Simulation and control of Thermally Activated Building Systems (TABS)

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Abstract

Buildings account for a significant amount of global energy use and CO₂ emissions. Thermally Activated Building Systems (TABS) are a technology with potential for significantly reducing buildings energy use. TABS are heating and cooling systems that are integrated in the building structure. They mainly exchange heat through radiation and are able to store heat in the building thermal mass. TABS high thermal mass and their interaction with the building structure make their energy evaluation and design process difficult. Development of simulation models has been essential to study the design and control of TABS. Control of TABS is challenging due to the slow response time and storage capacity. A lot of research has been conducted to develop control strategies that fully exploit its energy saving potential and that maximise the use of renewable energies. This paper summarizes the main characteristics of TABS and presents the developed simulation models and control strategies.

Keywords: Thermally Activated Building Systems (TABS), building, modelling, control

1 Introduction

On the last decades there has been much concern on the energy consumption and greenhouse gases emissions. According to the International Energy Agency (IEA) [1] buildings account for 32% of global energy use and almost 10% of total direct energy-related CO₂ emissions. Including electricity generation emissions (plus district heat), buildings are responsible for just over 30% of total end-use energy-related CO₂ emissions. Consequently there is a great potential on energy use reduction in the building sector.

Within this context Thermally Activated Building Systems (TABS) is a promising technology that can track its origin back to the Chinese kang and dikang [2], the Roman hypocaust [3] or the Korean ondol [4]. Radiant floor heating was introduced to United States on the 1930's and in the 50's and 60's to central Europe, although problems were found due to poorly insulated buildings which led to too high surface temperatures [5]. A new trend was started on the 90s with the extension of radiant floor for cooling and the introduction of concrete cores for heating and cooling [6,7].

TABS main advantages are high thermal inertia, big surfaces and radiative nature. TABS are used for peak load shaving, and shifting energy consumption to high efficiency or low energy cost periods [7,8]. The use of big surfaces allows significant heat exchange with a small temperature gradient, making TABS a technology with potential for the use of low grade energy sources [7,9]. TABS radiative nature can improve comfort conditions [10,11], operative temperatures are better managed and noises and draft caused by ventilation are reduced.

The high thermal inertia of TABS has dynamic effects that are difficult to calculate using steady state assumptions. Transient calculations are required for performance analysis and sizing of TABS [12,13]. It also makes TABS control difficult [14,15] as its response time is slow and heating or cooling loads cannot be dealt instantaneously. Furthermore, TABS cannot deal with humidity thus they need to be coupled to any ventilation system. Coordination of TABS and ventilation systems is indispensable for good energy performance of buildings [10,16].

Much research has been conducted around TABS as it is summarized on some reviews. Rhee and Kin [6] presented an historical review on TABS research. In contrast there are reviews on some specific subjects of TABS. In this context Xu et al. [9] presented a review on pipe-embedded systems coupled to low grade energy sources, and a review on air based TABS, referred as hollow core slabs, which is focused on design and calculation methods [17]. Similarly Zhao et al. [18] reviewed the application of radiant cooling to large spaces while others critically review heat transfer coefficients [19] or TABS coordination with ventilation [20]. Despite all these research, there is not a clear nomenclature for TABS [10]. This paper reviews TABS generalities, the simulation models developed and the control strategies proposed. Moreover, a summary of the different nomenclature existent in the literature is presented.

2 TABS generalities

2.1 Definition

TABS are building elements that are actively used for heat transfer and heat storage. Water pipes or air ducts are embedded in the building surfaces or in the building structure to work as heat exchangers transferring heat to the building rooms and storing thermal energy into the structure. TABS do not only supply or extract heat but directly affect on building thermal performance. The temperature of TABS surface is regulated, which modifies the heat gains through the structure and causes a direct heat exchange with the building structure.

2.2 Working principles

TABS have big surfaces that are kept to a certain temperature to heat or cool spaces. Heat is mostly exchanged to other room surfaces by radiation but heat is also exchanged to room air by convection. Heat transfer coefficients of radiation and convection [19,21] show the significant heat exchange due to radiation. The radiative nature of TABS and its influence on room surface temperatures makes essential to use Mean Radiant Temperature (MRT) and operative temperature to study comfort given by TABS [22,5]. TABS directly influencing on operative temperature can give better comfort conditions by maintaining lower operative temperatures in summer and higher operative temperature in winter [10,23,24].

Only sensible heat can be exchanged with TABS, humidity cannot be regulated with these systems, hence ventilation is required to deal with latent load. Nevertheless, ventilation is always needed for hygienic reasons [25,26]. However, as most heat load is dealt by TABS, ventilation systems only need to supply the minimum air change ratio for hygienic conditions, then fan and ducts can be reduced in size resulting in savings in energy consumption, installation cost and space [27]. Reducing the ventilation system can also improve comfort as there is less risk of discomfort by draft and noises [5,28]. In addition, TABS reduce ventilation losses as operative temperature is kept at comfort range with room air at higher temperature in summer and at lower temperature in winter, leading to more savings in ventilation. For cooling, TABS ventilation can be necessary to avoid condensation issues [16,27,29] as surface temperatures might go below dew point in hot humid climates. Coordination between TABS and ventilation system is essential to reduce energy consumption and keep comfort conditions [10,30].

Depending of its design, TABS can have high thermal mass, especially for systems embedded in the core of slabs. The thermal mass allows TABS to buffer the room temperature fluctuation by storing or releasing heat from the slabs. The energy lost or absorbed during the buffering is managed in other periods [7,23,31], normally shifting to energy efficient periods. As a result chillers and boilers can be downsized thanks to peak load being reduced and redistributed. Thermal mass allows TABS to be operated in off peak modes, adding further economic saving to the previous energy savings [7,32-34]. However, TABS have long response times which will not allow dealing with instantaneous heat loads. Control strategies for building incorporating TABS have to be carefully designed and temperature fluctuations need to be admitted [32,35-37].

By using the building structure, TABS have big surfaces which allow for significant heat transfer even for small temperature gradient between the fluid and the room operative temperature. The required low temperature gradient allows high temperature for cooling and low temperature for heating, which improves the efficiency of chillers and boilers and enables the use of low grade energy sources [9,23,27,30,33]. TABS peak load shifting ability helps to compensate the limited time availability of some renewable energy sources, such as night-time cooling or solar radiation, because energy can be stored when the source is available then the inertia of the slab buffers changes in the rooms. This increases the utilization of renewable energy and further increases economic savings. The low temperature gradient also has the advantage of causing an effect of self-control in TABS. A slight variation in room temperature results in a significant variation of heat flux which might even get to change operation mode if room temperature exceeds supply temperature [7,5].

TABS require an adequate building insulation and building thermal mass, and its performance is synergistic with building thermal performance [7,24,33]. A good control of heat gains is also important, especially those caused by solar gains [30], within this context the use of automated solar blinds is usually recommended in buildings equipped with TABS. Finally, TABS cooling and heating capacities depend on the position of the active surface (floor, ceiling or wall) and the operation mode [27].

2.3 Types of TABS and nomenclature in literature

A lot of research has been done around TABS but the nomenclature is still heterogeneous [10]. There are different types of TABS depending on their intended operation mode, position and working fluid. However, the labelling of similar systems can vary significantly between authors. The following sections present the different types of TABS and Table 1 summarizes the diverse nomenclature and acronyms found in the literature.

2.3.1 Radiant floor

Radiant floors are light-weight TABS placed above the floor structure. A layer of insulation separates the structure from the pipes, which are embedded in a thin layer of concrete and covered with a screed layer, as shown in Figure 1. Heat flux is mainly transferred between the pipes and the floor surface. It is commonly assumed that the surface between the radiant floor and the structure is adiabatic. The main use of radiant floor is heating but also cooling has been used with success.

Figure 1: Radiant floor structure [38]

2.3.2 Radiant ceiling

Radiant ceilings are light-weight TABS placed at the lower surface of ceilings. The pipes can be embedded into the slab very near to the lower surface. They can also be positioned into a layer separated from the ceiling with insulation or on suspended ceiling which might create an air chamber between the ceiling and the panels. Figure 2 shows different configuration of radiant ceilings.

A common assumption is that radiant ceilings only exchange heat through the lower surface. The heat is only exchanged with the room and the contact between the radiant ceiling and the structure is considered adiabatic. Radiant ceiling systems are applied mainly for cooling but they can also be found for heating applications.

Figure 2: Radiant ceilings: bottom slab embedded pipes (left) [39], suspended ceiling panel (middle) and embedded pipes insulated from ceiling slab (right) [40]

2.3.3 Hollow core slabs

Hollow core slabs are heavy weight TABS that use the empty cores of prefabricated concrete slabs to circulate air. The ends of cores are closed and connected with holes creating and air

path, a scheme of a concrete core is shown in Figure 3. Hollow core slabs are mainly used for cooling, night time ventilation with outdoor air is a typical use and an application for free-cooling. The air circulation through the cores can also be used for room ventilation.

Figure 3: Hollow core slab [41]

2.3.4 Concrete core

Concrete core are heavy weight TABS where water pipes are embedded deep on the concrete slab. Figure 4 shows the structure of a concrete core which consists in a deck slab, positioned between stories. They can provide either heating or cooling having heat flux to both upper top surface, as radiant floor, and/or to the bottom surface, as radiant ceiling. Depending on the purpose of the design, insulation can be used to ensure heat flux through only one surface.

Figure 4: Concrete core [15]

2.3.5 Pipe-embedded envelope

Pipe embedded envelopes are heavy weight TABS that have its pipes circuits inside walls and roofs of the building in contact with outdoor ambient, an example of pipe-embedded envelope is shown in Figure 5. They can provide active cooling or heating to the indoor space but they are also used to reduce the influence of external climate by maintaining a section of the wall at a constant temperature.

Figure 5: Pipe-embedded envelope [42]

Table 1: TABS nomenclature (*Usually TABS is used as sole reference for concrete core slabs)

Type	Specific nomenclatures	Acronym	Associated papers
Radiant floor	Concrete slab floor	-	[43]
	Floor heating	-	[44,45]
	In floor radiant systems	-	[29]
	Radiant cooling/heating	-	[6,46]
	Radiant floor	-	[4,5,18,38,47,61]
	Radiant Floor Conditioning	RFC	[62]
Radiant ceiling	Ceiling embedded piping	-	[12,63]
	Ceiling panels	-	[64,69]
	Ceiling radiant cooling	-	[70],[71]
	Ceiling Radiant Cooling Panels	CRCP	[72]
	Ceiling radiant panels	-	[73,74]
	Cold radiant ceiling panels	-	[28]
	Cooled ceiling	CC	[20]
	Cooling panels	-	[39,75]
	Core Cooled Concrete Slab	CCCS	[31]
	Hydronic Radiant Cooling	HRC	[22]
	Hydronic radiant panels	-	[76,77]
	Radiant ceiling	-	[78]
	Radiant cooling/heating	-	[79]
	Radiant hydronic slab	-	[23]
	Radiant slab systems	-	[30,80]
Hollow core slab	Active hollow core slabs	-	[17]
	Hollow core slabs	-	[41,81,82]
	Ventilated slab	-	[41,82,83]
Concrete Core Slab*	Concrete core activation	CCA	[84-86]
	Concrete core cooling/heating	-	[7,87]
	Concrete Core Conditioning	CCC	[11,15,34,37,40,62,88-96]
	Concrete radiant cooling slab	-	[97]
	Concrete slab cooling	-	[98]
	Floor-ceiling radiant panels	-	[99]
	Pipe-embedded slabs	-	[9]
	Slab heating/cooling	-	[14,100]
	Thermally activated concrete slab	-	[101]
	Thermo Active Building Systems	TABS	[8,10,31,37,85]
	Thermo active components	-	[102]
Pipe-embedded envelopes	Active pipe-embedded building envelope	-	[103-106]
	Thermal Barrier	TB	[42,107,108]
	Thermo-active cooled wall	-	[109]
	Vertical Thermo Active Buildings Systems	VTABS	[109]
	Wall panels heating	-	[110]
TABS (general)*	Hybrid Systems	-	[111]
	Thermal active building system	TABS	[112]
	Thermal slab	-	[113,114]
	Thermally activated building components	-	[115-118]
	Thermally activated building constructions	-	[119]
	Thermally Activated Building Systems	TABS	[13,15,16,23,24,29,33-36,40,52,89,90,93-96,120-126]

3 TABS design

The main standards around TABS design, sizing, installation and control are ISO 11855 [127], UNE 1264 [128] and UNE 15377 [129]. There are also guides as chapter 6 on ASHRAE Handbook Fundamentals [130] for radiant floors, REHVA Guidebook 7 [131] for radiant ceilings, floors and walls and REHVA Guidebook 20 [132] for concrete cores with ground coupled systems. For comfort analysis of TABS the standards are the same as for all HVAC systems, ISO 7730 [133], UNE-EN 15251 [134] and ASHRAE Standard 55 [135].

Moreover, different research has been done in the design methods of TABS. A concrete cores design method was developed to integrate the control strategy and heat gains boundaries in the design stage [33]. As heat gains are uncertain, a method was developed to calculate TABS capacity with upper and lower heat gains boundaries. It has also been pointed that cooling load for buildings equipped with TABS should be considered differently from conventional HVAC systems [40] due to the radiant nature of TABS. Design standards focus on heat flux and water conditions, on the other hand, comfort parameters such as maximum and minimum surface temperature or maximum surface temperature difference are not taken into account. To solve this issue design charts were developed to link the main design parameters with surface temperatures and heat flux [38].

3.1 Application range

The application of TABS in current buildings depends on its capacity to supply enough heating and cooling demand without exceeding the surface temperature limits for comfort or condensation issues. Olesen [58] calculated the maximum cooling and heating capacity according to the limits of comfort conditions, the values are summarized in Table 2. The maximum floor temperature is defined as the comfort limit from UNE 1264 [128] while the maximum wall temperature is the pain threshold for skin temperature in contact with the surface for a longer period of time and the maximum temperature for ceiling is the requirement to avoid radiant asymmetry. In contrast, the minimum temperatures consider the dew point and the condensation risk. Finally, heat transfer coefficients are obtained from previous research [21,58].

Table 2: Heat exchange coefficient, surface temperatures comfort limits for different position and operation mode of TABS [21,27,58]

		Total heat exchange coefficient (W/m ² ·K)		Surface temperature (°C)		Capacity (W/m ²)	
		Heating	Cooling	Maximum	Minimum	Heating	Cooling
Floor	Perimeter	11	7	35	20	165	42
	Occupied zone	11	7	29	20	99	42
Wall		8	8	~40	17	160	72
Ceiling		6	11	~27	17	42	99

Different heating and cooling capacities are reported in the literature. For instance, in simulations under Montreal climate, hollow core slab supplied with outdoor air reached a peak cooling load of 40 W/m² and an average cooling load of 28 W/m² [81]. These are significant savings compared to the peak cooling load of 51 W/m² and the average cooling load of 44 W/m² of the mechanical cooling system in the same conditions. Night-time ventilated core slabs with outdoor air in the United Kingdom reached 50 W/m² of cooling load [83].

In the case of radiant floor cooling literature typically reports a cooling capacity of 50 W/m^2 but with solar radiation directly incident on the cooled surface cooling capacity can reach up to 100 W/m^2 [5,58,136]. Maximum heating capacity for radiant floor was calculated to 100 W/m^2 at 20°C room temperature and 29°C surface temperature [5], which are the comfort limits.

In contrast, radiant ceilings are limited by the 27°C maximum surface temperature which results in a maximum heating capacity of 42 W/m^2 [102] although $30\text{-}40 \text{ W/m}^2$ is recommended for design purposes [137]. Room test measurements and simulation showed a $50\text{-}65 \text{ W/m}^2$ maximum cooling capacity in gypsum board radiant ceiling with supply temperature of 15°C [78]. In spaces directly illuminated with solar radiation an increase of 69% of cooling capacity was reported [40].

Finally concrete cores follow a similar trend. Lehmann et al. [90] calculated the maximum heat gains to maintain the temperature inside comfort ranges with concrete core cooling finding that the transitional periods are critical because of the high heat gains but short comfort range. In a well-insulated office building with night-time activated concrete core cooling the required cooling capacity was 25 W/m^2 [94]. A combined radiant floor and concrete core achieved 30 W/m^2 in an experimental study [112]. As reported in other types of TABS, concrete cores increased cooling capacity by 85% when direct solar radiation was incident on the surface [40].

The climate and cultural habits also influence in the application of TABS. In Korea, where the use of radiant floor heating is common, radiant floor can also be used for cooling if condensation issues in the hot humid summer and comfort problems due to floor sitting habits [48] are overcome. However, auxiliary cooling and ventilation systems were recommended [51]. In the similar climate of Hong-Kong, cooling radiant ceiling panels showed potential for significant energy savings if coupled with dehumidifying ventilation systems. In contrast, in the Nebraska continental climate TABS coupled with a ground system and with assisted ventilation showed great potential in terms of primary energy and comfort [10]. In Poland, another continental climate, Thermal Barriers coupled with different temperature ground sources showed significant savings [42] both in heating and cooling seasons. The comparison of the application of concrete core cooling or suspended ceiling panels in northern and southern Europe showed great potential in southern Europe and the Mediterranean area [11]. However, on northern Europe cooling with night ventilation and mechanical night ventilation might be more energy efficient than water based TABS. Finally, despite having demonstrated peak load shaving and peak load shifting potential some authors opined [31] to not recommend installation of TABS on exposed roofs for tropical climates as it reduces its cooling capacity.

3.2 TABS distribution topology

TABS control and performance are also influenced by the topology of the distribution system. A building with zones with different heat gains may need different supply temperatures to maintain comfort. It is possible that different control strategies have to be used in each zone, for example needing different heating curves [15], and even two zones could simultaneously demand heating and cooling.

Zone configuration defines the number of different areas that will be supplied. Each zone requires its own supply curve so it is recommended to group rooms with similar heat gains [121].

Single zones topology, shown in Figure 6 right, is the simplest to implement, as it has a single heating curve and only requires a two pipe configuration, one for supply and another for return. However its control is demanding because only a single supply temperature is available independently of the heat gains of the rooms.

In contrast multiple zones can consider different supply, circulation and return topologies:

- In the supply side separated supply pipes allow for simultaneous supply of cooling and heating to different zones, case shown in Figure 6 left.
- Circulation pipes allow mixing the outlet flow with the supply flow, thus allowing for different supply temperature. Each zone having a separated circulation pipe gives more flexibility in the supply temperature. In contrast, common circulation pipe can have undesired cooling demands if outside temperature is not within the range where heating curves overlap [36], as the common return water might be too hot for supplying the zone with less heat gains as shown in Figure 7.
- Separated pipes on the return side might avoid mixing the return flows from simultaneous cooling and heating in different zones, thus improving the efficiency of chillers and boilers if the return temperatures were significantly different, case shown in Figure 6 left.

Renggli et al. [95] showed a case with two supply pipes where heating demand is 28 % and the cooling demand 30% less with the separate circulation topology compared to common circulation pipe. However, Wit and Wisse [121] commented that separated circulation might not be necessary if heat loads are similar in all zones. Furthermore, they affirmed that two supply pipes and two return pipes are unnecessary, as simultaneously delivery of heat and cold occur in periods where heating and cooling are supplied at similar temperatures.

Figure 6: Separated zones with four pipe topology and separated circulation (left), separated zones with two pipes and separated circulation (middle), single zone (or no zone division) with two pipes topology and no circulation (right) [121]

Figure 7: Example of separate zones with common return pipe topology where heating curves do not overlap, overheating will occur on zone 1[36]

3.3 Parametric studies

Parametric studies have been carried to find the parameters that most influence to TABS performance. This is a crucial step in the improvement of TABS in the design step.

Antonopoulos et al. [12] showed that for ceiling with embedded piping, the parameters that affect more the slab performance are pipe spacing, pipe depth, water inlet temperature, indoor temperature and indoor heat load. For ceiling cooling panels at 20 cm spacing between pipes, the under-surface of the slab has temperature differences that are not found at 10 cm spacing [39], this is more pronounced at low fluid temperature. In pipe-embedded envelopes, a reduction of pipe spacing of 50 mm results in a reduction of heat transfer by 2.3 W/m^2 on the internal surface [103]. In the same study it was also found that the internal surface heat transfer may be reduced by 2.6 W/m^2 when supply temperature is reduced 1°C .

The width of the slab and the position of the pipes influence the volume of TABS that is activated. Babiak et al. [101] proposed an effective thickness of 15 cm to fully activate the slab. The position of the pipes depends on the operation mode and the thermal resistance of the surface, however, it was recommended to place them at the mean slab level at 7.5-10 cm from ceiling surface or less. On Thermal Barriers (TB) maintaining a surface at a constant temperature the pipes should be placed near the external surface of the concrete layer [42], near the external insulation. If the TB is positioned nearer the indoor surface its efficiency is reduced, although the ineffective area can be reduced adding insulation on the indoor surface.

Hauser et al. [98] compared comfort conditions achieved in rooms with various-weighted walls conditioned with ceiling panels. Heat extracted averages 60 kWh/m^2 annually in all cases. Heavy weight walls have slightly fewer hours outside comfort range compared to light-weight walls. Similarly Kolarik et al. [37] found that walls with higher thermal mass have slightly more energy consumption while lower thermal mass walls have higher temperature drift and exceed comfort range more often. Low thermal mass on TABS causes the building to not benefit from high thermal resistance [33]. Low thermal resistance increases the variation of mean operative temperature, however, the minimum operative temperature variation is about 1.5°C and it cannot be further reduced even increasing both thermal mass and thermal resistance. It is observed that radiant wall panels are more sensitive to insulation than conventional systems [110], better insulation improves TABS savings even further.

4 TABS simulation

TABS design and performance studies involve complex dynamic heat transfer calculations. Simulation models have to take into account convection from the fluid to the slab, conduction through the slab and both convection and radiation on the surfaces. Radiant panels on ceilings and floors are usually modelled to exchange heat only to the surface exposed to the room, while the other surface is often considered as adiabatic. Contrary, TABS embedded on the structure, concrete core slabs or wall embedded pipes, usually require to be modelled to exchange heat in both surfaces. Also TABS have multi-layered structures and significant thermal mass, which adds complexity to simulation. Dynamic simulation is usually necessary to study TABS performance.

Within this context, heat flow to rooms is the main parameter to be obtained by simulation. However, to study comfort conditions and to assess condensation issues, the surfaces average temperature or the temperature distribution might be required. Detailed temperature maps through the slabs might be required in parametric studies.

Only numerical methods as finite element method (FEM) and finite difference method (FDM) describe the heat transfer and heat storage capacities of TABS accurately. Unfortunately, numerical methods are time consuming and complex to couple with building simulation environments. Thus, lot of research have been conducted to develop simplified models for TABS which reduce computational effort and are accurate enough for the expected application range. These simplified models are usually validated with numerical methods and/or calibrated with field measurements.

A summary of the models for TABS simulation is presented in Table 1.

4.1 Numerical models (FEM, FDM, FVM)

Numerical models solve the differential equations of heat and mass transfer by limiting a set of finite elements, grid-points, in the calculation domain. The method establishes a set of algebraic equations to the unknown values of the dependant variable on these finite elements and then establishes an algorithm to solve these equations [138].

Zmeureanu and Fazio [81] developed a model for simulating a building with hollow core concrete ventilated slabs. Heat balance is applied to indoor air and radiation is calculated with Modified Thermal Balance (MTB) method. Solar radiation is distributed uniformly through surfaces. Walls are considered one-dimensional and modelled with three nodes. The hollow core slab is modelled in 2D finite difference (FDM), considering the direction of air flow and perpendicular to the surfaces. The bottom surface of the slab is considered adiabatic. For simplification air temperature variation along the ducts is solved analytically.

In a similar application, Fort [139] described a model for hypocaust under-floor heating 2D FDM model, which is coupled with TRNSYS. The model is designed for floor heating but it is also applicable to wall panels and cooling ceiling panels in which either air or water can be used. The model consists of a simplification of the slab where circular ducts are simplified to square pipes for an easier distribution of nodes. In case the ducts are pipes its width is not considered. Its input parameters are the fluid supply temperature, the flow rate and the thermal behaviour conditions of surrounding rooms and the output parameters of the model

are outlet temperature of the fluid, heat flux on the surfaces, surface temperatures and energy stored in the panel. The model requires a shorter time step than the usual TRNSYS time step.

FDM was also used for roof slabs, in that case Antonopoulos and Democritou developed a 2D FDM in a periodic steady state [39]. No temperature variation is considered in the fluid, and room temperature is used as a boundary condition to obtain the heat flow on both surfaces of the slab, the temperature distribution inside the slab and the heat flow absorbed by the fluid at each hour of the day while outdoor boundary conditions vary periodically. Later, Antonopoulos and Tzivanidis [63] developed a FDM 3D transient model for a roof slab where the slab around one pipe is modelled with a fine mesh as shown in Figure 8. It is assumed that the pipe wall thermal resistance is negligible and that there is no heat transfer between pipes, so walls between control volumes are adiabatic. Total heat flux is calculated with the total number of pipes embedded in the roof. This model calculates indoor temperature, temperature distribution in the slab and fluid temperature variation along the pipe. Comparing against the previous models [39,75], discrepancies reach up to 35% in temperature distribution, 15% in fluid temperature distribution and 7% in room temperature [63]. A correlation to calculate ceiling embedded-piping cooling power was developed with the obtained results.

Figure 8: x-y plane grid used by Antonopoulos and Tzivanidis [63] for discretizing pipes surroundings

Most of the FDM have dense grids thus long computational times, focusing on this point, Holopainen et al. [44] studied floor heating with uneven gridding to reduce the number of nodes. The cases of uniform concrete floor slab and multi-layered floor slab are chosen to use 2D analytical solutions in steady state as reference. Uneven distribution of nodes is done with geometric series for each layer as shown in Figure 9. With space incremental optimal values the uneven grid was compared to an even grid with the same number of nodes and to an even grid with the same accuracy. Results show that uneven grid can reduce the number of nodes and the computational time. The uneven grid has better results with uniform concrete floor slab than in a multi-layered case because nodes can be placed more freely than in the multi-layered floor slab.

Figure 9: Uneven TABS discretization [44]

Numerical models have also been applied to vertical TABS. Krzaczek and Kowalczyk [42] presented a 3D finite elements model (FEM) to simulate a prefabricated wall with Thermal Barriers. The control volumes are blocks of horizontal U pipe embedded in the middle of the wall, considering upper and bottom surfaces, those normal to active surface, as adiabatic. The model uses the FEM code of ABAQUS software with a complete discretization of the U pipe, which is shown in Figure 10 .

Despite most of the models are applied to time domain Zhu et al. presented a 2D Frequency Domain Finite Differences (FDFD) model [104] for active pipe embedded envelopes. Nodes are modelled with four resistances and one capacitance. The equations obtained are solved with Generalized Minimum Residual method (GMRES). The performance of the structure was simulated under different combinations of the perturbations of temperature of external surface; temperature of internal surface; and circular temperature of the fluid in the pipe. Computational Fluid Dynamics (CFD) was used for comparison. The developed FDFD has an error of 7% in amplitude but reduces computational time from 3 h to 5 min in the tested conditions.

Figure 10: FE discretization of a TB [42]

4.2 Analytical models

Analytical models are based on exact solutions of the differential equations of heat transfer. Due to the complexity of the equations these models are limited to specific cases and require adequate assumptions to describe accurately enough the heat transfer process. This factor limits analytical models to 1D or simple 2D and to steady-state conditions. However, once developed, an analytical model requires low computational effort thus it is very easy to implement to a building simulation environment or be used for control purposes.

An initial cooling panel analytical model was presented by Antonopoulos [75]. He solved a steady state 1D analytical model assuming the panel as a fin with heat flow between two pipes, convection one side and adiabatic on the other, the geometry of the panel is shown in Figure 11. The fin equations are combined through panel efficiency factor to use an analytic solution of a fluid along a pipe. The model calculates the heat absorbed by the slab according to fluid inlet temperature and room temperature. Heat exchange to the room is only considered with a heat transfer coefficient. Jeong and Mumma [71] also used the temperature distribution derived from the energy balance of a fin to improve a 2D steady analytic model for ceiling panels. The improvements were focused on estimation of the mixed convection effect on the cooling capacity, finding that mixed convection significantly increase ceiling panels cooling capacity.

Figure 11: Jeong and Mumma [71] ceiling panels geometry

A more elaborated model was developed by Koschenz and Lehmann [140]. A TABS with a parallel heating/cooling pipe system and a uniform slab was solved in an exact steady state 2D solution. The slab is considered to have convection on the upper surface and to be insulated on the bottom (adiabatic). This model was further developed to a 2D transient analytical model by Larsen et al. [141] who used separation of variables, superposition method and orthogonal expansion techniques to develop the dynamic solution. The resulting solution is in the form of infinite series in space variable with exponential time dependency. The method applied can be used to develop a model for TABS with convection on both surfaces, which is a more general case. Li et al. [56,57] also used Koschenz and Lehman [140] solution and developed a simplified method for calculating the mean temperature and minimum temperature of multi-layered radiant floor. The new model does not consider water temperature variation along the pipes, assumes symmetry around pipes and no heat flow on the bottom surface. It uses the Equivalent Thermal Resistance Method (ETRM) to transform the multi-layered slab in a homogeneous slab of fictitious thickness where the analytical 2D solution for homogeneous slabs [140] can be applied. The validation with experimental results showed an error of less than 0.4 °C.

In a different approach, Simoes and Tadeu [142] used Green equations to formulate the 2D heat flow across a multi-layered slab with heat sources. The thermal response was first studied in the frequency domain and then translated to time domain by Fourier transform. The effect of convection on the surfaces is considered and shows great effect on the performance. The results showed that the formulation was promising for simulating multi-layered constructions.

Yet Sarbu and Sebarchievici [99] proposed another different analytic model for thermal emission of radiant floors. The model is based on virtual tube method [143] and allows calculating the mean heat flow and the temperature at each point of the surface, considering

there is only heat flow in the 2D plane perpendicular to the pipes. The model does not take into account the dynamics of the system but was validated with measured values showing reasonable agreement.

4.3 Semi-analytical models

While analytic models have accurate results they are limited to geometries and conditions where solutions can be found with reasonable assumptions. To overcome the limitations of analytical models some authors proposed correlation between different analytic solutions to develop more complex solutions such as TABS heat transfer. Such models are described as semi-analytic. A first model for TABS simulation was a semi-analytic model developed by Zhang and Pate [68] for heating with ceiling panels, it is a two dimensional steady state model.

Usually TABS radiant floors models consider ground temperature as uniform. To compensate this, Chunagchid and Krarti [43] developed a semi-analytic 2D model in periodic steady for concrete slab floors. The model describes the temperature field of the slab and the ground and the heat gains or losses to the soil. It was validated with measurement and it was found suitable for TABS design as it considers many TABS variables.

Laouadi [46] presented a 2D semi-analytical model oriented to be implemented in simulations programs which were currently using 1D models for radiant heating cooling systems. On one set, the model uses analytical solution of a 2D slab with heat sources. Separately, it calculates the heat transfer inside the tubing. The semi-analytical model was found to have excellent matching to a numerical model in uniform physical properties case and it only has up to 11% error in no-uniform physical properties case.

In contrast, Jin et al. [53] presented a method for estimating the surface temperature of multi-layered radiant floor systems. The floor is divided into two layers, one containing the pipes and the other containing all other layers of different materials. Using a numerical model, authors developed a correlation to calculate the conductivity of the layer containing the pipes as a function of the characteristic parameters of the radiant floor. The model assumes that temperature at each layer surface is uniform and that the bottom surface is adiabatic, heat flux is 1D from the pipes to the floor. The model was compared to experimental results of Song and Buttock [45] finding a difference with calculated results of less than 2.5K. The model was also compared against other numerical models [44] finding the same surface temperature.

The effect of assumptions on a semi-analytic model has been studied by Tye-Gingras and Gosselin [76]. They considered panels with negligible mass so that steady state assumption could be applied to a 2D semi-analytic model. The results are that assumptions led to negligible errors in a large range of geometries. Furthermore, the semi-analytic model is faster than a numerical model and more flexible than an analytical model [71]. The model was later applied for panels optimization coupled to a room CFD model showing its capacity for TABS design calculation [77].

4.4 Resistor Capacitor models (RC)

RC or lumped models parameter models simplify the description of heat transfer in a space by describing heat transfer between selected nodes as an equivalent electric circuit. Resistances

(R) represent the thermal time constants and the capacitances (C) represent the heat capacity of the element.

Ren and Wright [41] developed a lumped model (resistor capacitor model) for hollow core concrete slab and associated zone. The walls are represented as a capacitance and two resistances, each representing the resistance to indoor and outdoor disturbance. For the ventilated slab it is assumed that there is no heat transfer between upper and lower surface and that the temperature was uniform in the direction of air-flow. Then the slab is represented as shown in Figure 12 with two walls with a common node that is the mean temperature of the air. The model is compared to a set of measured values giving good accuracy.

Figure 12: Simplified lumped model representing two walls with the mean air temperature in the ducts as a common node [41]

Using a similar concept and bringing it a step further Koschenz and Dorer [88] proposed a simplified 2D transient model for slabs. The model is coupled to the multi-zone building model of TRNSYS. TABS are modelled as two walls separated with a dummy zone that represents the water system. Heat transfer coefficients in this area are applied as three resistances as shown in Figure 13 left. For transient cases, thermal resistances are time-dependent.

Figure 13: 1D resistance modelled by Koschenz and Dorer [88] (left) and improved model by Weber (right)[115]

Using the same concept of the core layer temperature Liu et al. [87] define a simplified star-type RC-network model for simulating concrete core cooling slabs. Here, heat transfer through the slab is defined as heat transfer from chilled fluid to the core layer and heat transfer from core layer to slab surfaces. In the star RC-network the central node is treated as the core layer. Compared to a FEM model the RC-network shows good accuracy in both steady and unsteady conditions. Authors study the application range of the model finding that temperature fluctuation cycle should be above 2.51 h.

Also based on Koschenz and Dorer concept [88], Tian et al. [97] developed a simplified 2D model for dynamic simulation of concrete radiant cooling and validated it with experimental

measurements. The model was developed based on the reaction coefficient method, simplifying the Koschenz and Dorer model to the heat transfer between four nodes in star configuration. The developed model is also compared to other simplified models [44,87] and to a full scale laboratory model. Bland-Altman is used to analyse the consistency of experimental and simulated results. In steady conditions the developed model had an error lower than 1.5 % compared to experimental results and an error lower than 2 % compared to other simplified models. In un-steady conditions the error was lower than 7 % compared to experimental measurements.

The network proposed by Koschenz and Dorer [88] was improved by Weber [115] using w-RC-Transform methodology and applying multipoint RC-networks for TABS. The improved model represents links between points with quadrupoles and uses the transformation from triangle to star networks leading to an optimized configuration [118], the resulting configuration is shown in Figure 13 (right). Calculation in frequency domain shows that the RC model matches the FDM in the range of application. In time domain, the RC model matches accurately to measured temperatures in a concrete slab of a building [117].

The w-RC-Transform method was also used by Schmidt and Jóhannesson [111] who presented a method for modelling hybrid building constructions with few nodes. The method consists in studying the thermal admittance and capacitance of the TABS system in the frequency domain with the analytic solution of Finite Difference Method. The obtained admittance values and capacitance values are used to optimize an RC-network with the method of w-RC-Transform. The RC network can then be used coupled with simulation environments to study the whole building performance. On a later study Schmidt and Jóhannesson [119] described the method to apply this simplified RC model to macro-elements modelling (MEM), where the structure is divided to limited number of mass nodes each with its own optimized RC-network. This method is accurate and requires fewer nodes than numerical models.

In less complex approach, Zhang et al. [55] developed a simplified calculation for key parameters of radiant floor. Heating/cooling capacity, surface temperature distribution and lowest temperature are calculated considering heat transfer in the slab as heat resistance in series based on the principle of superposition of heat resistance. Assumptions are symmetry between pipes, no heat transfer in pipes direction, and adiabatic bottom surface. Compared to previous studies [59,88] the simplified calculation has only 8-10 % of heat flux error.

Following their own previous research [104], Zhu et al. [105] used the FDFD model to verify a simplified RC model. The walls are modelled as 5 resistances and 2 capacitances as can be observed in Figure 14 and it is referenced as 5R2C model. The parameters of this model are estimated using a genetic algorithm. However, the 5R2C model alone cannot predict temperature variation along the pipe. To solve this problem authors coupled a Number of Transfer Units (NTU) model to the 5R2C model, thus creating a semi-dynamic model [106]. Compared to CFD the simplified model has a deviation up to 5% on high frequency periods, although it was influenced on physical properties.

Figure 14: 5R2C model used by Zhu et al. in [105,106]

4.5 Transfer function models

Mathematical methods based on transforms and operators are widespread methods for solving non-steady heat transfer problems. Transfer Function Method is considered an accurate method for calculating time-variable heat loads that establish a relation between an input and output. In the current case, the transfer function of TABS will establish a relation between the outdoor conditions, the input, and the internal heat gains, the output.

Chae and Strand [82] developed a model for ventilated slabs integrated in EnergyPlus. It considers the slab as a heat exchanger with a stationary fluid on the room side and a cooling coil on the other. The room side of the heat exchanger connects with the surface heat balance. The cooling coils are represented with modified conduction transfer functions that accept internal heat sources and sinks [144] which are already implemented in EnergyPlus. The heat exchanger is modelled using the ϵ -NTU model. In the ceiling slab presented in the paper no heat flux is considered to the upper storey. The model is verified against a numerical model [81].

4.6 Identification models

Identification models use statistical methods to obtain a model from a set of data. Logically, these models require to have previous measurement of the involved building, however, once developed these models are very easy to apply. Identification models are frequently related to Model Predictive Control (MPC).

The two main streams in identification models were compared by Ferkl and Šyroky [70] on a building equipped with the “Critall” ceiling radiant cooling system. On one side Auto-Regressive Moving Average model with exogenous inputs (ARMAX) shows better results in systems with high signal noise. On the other, subspace state space identification is faster to implement and to tune.

In a study on identification methods applied concrete core activation modelling Sourbron et al. [86] tested the impact of the model structure and the identification data set on Model Predictive Control performance. The findings were that second-order models achieve the same performance than fourth order models and the inclusion solar or internal gains improve control performance.

The application and improvement of identification models was carried by Prívarva et al. [74]. The authors proposed and improved MPC Relevant Identification (MRI) coupled to Partial Least

Squares (PLS). This was compared to standard one-step ahead minimization and to a conventional MRI into an application to a TRNSYS building model and to an actual office building [90]. Both MRI have similar results and significantly improve the one-step ahead minimization.

4.7 Simulation software

Modelling is useful for parametric studies of TABS. However, the main motivation of TABS modelling is to obtain reliable tools that can be integrated in building simulation environments. Free building simulation software area available such as ESP-r [145], DOE2 [146] or its evolution, the eQuest [147] which adds a radiant module that the first version lacked. Some authors developed their own simulation programs like ACCURACY [69], for simulating rooms with radiant ceilings, and DIGITHON [78], which simulates rooms equipped with radiant systems. Also some companies developed building simulation software like Clim2000 [148], ESP-r/HOT3000 [149]. Building simulation environments like EnergyPlus [150], IDA-ICE [151] and IES-VE [152] or transient simulation software like TRNSYS [153] integrate modules for simulation of different types of TABS. Some research have been done to compare the different software capabilities [154] finding significant magnitude differences in the same conditions [126] which are related to the different detail in the models.

Table 3: Summary of TABS simulation models

Reference	System	Model type	Study type	Main findings
Zmeureanu and Fazio [81]	Hollow core slab	2D Transient FDM	Energy and thermal comfort analysis	Hollow core slabs provide comfort during occupancy and reduce cooling loads. Ventilation rate should be increased during night to ensure reduction of cooling loads
Fort [139]	Hypocaust and murocaust	2D Transient FDM	Model development and integration to TRNSYS	The model can be coupled to TRNSYS building simulation but requires shorter time step
Antonopoulos and Democritou [39]	Ceiling cooling panels	2D periodic steady state FDM	Parametric study	Pipe spacing is the parameter most influencing on the surface temperature field, its influence is more significant at low fluid temperature
Antonopoulos et al. [63]	Ceiling embedded panels	3D Transient FDM	Heat transfer model	Temperature discrepancies up to 35% in the slab, 15% in the fluid and 7% in the room compared to 1D steady and 2D transient models
Holopainen et al. [44]	Radiant floor	2D Transient FDM	Model development	Uneven discretization can reduce by 95% the number of nodes on homogeneous slabs and 55% in multi-layered slabs thus significantly reducing simulation time
Krzaczek and Kowalczyk [42]	Thermal barrier	3D transient FEM	Parametric study	TB stability is not affected by active layer position but for wall composition. TB maintained at 17°C reduces indoor heating demand
Xu et al. [104]	Pipe-embedded envelopes	Finite Difference Frequency Domain +CFD	Model validation And heat transfer analysis	The developed FDFD model matches accurately the results of the CFD model. The pipe-embedded envelopes actively intercepts heat and cools
Antonopoulos [75]	Cooling panels	1D Steady Analytical	Model development and verification	The analytical solutions in the normal and parallel direction of the pipes agree with the results of a 2D model with much easier implementation
Jeong and Mumma [71]	Ceiling radiant cooling panels	2D steady analytical	Model development, cooling capacity analysis	Mixed convection can improve significantly the cooling capacity of ceiling panels
Koschenz and Lehmann [140]	TABS	2D Steady Analytical	Model development	Exact model for uniform slabs and parallel pipes distribution
Larsen et al. [141]	Embedded array of pipes	2D Transient Analytical	Model development	Application of variables separation and orthogonal expansion allows to develop a transient solution from a previous 2D steady model [140] and apply it to a case with convection in both surfaces
Li et al. [56,57]	Radiant floor	Steady Analytical	Model development and validation	Model determines max, min and mean surface temperature with an error about 0.3°C compared to experimental values
Simoes and Tadeu [142]	Multi layered slabs with heat sources	2D Transient Analytical	Model development	The application of green equations has potential for studying transient heat transfer on multi-layered slabs
Sarbu and Sebarhievici [99]	Floor heating panel	Steady Analytical	Model development, validation and comparative energy performance study	Model determines the temperature at any point on the surface and the mean heat flux and give coherent results with experimental measurements

Zhang and Pate [68]	Ceiling panels	2D Steady Semi-analytical	Model development	A simplified model for ceiling panels is developed from a numerical model
Chuangchid and Krarti [43]	Concrete Slab Floor	2D Periodic Steady Semi-analytical	Model development	A semi-analytic model using Interzone Temperature Profile Estimation (ITPE) is good for TABS design and to account the effect of heat losses to the ground
Laouadi [46]	Radiant heating and cooling	2D Semi-analytical	Model development and integration to building simulation	Couples the radiant system 1D analytical solution to the tubing system 2D analytical solution with a heat source node. It allows to predict tubing-concrete contact surface temperature in building simulation environments currently using 1D heat transfer models
Jin et al. [53]	Radiant floors	Identification model	Model development and validation	A new formula is derived to estimate the floor surface temperature, the results show good agreement with experimental values
Tye-Gingras and Gosselin [76]	Hydronic radiant panels	2D Steady Semi-analytical	Model development	The developed semi-analytical model has negligible errors from assumptions and is faster than numerical models and more flexible than analytic models
Ren and Wright [41]	Hollow core concrete slab	Transient lumped model (Resistor Capacitor)	Model development and validation	The model has good accuracy with experimental measurements. The heat transfer around the corners of the core ducts is 50 higher than that for the plain ducts
Koschenz and Dorer [88]	Concrete core conditioning	Transient lumped model (Resistor)	Model development and validation	The model uses a core node that represents the water pipes layer and that connects both surfaces of the slab. It is in good agreement with FEM results and can be applied to building simulation programs without modifying the code
Liu et al. [87]	Concrete core cooling slabs	Transient lumped model (Resistor Capacitor)	Model development and verification	A star type RC model is developed and verified against a FEM model. For applying this model the temperature fluctuation cycle should be higher than 2,51h
Tian et al. [97]	Concrete radiant cooling	Transient lumped model (Resistor Capacitor)	Model development and validation	Uses core temperature layer concept and reaction coefficient method for 2D heat transfer model. It has an error lower than 1,5% compared to experimental results and about 2% compared to numerical models in the literature
Weber [115]	TABS	Transient lumped model (Resistor Capacitor)	Model development and verification	The use of matrix formulation eases the change from a triangle configuration to a more easy to optimize star configuration. The latter can then be optimized using w-RC transform method.
Weber and Jóhannesson [118]	TABS	Transient lumped model (Resistor Capacitor)	Model development	Star-network configuration its easier to optimize but fail to simulate very thin slabs while triangle-networks handle all configuration but are more difficult to optimize
Weber et al. [117]	TABS	Transient lumped model (Resistor Capacitor)	Model development and validation	A 2D FEM coupled to analytical solution of heat and mass transfer in the pipe is accurate enough to verify RC-networks coupled to filters describing heat and mass flow in the pipes
Schmidt and Jóhannesson [111]	Hybrid building constructions	Transient lumped model (Resistor Capacitor)	Model development	The parameters of the RC model are calculated using (FDFD) and the w-RC-transform method. The obtained RC model can be applied to TRSNYS, IDA or SPARK building simulation softwares
Schmidt and Jóhannesson	Thermally activated	Transient lumped	Model development	Incorporating optimized RC networks reduces the required elements in FEM or FDM

[119]	building constructions	model (Resistor Capacitor)	and verification	simulations
Zhang et al. [55]	Radiant floor	Steady lumped model (Resistor)	Model development and validation	The model has a heat flux error around 8-10% compared to experimental values and other numerical models in the literature. The main limitation is the heat transfer coefficient between surface and indoor environment
Zhu et al. [105]	Pipe-embedded building envelopes	Transient lumped model (Resistor Capacitor)	Model development	The parameters of the 5R2C model are estimated with a genetic algorithm using the frequency characteristics obtained with a Frequency Domain Finite Difference (FDFD) model.
Zhu et al. [106]	Pipe-embedded building envelope	Semi-dynamic lumped model (Resistor Capacitor)	Model development	Adds the Number of Transfer Units (NTU) technique to a 5R2C model to allow calculation of the heat transfer along the pipe. Compared to a CFD model the error is lower than 5% and the computational effort is reduced from several hours on the CFD to 10 min in the simplified model
Chae and Strand [82]	Hollow core slab	Transfer function	Model development and verification	The model can be included to EnergyPlus easing the simulation of ventilated slabs in different building configuration and allowing the comparison with other HVAC systems
Ferkl and Šyroky [70]	Ceiling radiant cooling	Identification model	Identification comparison	Subspace state identification method is faster to implement and easier to tune but ARMAX method still yields better results in systems with high noise
Privara et al. [74]	Ceiling radiant heating and cooling	Identification model	Identification comparison and improvement	MRI improves the model quality compared to one-step ahead, in cases with collinearity the enhanced MRI-PLS shows better performance

5 TABS control strategies

The dynamic nature of TABS makes its control challenging. Much research has been conducted to design and optimize control strategies under different conditions. Focus is on maintaining good thermal comfort conditions and reducing energy use, but research also studies the coordination with ventilation and the optimization of the use of free-energy through low-energy sources [65].

The controlled variables for TABS are the supply temperature and the flow in the ducts or pipes [48,60]. The magnitude of both parameters can be interchanged to obtain the required power [90]. The most common controlling parameters are outdoor temperature with or without indoor temperature feedback and indoor dew-point [48,51,85] and the relation between controlled variables and controlling parameters is defined by the control strategies. Advanced control strategies might use weather forecast or historical data to define the controlled variables. Also the operation of TABS can be continuous or intermittent [50].

5.1 Control limitations

Low thermal mass TABS, as ceiling panels or radiant floors, have a response time fast enough to react to changes in room conditions, allowing for individual room control. However, TABS with high thermal mass, as hollow core slabs or active concrete core, have significant slow response time. Peak loads cannot be dealt instantaneously, however, TABS can buffer energy during the day due to thermal mass [155]. Under these conditions, individual room control is

not possible, buildings with high thermal mass TABS are commonly divided in zones with similar heat gains [121], where each zone might have its own controlling parameters.

As previously stated, TABS supply system topology also affects to building control [95,121]. It can give flexibility to supply different temperature at each zone and even supply heating and cooling simultaneously if required. The system topology has to be taken into account when defining the control strategy to avoid comfort and energy squandering issues related to rooms with different heat gains. The topology might allow circulation, which might be needed in some strategies for homogenisation of room temperature with different heat gains.

As pointed out in Table 2 on section 4, TABS heating and cooling capacity is limited depending on operational mode and position. The temperature of a certain surface could be limited to certain maximum or minimum value to avoid discomfort [48,51].

Finally, buildings always require ventilation for hygienic reasons. Ventilation can cause additional heat losses or can be used to supply auxiliary energy to complement TABS, and in addition, it is also used to control humidity. Synchronisation between TABS and ventilation is an important point to take into account in the control design [10,51,67].

5.2 ON/OFF criterions

The ON/OFF criterions establish when there is flow to TABS or when activation of heating or cooling is done. Day-long continuous operation is possible, where supply temperature or variable flow regulate indoor temperature [33,36,98]. However, limited operation schedules reduce energy consumption [90]. The peak load shifting ability of heavy weight TABS can be used to operate in energy production favourable periods [8,33,100,102]. On the other side, radiant floors or ceiling panels can be used to react to heat loads during occupancy. Intermittent operation can improve heat transfer and reduce operation time [14,50,81]. Moreover, circulation in TABS circuits without active cooling or heating, is used to homogenise temperatures or to select operation mode in advanced controls.

ON/OFF criterion is usually the most basic parameter of a TABS control.

5.2.1 Three step control in dependency of the room temperature

This control, also known as bang-bang on/off or hysteresis control, uses a control parameter, usually room air temperature, to set pumps operation mode. Pumps are set “ON” to reach the set-point temperature. When set-point is exceeded the pumps are set “OFF”. To avoid constant switching hysteresis can be implemented with a dead band. Supply temperature is maximum in heating mode and minimum in cooling mode. This is a very simple control that does not integrate information regarding the dynamics of the system.

Cho and Zaheer-uddin [47] studied ON/OFF control on radiant floor heating with air room temperature feedback obtaining good control of room air temperature, with fluctuation of only 2 °C. Switching the control parameter in short periods from air room temperature to slab surface temperature obtained the same room air temperature control and reduced temperature variation on slab surface. In an ON/OFF control switching, heating and cooling set-point temperature is maintained with low margin, however, surface temperature varies greatly causing discomfort [48,51]. Sourbron et al. [52] showed that wider dead band extended

the time to switch from heating to cooling and resulted in less energy consumption with same comfort conditions. Some studies [98,124] extended ON criterion to operative temperature exceeding set-point temperature and the average outdoor temperature of the previous day exceeding a certain value.

Although ON/OFF control is very simple to apply and achieves good comfort conditions it is not the most optimal for energy use [51,52].

5.2.1 Night operation

TABS can be operated on night-time or according to occupancy periods because of its thermal storage capacity. Night-time operation might have the advantage of operation in low cost energy periods [113] and of free cooling with cool air [7,23,90,100]. Ma et al. [33] showed that night-time operation kept an average indoor temperature 1K higher than continuous operation, however, temperature fluctuations had the same amplitude in both operation modes. In another study [94] the temperature rise was 2.5 K, a fluctuation that kept temperatures inside comfort range [27].

5.2.2 Intermittent operation

The objective of intermittent operation is to release the heat in pulses to the TABS by regulating the periods when flow circulates through the TABS. In cooling mode when the fluid flow is stopped the heat will continue to flow toward the cooler centre, where the temperature will increase. When the flow starts again, it will operate with a larger temperature gradient between water and concrete, then it will transfer more heat in a shorter time [14,50,81]. The pulses can be fixed time periods of intermittent operation [14] or variable time periods [50]. These last can be defined with different techniques like Pulse Width Modulation (PWM) and Model Predictive control, which are advanced controls that define the length of the pulse and are explained on following sections. The results show that intermittency reduces energy consumption and it can even reduce room temperature drift [14,36,80].

Cho and Zaheer-uddin [50] tested an intermittent operation strategy with pulses length defined by a forecast prediction model and compared it to a conventional intermittent control achieving 10-20% energy savings.

5.3 Supply temperature control

Supply temperature is an essential parameter to achieve good energy performance and comfort conditions with TABS. Usually the regulation of the supply temperature is the base for any control strategy.

Theoretically TABS can work using the self-regulating effect. If TABS are supplied at constant temperature then heating or cooling is supplied when the indoor temperature is respectively below or above the supply temperature. However, the self-regulating effect is not enough to compensate large thermal variation and a control of supply temperature is needed [121]. In the case of floor cooling, Lim et al. [60] concluded that control based on supply temperature performed better than controls based on flow control.

Usually supply temperature is defined according operational experience. Lim [16] et al. defined a supply temperature of 29°C for heating and 19°C after measurement and simulation of heating and cooling in a building with concrete core activation. For cooling, a supply temperature equal to dew point temperature in the room maximizes the cooling capacity avoiding condensation issues [14,98]. For TABS heating in well insulated buildings supply temperatures higher than 45-55°C squander energy [99].

Supplying at constant temperature causes significant room temperature fluctuations [14] so control of supply temperature with heating and cooling curves is common [5].

5.3.1 Supply water temperature curves

The controls of supply water temperature with heating and/or cooling curve define the supply temperature as a function of a parameter, commonly outdoor temperature. The curves have higher supply temperature for low outdoor temperatures and lower supply temperatures for high outdoor temperatures. In order to increase the efficiency, it is need to select the curves according to the building mass and thermal losses [5]. Different studies [14,48,51] showed that outdoor compensated supply temperature gives more stable conditions than on/off and variable flow controls. Dead band is also useful for reducing energy consumption with supply temperature curves [32].

Instantaneous outdoor temperature is the most common independent variable for supply temperature curves. Alternatively, the average temperature of the previous hours or the average temperature of the predicted hours was used with concrete core activation although no improvement was found even with perfect predicted data [27]. Wit and Wise [121] used the Running Mean Outdoor Temperature (RMOT) which averages with different weight the average temperature of the current day and those of the previous.

Without affecting the performance, the supply curve can either define the supply temperature or the average fluid temperature [14,32], where the supply temperature is also related to the temperature drop inside the TABS.

5.3.2 Unknown But Bounded (UBB)

The UBB is a method for designing heating and cooling curves of TABS that was implemented in a project for developing a control for TABS [89]. Heat gains are uncertain in present buildings and TABS are slow responsive systems. The UBB calculates the upper and lower bounds of heat gains and defines the heating and cooling curves so the operative temperature is maintained inside the acceptable range [15,34]. The calculation needs the knowledge of the physical characteristics of the building and the TABS. This method also helps to define the zones of a building by identifying rooms with different heat gains boundaries.

Saelens et al. [124] used the UBB control to study the influence of occupants behaviour in a building with TABS. The variable temperature control helped in reducing cooling load and overheating issues. It was also pointed that management of shading devices affects the control performance as it influences on solar gains, thus automated control of shading was proposed. Arteconi et al. [120] studied the effect of Demand Side Management (DSM) on a building with TABS controlled with UBB method. TABS cope well with the superimposed external request

and good comfort conditions were maintained, but DSM did not reduce TABS energy consumption.

5.4 Pulse Width Modulation (PWM)

Pulse Width Modulation (PWM) is a discontinuous operation control developed as part of TABS control project [89] that also involved UBB supply temperature control. PWM [93] operates on cyclic activation periods. At the beginning of each cycle the activation time of pumps is calculated using the supply temperature defined by UBB and the actual temperature of the fluid as input data. Each activation period starts with a purge where the fluid circulates inside the TABS, without active heating or cooling. After each purge, the control defines if circulation is continued, if pumps are switched off or if active cooling/heating is needed. In case of active conditioning, the duration of the pulse is also defined. The proposed control has four modules [96], a sequence controller, an outside compensated temperature control room feedback, and the PWM. The sequence controller for defining heating or cooling season and the module to define the supply temperature based on UBB method are compulsory modules. Room temperature feedback and Pulse Width Modulation modules are optional modules. Lehmann [36] et al. obtained savings of 50% of electrical energy consumption of pumps with PWM compared to continuous operation.

5.5 Model Predictive Control (MPC)

The reduction of the cost of data processing, storage and communication makes the design and implementation of advanced controller feasible [156]. MPC is one the most promising controls for HVAC, TABS included. MPC uses an identified model system to predict future states and generates a control vector that minimizes a certain cost function over a prediction horizon in presence of disturbance and constraint. Only the first element of the control vector is used, the rest are discarded. At each new time step all the calculation process is done again.

Prívara et al. [73] applied MPC to a building equipped with radiant heating panels. The model for the control was obtained with discrete-time linear time invariant stochastic model considering it as a Kalman filter. The results showed that classic identification techniques are insufficient for modelling the control, the performance of the control improved when measured data of the building was used in the identification. Compared to the weather compensated control, the MPC showed savings potential about 17-25%. MPC also tracked set-point temperature better than weather compensated control, it did not have fast changes in operation mode and it reduced energy peaks. Similar results were obtained by Sourbron et al. [86] with a MPC using a statistical identification model which reduced energy consumption by 15% compared to a reference controller. Also savings of 20% were obtained by Prívara et al. [74] applying MPC to an actual office building.

Applied to radiant cooling slabs Feng et al. [80] developed a first order dynamic model. The MPC model defines the opening of the valve with an algorithm that minimizes energy consumption and time outside comfort limits. It calculates external disturbance with the expected value of predicted weather data, as it considers certainty equivalence as adequate for the radiant slab problem. Simulations showed that MPC control could maintain EN 15251 Category II [134] thermal comfort level more than 95% of the occupied hours for all zones while the heuristic method thermal comfort could not be maintained in all zones. MPC

reduced the cooling tower energy consumption by 55% and pumping power consumption by 25%.

According to Zakula et al. [157] there are not current commercial tools for MPC simulation and most of the research done involved significant modification of existing building simulation programs. That is the motivation for developing a Modelling Environment (ME) for simulation of building with HVAC controlled with MPC. The ME uses TRNSYS for the detailed building simulation and a MATLAB algorithm for the optimization of the control settings. It is a modular environment that allows simulation of different types of HVAC, TABS included, and flexible MPC parameters.

5.6 Adaptive and predictive controls

Adaptive and predictive controls are techniques that adapt a controlled system with parameters which might vary or are uncertain. The bounds of the system are not required “*a priori*” because adaptive controls can modify the control law by themselves.

A predictive control was developed by Chen [49] in the form of a Generalised Predictive Control (GPC). The control was applied to a test room equipped with floor radiant heating. The model used for the GPC was developed from a z-transfer function where the operative temperature was the controlled variable. The parameters were identified with a recursive least squares algorithm and reorganised in the Controlled Auto-Regressive and Integrated Moving-Average (CARIMA). It formulates a j-step-ahead predictor. The GPC control performance was compared to an on-off controller without dead band and to an on-off PI controller. The GPC showed the best control performance with the lower rise time to set-point and a null offset to set-point.

A more developed control was presented by Schmela et al. [85] in the form of the AMLR, an adaptive and predictive algorithm for control of TABS. The control is based in multiple linear regressions and uses Ordinary Least Squares method (OLS) for calculating the regression coefficients. It uses weather data from the previous 15 days and the weather forecast of the following 24 h in conjunction of a RC network model of TABS to calculate the package of heat to be supplied or extracted from the building. The control uses the thermal storage capacity of TABS as it charges the heat or cold calculated in a single pulse at the beginning of the day. Compared to outside temperature compensated supply temperature, AMRL achieved better comfort conditions. Its main advantage is a self-learning capacity that allows it to be adapted to variations of internal load charges.

5.7 Gain Scheduling Control (GSC)

Gain Scheduling Controls are an evolution of PID controls that improve the management of a process with gains and time constants that change according to the current value of the process variable. Heat flux on TABS strongly depends on the temperature gradient between the supply temperature and the room temperature. Additionally TABS have significant thermal lags. For this reason GSC capacity to adapt changes on the scheduling variable makes it promising for TABS control.

Krzaczek and Kowalczyk [42,108] presented a controller based on Fuzzy Mixing Gain Scheduling (FMGS) for TB coupled to a geothermal system with different temperature levels. The fuzzy

mixing in the FMGS is used for both scheduling controller gains and fuzzy mixing of fluids flowing from geothermal heat sources. The scheduling variable is the solar-air equivalent outdoor temperature and the controlled variable is the TB active layer temperature. A fuzzy mixing equation interpolates the contribution of each operation mode to the calculation of supply temperature and mass flow by defining FMGS-PI controller. A decision module is used to block the controller integer part on mass flow calculation to avoid wind-up. An interference engine block is used to introduce rule base knowledge of TB performance that can avoid flow reversal. A time lag block represents the heat capacitance effect on delaying the heat waves. Simulations showed that the controller kept the mass flow inside optimum range and it also exploited effectively all the multiple geothermal heat sources.

5.8 TABS control coupled to dehumidification and ventilation

TABS operation interacts with the ventilation system thus the control and coordination of both systems have to be considered. The ventilation system can supply additional cooling or heating on peak demand or it can reduce humidity to avoid condensation on cooled surfaces then keeping TABS cooling performance high. Ventilation strategies are dependent on climatic conditions [79].

Lim et al. [51] proposed that for radiant floor cooling in domestic buildings, TABS and ventilation system are better operated independently. However, Tian and Love [30] found energy squandering caused by simultaneous TABS cooling and ventilation air heating. TABS with ventilation have faster response times and maintain more stable conditions [79,61]. Supply air temperature and surface temperature set-points are the essential parameters to coordinate ventilation and TABS [10]. Ventilation with outdoor air can be enough to maintain comfort conditions and avoid condensation [100] but better results were obtained with supply air temperature management [114]. Lim et al. proposed TABS to deal with a maximum of 50% of the cooling load in building operation [16]. Meierhans [7] provided specific cooling loads values for combined ventilation and radiant cooling, showing that ventilation at constant temperature on continuous operation dealt with all latent load and 5 W/m^2 of sensible load while concrete core cooling operating 7 h over a day achieved an average of 15 W/m^2 . In contrast ceiling panels were found to deal with up to 50 W/m^2 of sensible cooling load while its associated ventilation dealt with all latent load and $16\text{--}19\text{ W/m}^2$ of sensible load [72]. The research done showed that the risk of condensation is greatly reduced with ventilation [61,72, 79]. To further reduce this issue, it was proposed to start dehumidification one hour earlier than cooling [67].

Table 4: Summary of TABS control strategies

Reference	System	Control type	Application	Main findings
Cho and Zaheer-uddin [47]	Radiant floor heating	ON/OFF	Full room experimental laboratory study	Alternating the control parameter from indoor temperature to surface temperature improve temperature regulation
Lim et al. [48]	Radiant floor cooling	ON/OFF and Supply temperature curves	Room simulation	Continuous operation with supply temperature curves has better room temperature stability and less condensation occurrence
Lim et al. [51]	Radiant floor cooling	ON/OFF, variable flow, supply temperature curves and ventilation	Room simulation	With supply temperature curves the dehumidification system operates less than half the time compared to ON/OFF control
Sourbron et al. [52]	Radiant floor heating and TABS	ON/OFF	Office building monitoring and room simulation	Increasing dead band reduces energy squandering from switching from cooling to heating. Night operation reduced up to 85% energy use compared to room feedback control
Ma et al. [33]	TABS	Night-time ON/OFF	Office building simulation	The temperature rise with night-time is the same as with continuous operation but with slightly higher average temperature
Rijksen et al. [94]	Concrete core cooling	Night-time ON/OFF	Office building monitoring and simulation	With night-time operation of TABS the temperature rise during occupancy period was kept below 2.5 K
Dossi et al. [113]	Thermal slabs	ON/OFF	Office building simulation	Massive radiant systems help to reduce peak loads and can operate at low cost periods
Olesen [14]	Water based radiant systems	Intermittent ON/OFF and supply temperature curve	Office building simulation	Intermittent operation reduces temperature fluctuation and energy consumption
Cho and Zaheer-uddin [50]	Radiant floor heating	Intermittent ON/OFF	Room simulation and monitoring	Intermittent operation with pulses defined with forecast reduce energy use
Lim et al. [60]	Radiant floor	Supply temperature curve and ON/OFF	Residential building simulation	Supply temperature controls have better temperature fluctuations than flow controls
Lim et al. [16]	TABS	Supply temperature control	Office building simulation and monitoring	Establish operational guidelines through field experience
Hauser et al. [98]	Concrete slab cooling	Supply temperature control	Office building simulation	Control with supply temperature equal to dew-point temperatures achieve good comfort
Sarbu and Sebarchievici [99]	Radiant surface	Supply temperature control	Residential building simulation	For radiant surface systems there is no need of supply temperature higher than 45-55 °C
Olesen [32]	Thermally activated slab	Supply temperature curve	Office room simulation	The best performance is obtained by supply temperature curve with outside temperature as control parameter.
Gwerder et al. [15]	TABS	Supply temperature curve UBB	Office building simulation	UBB facilitates TABS dimensioning and control definition. Comfort can be maintained in a range of internal gains

Tödli et al. [34]	TABS	Supply temperature curve UBB	Design method	Defines a design and dimensioning flow chart using UBB supply temperature curves
Saelens et al. [124]	TABS	Unknown But Bounded supply temperature curves	Office building simulation	Occupants behaviour have great impact on cooling demand although TABS can cope with the demand if good solar protection is present
Arteconi et al. [120]	TABS	Supply temperature curve UBB	Office building simulation and monitoring	TABS controlled with UBB cope well with superimposed demand to manage energy demand
Gwerder et al. [93]	Concrete core conditioning	PWM and supply temperature curves UBB	Room simulation and laboratory testing	The PWM design method and control is accurate enough and allows shifting switch-on times to high energy efficiency periods
Lehmann et al. [36]	Concrete core conditioning	PWM and supply temperature curves UBB	Office building simulation	PWM control reduces electric energy use by 50% compared to an standard control
Chen [49]	Floor radiant heating	MPC	Room simulation and monitoring	The GPC control has faster response and less set-point deviation compared to ON/OFF and PI controls
Prívvara et al. [73]	Ceiling radiant heating panels	MPC	Office building monitoring	MPC control reduces energy use by 17-24% and tracks set-point temperature better than a weather compensated control
Sourbron et al. [86]	Concrete core activation	MPC	Office building simulation	MPC control using identification model reduces 15% energy use compared to a reference controller
Prívvara et al. [74]	Ceiling radiant heating panels	MPC	Office building monitoring	MPC control with a model identified with MRI method reduced by 20% energy use for heating
Feng et al. [80]	Radiant slabs	MPC	Office building simulation	MPC control was able to maintain comfort for all building zones
Schemlas et al. [85]	Concrete core activation	Adaptive and predictive	Room simulation and laboratory monitoring	The proposed control achieve better comfort conditions than supply temperature curves with simpler computation than MPC
Krzaczek and Kowalczuk [42]	TB	GSC	TB simulation	The control maintains the TB active layer at 17 °C with a variation lower than 0.2 °C
Krzaczek and Kowalczuk [108]	TB	GSC	TB simulation	Control improvement reduced TB active layer variation to 0.07 °C
Tian and Love [30]	Radiant slab cooling	ON/OFF control and ventilation	Office building simulation	Radiant cooling savings are larger in dry hot climates than in cold moist climates
Song et al. [61]	Radiant floor cooling	Supply temperature curves and ventilation	Laboratory room monitoring and building simulation	Integration of radiant cooling and dehumidification increase responsiveness to internal load changes and avoids condensation
Henze et al. [10]	TABS	Supply temperature curves and	Office building simulation	The full VAV systems used 20% more energy than the coordinated TABS + VAV system

		ventilation		
Fellin et al. [114]	Thermal slab	Supply temperature control and ventilation	Office building simulation	Handled air could help thermal slab performance

6 Conclusions

TABS are a promising technology for reducing the energy use in the building sector. The main challenges this technology faces are the heat transfer calculation, the dimensioning integrated to building design and the development of efficient controls. This paper reviews the TABS generalities and the research on heat transfer calculation models, the simulation models and the control strategies.

TABS simulation models have been essential to study their performance and to improve both their design and control. Many types of models have been developed with different application purposes and different degrees of accuracy. From 1D, 2D and 3D numerical or analytical models, mathematical correlations and simplified models have been developed. Detailed numerical models as FDM, FVM or FEM give the most accurate results and have been used for model verification. However, many simplified models have good accuracy in the application range while reducing significantly the computational effort. The latter are usually integrated in building simulation packages and in control strategies. Though steady state models have been used in research, it has been proved that the dynamic behaviour of TABS requires transient models for accurate studies.

Control strategies for TABS directly affect the comfort conditions and energy saving potential. Simple strategies can obtain good comfort conditions, but for reducing energy demand and fully exploiting renewable energies it is required to use strategies that take into account the characteristics of the system. Control of supply temperature with heating and cooling curves is common for most TABS controls. More advanced controls use heating curves as the base of its control to later calculate the energy that has to be supplied and the periods of activation. Control strategies are essential for optimizing the use of renewable energy sources. The controls have to consider the storage capacity of TABS to estimate the requirements of energy in advance so renewable energy sources are used when available.

Research has proved the great energy savings potential and CO₂ emission reduction that can be achieved with TABS. Still research is required to solve some design issues and to encourage application of TABS in refurbishment. Coordination of TABS control with ventilation and heat gains control as shading systems or lighting is also a point for further research.

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