, temperature of the fluid use inside the embedded pipes and ambient thermal conditions. It has been demonstrated that the study of the thermal behaviour of sand and gravel active slabs can be extrapolated to concrete, real slabs. This paper presents the experimental results obtained in slabs of 15 and 20 cm thickness, charged until reaching steady state. Then the work discusses the thermal behaviour of the slab for different water temperatures supplied to the pipes. Thus, it illustrates the possible experimental study of active slabs to predict the thermal behaviour of TABS in real applications.

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Keywords: Thermaly Activated Building Systems; Energy storage; radiant systems; experimental slab.

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1. Introduction

The reduction in the energy consumption has become a need. It is the only real alternative to stretch the horizons of the available energy resources and limit their cost and the impact of their use. The building sector has significant potential of energy saving, partly due to the number of existing dwellings and the lack of consciousness of their residents. As a consequence, different directives are being driven [3,4] in order to reduce the energy consumption in buildings.

Thermally Activated Buildings Systems (Fig. 1) permit the building structure to store energy, then enabling the separation in conditioned spaces between thermal energy generation and use. In this way, thermal energy can be generated when costs are lower and/or efficiency is higher, and then stored within the structure, which dissipates it when there exist an energy demand indoors for thermal comfort. Examples of this sort are the use of solar thermal energy for heating the building structure once reached the heating set temperatures indoors [1], or the use of cooling towers to provide cold water to the embedded pipes during nighttime in summer [2].

Because the temperature of the building envelope on the inside need to ensure thermal comfort requirements in terms of radiant temperature, either hot or cold water driven inside the piping must be generated at low and high temperatures compared to the environment, respectively. This enhances the efficiency of the thermal generation systems, which can be Low-Ex.

Fig. 1. TABs systems (a) view; (b) Cross section

The number of parameters involved in the design of the TABs, make not only interesting but also necessary the availability of experimental results that provide models of thermal behaviour. Existing research work review this technology [5,6, 7], taking into consideration the different criteria for simulation, modelling, etc. always aiming at optimizing the design. Characterization of these systems is usually as radiant dissipation systems. Thus, heat flow dissipated is analysed in terms of the operating parameters [8] through the definition of the equations that allow the computation of the heat transfer coefficients. Nevertheless, few experimental results exist and the available ones focus on the analysis of TABS implemented in real buildings, where the operation parameters cannot be controlled.

Hence, TAB systems are not easily approachable through experimentation due to the null accessibility of the structure for further intervention or replacement of existing temperature probes if damaged. With the aim of providing an alternative, easier method to study experimentally the thermal behaviour of a concrete slab, the authors proposed in previous research work the analysis of sand and gravel slabs [9]. By developing experimental tests on slabs of the same thickness made of either concrete or sand and gravel, both thermal behaviours were compared through the non-dimensional analysis of the temperature distribution as a function of the thermal diffusivity. Extrapolation of the results on the sand and gravel slabs to the concrete ones turn active slabs much more approachable through experimental procedures.

Once justified the use of sand and gravel slabs, in the present paper the authors present and discuss the results obtained from the experimental tests developed for different thicknesses of this sort of material.

2. Experimental device

The active slabs are studied in a climate chamber equipped with a heat pump that controls temperature conditions indoors. A cold and hot water generation system permits providing the water flow at the temperature level required to the active slabs in order to develop the tests at the different operating conditions desired (Fig. 2. a).

Two sand and gravel slabs of 15 and 20 cm thicknesses are built. Each slab has an upper surface of 1 m^2 exposed to the indoor environment of the climate chamber and its bottom and side surfaces isolated with 8 cm of expanded polystyrene (Fig. 2. b and c). This is to ensure that heat flow through conduction from the active layer, where the pipes are disposed, to the upper, exposed surface of the slab is one-dimensional. From this surface heat flow then dissipates to the environment of the chamber through convection and radiation. The active layer consists of PVC 8/10 mm pipes arranged in a serpentine pattern spaced 10 cm on center, through which water previously heated flows.

Fig. 2. (a) Climate chamber; (b) Concrete slab; (c) Sand and gravel slab

Inside the slab there are temperature probes homogeneously distributed throughout the cross section in layers spaced 5 cm from the active one and between them. In addition to the temperature distribution in the slab, air temperatures inside and outside the chamber are measured. Temperature probes are Pt100 previously calibrated on a dry well and connected to data loggers to register the measurements.

Heat flow to the slab is determined by measuring both the water flow inside the pipes and the temperature difference between inlet and outlet. On the other hand, heat flow dissipated from the top to the inside of the climate chamber is measured with a heat flow plate placed on the exposed surface of the slab.

Factors studied are: charge time (2h, 4h, 8h and indefinite till steady) and water temperature (35˚C, 40 ˚C and 45 ˚C). The present work presents the effect of modifying the slab thickness and water temperature on the charge time of the slab until steady state (when there is no difference between provided and dissipated heat flow while operating conditions remain stable).

The experimental procedure is as following: first, hot water is generated and its temperature maintained at the required level in a water tank equipped with a controlled heating system. Before the charge of the slab begins, the data loggers start to register the measurements of the temperature probes and the heat flow plate. Then water is driven to the piping of the active layer of the slab. Water mass flow rate is measured with a rotameter and the measure is checked during the tests through weighting.

3. Experimental results and discussion

All tests have been developed for water flows in the range from 480 to 500 ml/min. This would ensure laminar flow inside the pipes, with Reynolds numbers between 1600 and 2000, then close to turbulent flow. Water flow inside the pipes is a key parameter in these tests due to the experimental setup. Higher levels of water flow would incur into little temperature drops and thus to important uncertainty of the results due to the accuracy of the temperature probes. On the other hand, lower water flows, although they would result into desired larger temperature drops between water inlet and outlet, also generate low convective heat transfer coefficients between water and the inside of the piping. In that case, the heat transfer resistance between water and the pipes could be determinant in the process, instead of that of the target one generated by the slab. It is estimated that a Nusselt number corresponding to laminar flow inside the pipes of 3.66 would result into a thermal resistance through convection lower than 10% of the global one in the whole system. Hence, water flows used in the tests have been calculated in consequence.

The results that best show the thermal behaviour of the slab are the evolution of the temperature distribution and the heat flows supplied in the pipes and dissipated from the top surface. Fig. 3. shows an example of these results, for the 20 cm thick slab fed with water at 40˚C and charged until steady state.

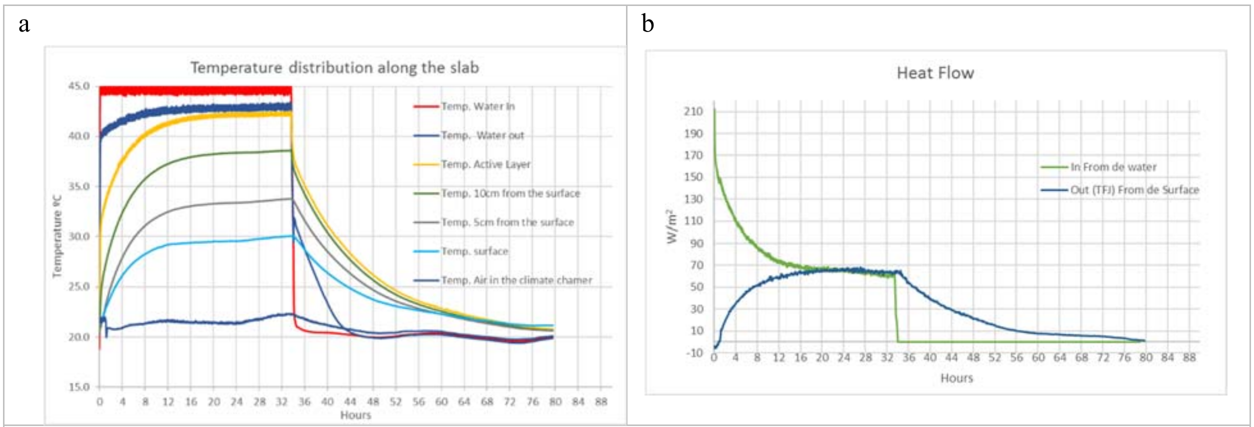

Fig. 3. (a) Temperatures measured (slab, ambient air, water at the inlet/ outlet); (b) Heat flows: supplied/ dissipated

Test of Fig. 3 permits observing that, under those operating conditions, the slab does not reach steady state before 16 hours had passed. This result highlights that TABs, usually operating with shorter charging times, would find it difficult to get completely charged before energy demand indoors require dissipation of the energy stored. Focusing on Fig. 3 (a), temperature distribution at the different depths of the slab thickness is homogeneous, which enable its correlation with the dissipated heat flow.

In addition, there is significant difference between supplied and dissipated heat flow during the charging time at the beginning of the test. This evinces the energy storing inside the slab, which later dissipates to the environment of the climate chamber once the water flow inside the pipes gstops. Charging time then needs optimization, given that as time passes energy stored in the slab diminishes whereas pumping power remains.

Fig. 4. presents the results for the slab 15 cm thick charged during 4h with water supplied at 25 ºC. Discharge time in this case is studied modifying indoor conditions in the climate chamber during two periods of 6 and 4 hours, to a different set point. The aim is to observe how a change in the ambient conditions affects to the dissipated heat flow. The consequence is that, when ambient conditions vary, they have an immediate effect on the dissipated heat flow. Hence, under real operating conditions these systems would be capable of adapting on the instant to changes in the thermal demand of a conditioned space.

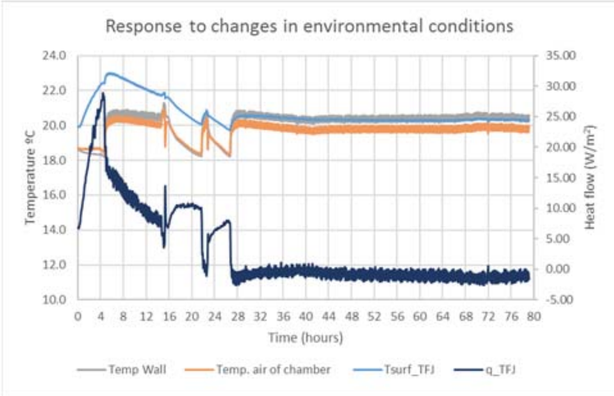

Fig. 4. Effect of the environmental conditions in the dissipated heat flow.

The thermal behaviour observed demonstrate that, if thermal loads are small, variations in the ambient conditions can be neutralized by the active slab, succeeding to maintain the required levels of thermal comfort. Otherwise, and despite larger dissipated heat flow, indoor conditions would diverge from those of thermal comfort. Consequently, meeting the requirements may depend on an auxiliary system. Nevertheless, heat provided from the active slab, generated when being most efficient, always reduce the energy demand of the conventional systems.

Fig. 5. represents the evolution of the supplied heat flow until steady thermal behaviour of the two slabs 15 and 20 cm thick under the different water temperatures studied. Table 1 gathers these steady values of the supplied heat flow, which also reveal the maximum heat flow dissipated under the same ambient conditions of 21˚C.

a b

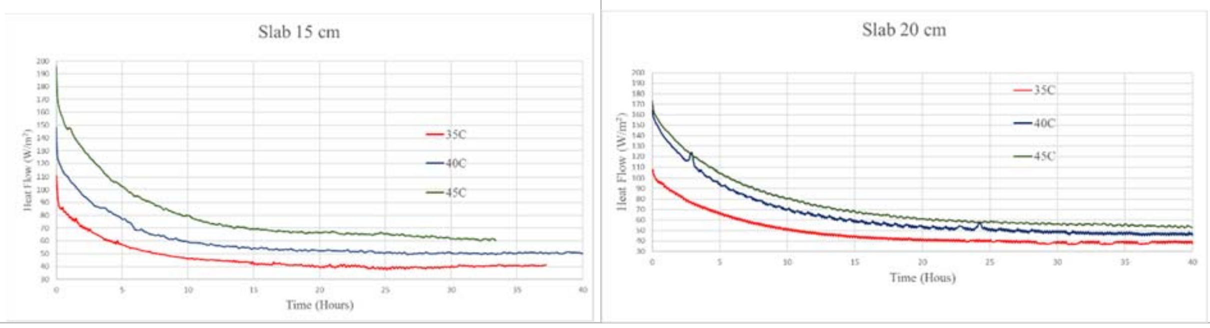

Fig. 5. Effect of the inlet water temperature in the slab (a) 15 cm thick; (b) 20 cm thick.

Table 1. Supplied heat flow per square meter in steady state for slabs 15 and 20 cm thick.

Water temperature (inlet)	Slab 15 cm	Slab 20 cm
35 ºC	40.7 W/m^2	39.4 W/m^2
40 ºC	50.4 W/m^2	44.5 W/ m^2
45 ºC	61.3 W/m^2	52.5 W/ m^2

For larger water temperatures, heat flow dissipated from the top surface increases. An increase in the water inlet temperature generates a larger temperature gradient in the slab with the consequent greater heat flow dissipated once reached the steady state, when the slab does not store further heat. It must be noticed that values given in table 1 are the maximum ones achievable for these slab thicknesses besides operating under the same temperatures. Because in real buildings TABs would rarely reach a steady thermal behaviour and charging times would be limited to 8-10 hours maximum, the system could only dissipate a lower quantity of energy. This fact highlights the interest in applying these systems to buildings where thermal loads per square meter are small.

However, for thicker slabs heat dissipated diminishes. This last effect is more noticeable for higher water temperatures. This effect is due to the increase in the thermal resistance of the slab. Thus, if the same water temperature feds the active layer of the slab, heat dissipated is lower. Consequently, although thicker slabs enable greater energy storing, it would only result into longer times of discharge but not on greater heat dissipation.

Conclusions

The experimental study of the thermal behaviour of sand and gravel slabs can be used to predict and understand the operation of TAB systems. This work presents the experimental results of active slabs of 15 and 20 cm thick under different operating conditions, when charging time is prolonged until steady state.

Long charging times demonstrate that real TABs applications would rarely arrive to their maximum energy storing. Besides, the reduction of the amount of energy stored in the slab while hot water at a constant temperature is pumped to the active layer highlights the need of optimizing the charging time.

The homogeneous temperature distribution observed at the different depths of the slab show that, by measuring temperatures at different layers of a sand and gravel slab, heat flow dissipated can be easily predicted with no need of the heat flow plate.

The immediate effect on the dissipated heat flow of any variation on ambient conditions show how TABs instantaneously adapt to changes in the thermal loads.

As expected, higher water temperatures result into greater heat flow dissipated. However, due to the thermal resistance, thicker slabs enable larger energy storing and thus discharge, operating time; but also incurs into smaller heat flow dissipated from its surface.

This paper then illustrates the possible experimental study of active slabs to predict the thermal behaviour of TABS in real applications.

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