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Publication Date
2017-02-01

DOI
10.1016/j.enbuild.2016.12.013

A novel classification scheme for design and control of radiant system based on thermal response time

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Keywords: Radiant system, dynamic thermal performance, classification, response time, time constant, design and control

Highlights

1. Design and control of a radiant system depend on its thermal response time
2. State space and thermal resistance models are used to calculate response time
3. Response time can vary between a few minutes (RCP) up to 20 hours (TABS)
4. Concrete thickness, pipe spacing, and concrete properties impact response time
5. A classification scheme for radiant systems based on response time is proposed

Abstract

Radiant system design and control standards and guidebooks currently classify radiant systems as a function of their structure and geometry. We assume that design solutions, testing methods, and control strategies of radiant systems can be more clearly described and classified based on their thermal parameters. In this study, we use the thermal response time to evaluate the dynamic thermal performance of radiant systems. We defined the response time (τ_{95}) as the time it takes for the surface temperature of a radiant system to reach 95% of the difference between final and initial values when a step change in control of the system is applied as input. The state space and thermal resistance models are used to calculate the response time for different radiant system types with a variety of configurations and boundary conditions. We performed 56,874 simulations. Concrete thickness, pipe spacing, and concrete properties have significant impact on the response time of thermally activated building systems, while pipe diameter, room operative temperature, water temperature and water flow regime do not. We find τ_{95} < 10 min for radiant ceiling panels; 1 < τ_{95} < 9 h for embedded surface systems; 9 < τ_{95} < 19 h for thermally activated building systems. A preliminary radiant system classification scheme based on thermal response time is proposed.

1. Introduction

Interest and growth in radiant cooling and heating systems have increased in recent years because they have been shown to be energy efficient in comparison to all-air systems [1,2]. Current design standards (e.g., ISO 11855 2012 [3]) and guidebooks (REHVA guidebook NO.7 [4]) categorize radiant systems as a function of their structure and geometry. The main categories are: radiant ceiling panels (RCP), embedded surface systems (ESS), and thermally

www.escholarship.org/uc/item/2j75g92w
http://dx.doi.org/10.1016/j.enbuild.2016.12.013

activated building systems (TABS). According to the position of the embedded pipes, ESS is sub-classified as Type A, Type B, Type C, Type D, and Type G. As shown in Fig. 1, Type A is the system with pipes embedded in the screed (or topping slab); Type B contains pipes embedded outside of the screed; Type C contains pipes embedded in the screed below the separating layer; Type D contains capillary mats in a thin (e.g., gypsum) layer with insulation separating it from the building structure; Type G contains pipes embedded in the sub-floor of a wooden construction. TABS are sub-classified as Type E and Type F. Type E is the system with pipes embedded in massive concrete slab, and Type F is the system with capillary pipes embedded in a thin layer that can be thermally connected to a massive slab.

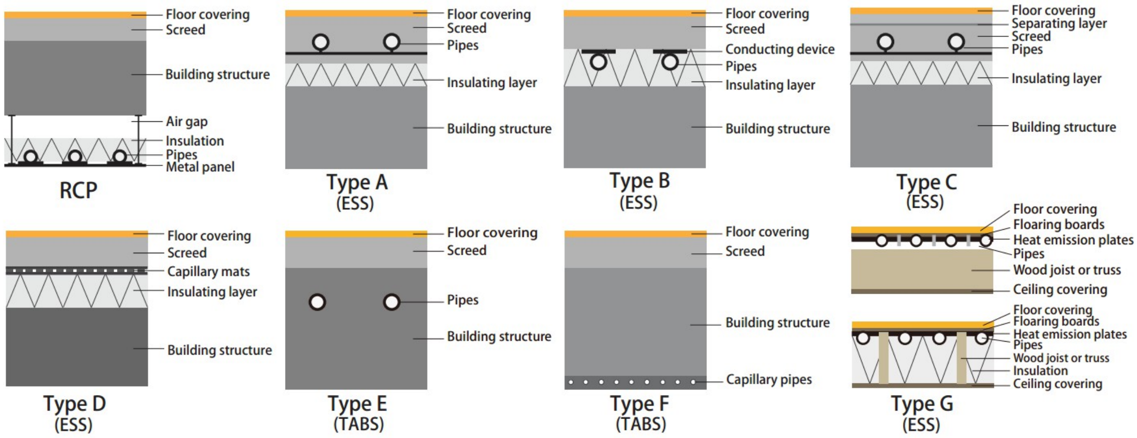


Fig. 1. Schematic drawing of radiant systems.

Cooling and heating capacity assessment methods are specified based on this classification, for example: laboratory testing for RCP, a steady-state calculation method for ESS, and a dynamic simulation for TABS [4]. Besides this, cooling load calculations, control strategies, and design methods can also be different for different radiant systems. Feng et al. (2013) pointed out that cooling load definition should be distinguished for the quick response and slow response radiant systems [5]. For control strategies, the ASHRAE Handbook - HVAC Systems and Equipment indicates that high-mass panels such as concrete radiant slabs require a control approach different from that for low-mass panels [6]. In addition, Feng (2014) pointed out that design methods for radiant systems can be quite different depending on the type of radiant systems [7]. Radiant panel systems and lightweight embedded systems can respond quickly to control signals and are able to change space conditions relatively fast, and thus sizing of those systems based on a peak cooling load could be adequate. However, for heavyweight embedded surface systems, mostly TABS, that are designed and controlled for load shifting, sizing based on a peak load is unlikely to be a good solution. We found thermal performance is more relevant for design, testing and control of different radiant systems than geometry and structure. Moreover, thermal performance is quantitative, while geometry and structure are qualitative. In this study, we assume that design approaches, testing methods, and control strategies of radiant systems can be more clearly specified and distinguished based on their thermal performance.

The thermal performance of radiant systems can be described by steady-state and dynamic thermal parameters. The most common steady-state thermal parameters are cooling or heating capacity and thermal resistance [3,4,6]. It is expected that steady-state parameters are most suitable for the evaluation of quick acting radiant systems, such as RCP. However, these parameters alone may be insufficient to characterize the operational performance of radiant systems involving larger amounts of thermal mass, including both ESS and TABS. Therefore,

http://dx.doi.org/10.1016/j.enbuild.2016.12.013

a parameter that can evaluate the dynamic thermal performance of radiant systems is needed. Current evaluation of the dynamic thermal performance of radiant systems in the standards, guidebooks and researches are summarized in Table 1.

Table 1. Current evaluation of dynamic thermal performance of radiant systems

Source	General description	Parameter used	Definition	Method
ISO11855 2012 [1]	NA[1]	NA	NA	NA
REHVA guidebook [2]	Response fast or slow	Time constant	Time for 63% of temperature change	NA
ASHRAE 2012 [5]	Response fast or slow	NA	NA	NA
UPONOR Inc. [8]	Response fast or slow	NA	NA	NA
BEKA Inc. [9]	Response fast	Response time	No definition; less than 15 min	NA
Zehnder Carboline Inc. [10]	Response quick	Response time	Have good performance after 25 minutes	Thermo graphic imaging testing
Weitzmann 2004 [11]	Light floor or heavy floor	Time constant	Time for 63% of final value light floor: 30 min-2 h heavy floor: 3 h-6 h	NA
Thomas et al. 2011 [12]	Light-weight floor	NA	Time for 80% of maximum emitting power; 30 min	Experiment
Zhao et al. 2014 [13]	Light floor or heavy floor	Time constant	Time for 63% of temperature change light floor: 10 min-2 h heavy floor: 3h-6 h	Analytical calculation
ISSO 85 [14]	Response time for different radiant systems	Time constant	Time for 63% of the final heat release	NA
Zhang et al. 2014 [15]	Lab test based on ISSO 85	Time constant	Time for 63% of the final heat release	Experiment

[1] Not Available (NA)

We can see that “response time” and “time constant” are generally used to describe if a radiant system response is fast or slow. However, the definition, description and evaluation method are not clear or unified in standards or guidebooks. A systematic assessment of dynamic thermal response is missing. Moreover, the effect on the dynamic thermal performance of variables (named here “impact factors”) like thermal capacity of different materials, water temperature, water flow rate, pipe spacing, room operative temperature, etc. are not clear. Therefore, the objectives of this study are to: (1) select, define and assess which index should be used to characterize the dynamic thermal performance of radiant systems; (2) evaluate how the index varies for different type of radiant systems; and (3) propose a classification scheme based on the index.

2. Which index ?

We can see from Table 1 that “response time” and “time constant” are two expressions widely used for the evaluation of the dynamic thermal performance of radiant systems. Since there is no clear definition or description of the two parameters, an analysis of the application of “response time” and “time constant” is needed to find out which is the most suitable term to evaluate the dynamic thermal performance of radiant systems.

2.1 Comparison of response time and time constant

Response time is widely used to describe if a radiant system response is fast or slow. Radiant system manufacturers tend to use “response time”, which to a large extent refers to the time for the system to change from one stable condition to another. Nevertheless, we did not find a rigorous mathematical definition or method of testing.

On the other hand, thermal time constant has a rigorous definition common to many scientific and technological fields. In physics and engineering, the time constant, usually denoted by the Greek letter τ, is the parameter characterizing the response to a step input of a first-order, linear time-invariant system [16]. Physically, the time constant represents the time it takes the system's step response to reach 1-1/*e* ≈ 63.2% of its final value for systems that increase in value (say from a step increase), or it can represent the time for systems to decrease in value to 1/*e*≈ 36.8% (say from a step decrease). The concept of time constant is widely used for evaluating if a sensor response is fast or slow [17–19]. In some sensor's manuals [18], "time constant" and "response time" are equivalently used, because the sensors can be well-approximated to linear time-invariant system.

2.2 Limitations of applicability of time constant to radiant systems

In the field of heat transfer, time constant is a feature of the lumped heat capacity system, which assumes the temperature distribution of a body is uniform and the temperature of the whole body changes uniformly with time. The criterion for using the lumped capacity analysis is:

$$Bi = \frac{hL}{\lambda} < 0.1 \tag{1}$$

Where *Bi* is the *Biot* number, *h* is the heat transfer coefficient, *L* is the characteristic length [20]. For radiant systems, especially pipes embedded in the screed or concrete layer, the lumped analysis method may not work because some of the assumptions may not be valid. As indicated by Weritzmann (2004), the requirement can be met by lightweight radiant systems, but not for heavy weight radiant systems [11]. For example, one radiant floor cooling system has pipes embedded at 0.1 m from the surface. The thermal conductivity of the material λ=1 W/(m K), and heat transfer coefficient on the floor surface h = 7 W/(m^2 K) [4]. For this example, we find:

$$Bi = \frac{hL}{\lambda} = \frac{7 \times 0.1}{1} = 0.7 > 0.1$$

Since *Bi* is larger than 0.1, we cannot use lumped analysis method for this radiant system. Therefore, the concept of time constant derived from lumped analysis method is not suitable for radiant systems involving large amount of thermal mass.

In addition, for an ideal lumped system, if the time constant equals τ, the time for the system to reach 95% of the difference between its final and initial values equals 3τ *[21]*. Below we will show that we can't use this relationship for radiant systems. The time for the surface temperature to reach 63.2% and 95% of the difference between the initial and steady-state values are named "$\tau_{63.2}$" and "τ_{95}". We conducted a numerical comparison (described later) of $\tau_{95}/\tau_{63.2}$ for two radiant system types: ceiling cooling of Types A (ESS) and Type E (TABS). The comparison is based on the same boundary conditions and involves a variety of structure combinations. The relationship of τ_{95} and $\tau_{63.2}$ for Type A and Type E are shown in Fig. 2. We found that for different radiant system types; the ratio of $\tau_{95}/\tau_{63.2}$ is not 3 and varies between 2.3 and 3.6. In addition, an analysis and comparison of $\tau_{95}/\tau_{63.2}$ for Type E and Type F of TABS can be found in the *Supplementary materials, Part 1*. These results confirm that ESS and TABS cannot be modeled with the lumped analysis method.

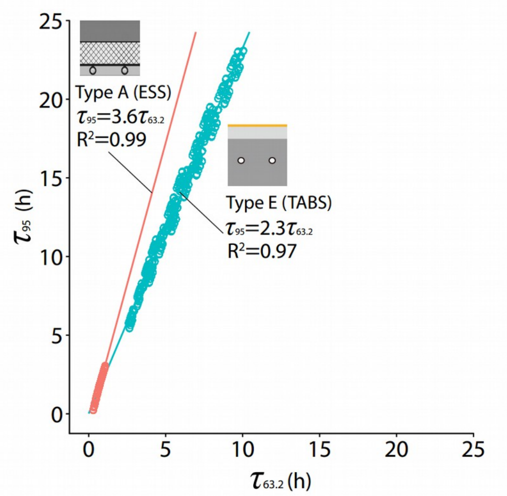


Fig. 2. The relationship between $\tau_{63.2}$ and τ_{95} for Type A (ESS) and Type E (TABS).

2.3 The definition of response time for radiant systems

From the above analysis, we found that some radiant systems do not behave even approximately as a first order system (in particular for Type F), therefore, knowing the time constant does not fully reflect dynamic behavior of a radiant system.

In addition, we should specify which variable is observed and therefore what the "final value" is. For radiant systems, it could be cooling or heating capacity, radiant surface temperature, or room operative temperature. These are all related. In this study, we selected the surface temperature because it is easy to measure and it is familiar to the industry.

We propose to use the term "response time (τ_{95})" with the following definition: "*The time it takes for the surface temperature of a radiant system to reach 95% of the difference between its final and initial values when a step change in control of the system is applied as input*".

It should be noted that if a system behaves as a first order system, then the time constant ($\tau_{63.2}$) could be deduced from τ_{95}, and vice versa. For more complex systems, there is not a single representative number like $\tau_{63.2}$ or τ_{95}, and therefore the user should look for the entire response curve or several response times, e.g., to reach 25%, 50%, 63.2%, or 80% of the difference between the final and initial values. This could be important for the prediction of the system behavior in the development of a control strategy.

3. Methods

We can use testing and calculation methods (including simulation and analytical solution) to obtain the response time for radiant systems. The testing approach is reliable but expensive. It is not practical to evaluate a variety of radiant systems. Computational fluid dynamics (CFD) method was used for computing the response time for radiant systems. The main limitation is that a large amount of time is required for modeling and computing. Therefore, a simplified calculation method is needed to evaluate radiant systems with a variety of structures and boundary conditions. In this study, we used an adapted state space method (SSM) for calculating the response time for most radiant system types like ESS and TABS. The advantage of this method is that it can calculate the response time very fast and can evaluate radiant systems with a variety of structures and boundary conditions. In addition, for the cases (for example, some RCP system) that the adapted SSM method is not appropriate, CFD simulation method can be applied. The description of CFD method for the application of radiant system can be found in Ning et al. 2015 [22]. The adapted SSM method is described below.

3.1 Heat transfer process of radiant systems

Dynamic heat transfer in radiant systems includes heat exchange between chilled water, pipes, building structure and room thermal environment. To simplify the heat transfer process, the following assumptions are usually applied, as shown in Fig. 3: (1) room thermal environment is represented by the operative temperature; (2) the materials of each layer are homogeneous and their thermal properties don't vary with temperature; (3) the pipes have a symmetric layout, a calculation unit with two symmetric pipes is used for each calculation case; (4) the water temperature along the pipe is uniform and equals to the average water temperature, and (5) the flow regime of the water is turbulent for most radiant system types, and laminar for capillary mats [3].

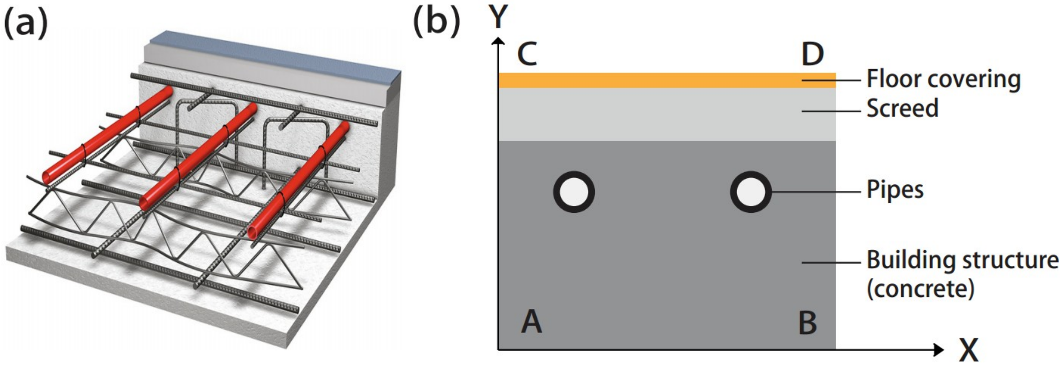


Fig. 3. An example of radiant system: (a) 3D graphical representation [23], and (b) schematic representation of simplified 2D model.

Based on the above five assumptions, the heat transfer process of a radiant system can be simplied from 3D to 2D. The adapted SSM for solving the 2D dynamic calculation of a radiant system is comprised of thermal resistance model and it's coupling with SSM.

3.2 Thermal resistance model and SSM

Thermal resistance model is widely used for cooling capacity calculation of radiant system. Koschenz and Dorer (1999) found the steady-state analytical solution for radiant systems with pipes embedded in the concrete layer [24]. The model sets up a straightforward relationship, expressed in terms of thermal resistance, between the supply water temperature and the average temperature at the pipe plane (named core temperature T_c). In this way the slab can be split into two parts. The upper slab (which is above the pipe plane) and the lower slab (which is below the pipe plane) are considered separately. The calculation of the core temperature T_c should involve conduction heat transfer from the upper slab and lower slab, as well as heat transfer from the supply water temperature in the pipe with an equivalent thermal resistance R_t. The heat transfer calculation from the core temperature T_c to the above or below room temperature can be analyzed through the SSM.

http://dx.doi.org/10.1016/j.enbuild.2016.12.013

The SSM is a simplified heat transfer method used for solving conduction transfer functions [25]. The basic state space system is defined by the following linear matrix equations:

$$\frac{d[x]}{dt} = [A][X] + [B][u] \tag{2}$$

$$[y] = [C][x] + [D][u] \tag{3}$$

Where [*x*] is a vector of state variables, [*u*] is a vector of inputs, [*y*] is the output vector, *t* is time, and A, B, C, and D are coefficient matrices. This formulation can be used to solve the transient heat conduction equation by enforcing a finite difference grid over the various layers in the slab being analyzed. In this case, the state variables are the nodal temperatures, the environmental temperatures (interior and exterior) are the inputs, and the resulting heat fluxes or surface temperature at both surfaces are the outputs. Through the use of matrix algebra, the vector of state variables [*x*] can be eliminated from the system of equations, and the output vector [*y*] can be related directly to the input vector [*u*] and time histories of the input and output vectors. This feature makes SSM have a higher efficiency for modeling dynamic heat transfer of the slab. Detailed descriptions of thermal resistance model and SSM are available at *supplementary material Part 2*.

3.3 Input parameters

In this paragraph, we summarize the input parameters used for assessing the influence of: (1) room operative temperature; (2) average water temperature; (3) water flow regime; (4) pipe spacing; (5) pipe diameter; (6) floor covering; (7) screed layer; (8) concrete type and thickness. The boundary conditions for the radiant system shown in Fig. 3 are as follows: room set-point operative temperature: 18-22 °C (heating mode) and 23-26 °C (cooling mode); water temperature: 35-45 °C (heating mode) and 14-18 °C (cooling mode). Total heat exchange coefficient h_t between radiant surface and room condition are as follows: h_{FH} = 11 W/(m^2 K) for floor heating; h_{FC} = 7 W/(m^2 K) for floor cooling; h_{CH} = 6 W/(m^2 K) for ceiling heating; and h_{CC} = 11 W/(m^2 K) for ceiling cooling [4]. The convective heat transfer coefficient for the water and pipe inside surface is calculated based on the method given by ASHRAE Handbook of Fundamentals [26].

Input parameters include geometric parameters and thermal parameters (density, thermal conductivity, and specific heat). These data are collected from several sources, such as radiant system design guidebook [4], engineering manuals (Uponor 2013 [8]; Price 2011 [27]; BEKA 2014 [9]; Viega 2013 [28]), ASHRAE handbook (ASHRAE 2013 [29]), and standard (ISO 10456:2007 [30]). The input parameters for the radiant system shown in Fig. 3 are listed in Table 2 as an example. The input parameters for all the other radiant systems are available in *Supplementary materials, Part 3*.

Table 2. Input parameters for one example of radiant system

Type A Radiant floor	Layer name	Material name	Thermal properties source	Density (kg/m^3)	Thermal conductivity (W/(m K))	Specific heat J/(kg K))	Thickness (mm)
1	Floor covering	Tiles ceramic	ISO 10456:2007(E)	2300	1.3	840	8.3
2	Weight bearing, and thermal diffusion layer	Sand aggregate	C 26.5 ASHRAE (2012)	1680	0.81	840	45
3	Building structure	Low-mass aggregate or limestone concretes	C 26.5 ASHRAE (2012)	1920	1.1	840	200
4	Pipes	Cross linked polyethylene (PEX)	UPONOR (2013)	936	0.38	1470	OD=19.05 ID=14.58

	Su=80 l=200

Note: "OD" = outside diameter; "ID" = inside diameter; "Su" = distance from the center of the pipe to the bottom of the embedded layer; "l" = pipe spacing.

4. Results

4.1 Calculation example and comparison with CFD model

An example of how the response time is calculated is described in this section. The selected radiant system is TABS (Type E) in cooling mode, with detailed input parameters listed in Table 2. The room operative temperature is 25 °C, the supply chilled water temperature is 15 °C. Since the TABS provides cooling to both the floor side and ceiling side, the change of surface temperature for both the floor and ceiling sides are reported here. Fig. 4 shows the dynamic change of the temperature for floor and ceiling surface. The calculation using both adapted SSM and CFD method are listed for comparison.

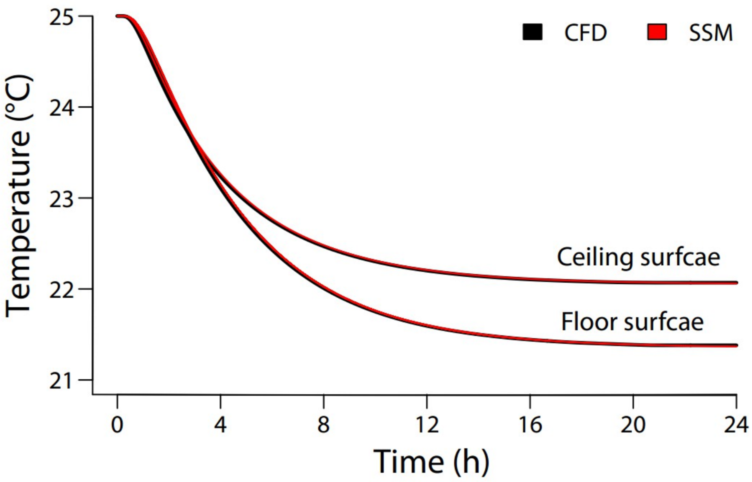


Fig. 4. Comparison of surface temperature change for CFD and SSM methods.

We can see from Fig. 4 that at first, the surface temperatures decrease very fast, and then the rate of decrease becomes slower. For the floor side after about 20 h, the surface temperature does not have much change; and τ_{95}= 13.2 h. For ceiling side, τ_{95} = 12.2 h. In addition, we found that the calculation results using SSM are very close to CFD method; which means the SSM has enough accuracy to calculate response time for TABS compared to CFD method. However, for the radiant systems with pipes not embedded in the structural layer, like RCP, this adapted SSM might not be accurate enough. In these cases, the CFD method, as described in [22], is used.

4.2 Evaluation of impact factors on response time for radiant systems

Geometric parameters, thermal parameters, and boundary conditions can impact the response time. We selected the following parameters (room operative temperature, heat transfer coefficient between radiant surface and room operative temperature, water temperature, water flow pattern, pipe spacing, pipe diameter, concrete thickness, concrete type, pipe-embedded depth, floor-covering material). Since there is no published work on the most important parameters that can impact the response time, we did a preliminary assessment to select the

http://dx.doi.org/10.1016/j.enbuild.2016.12.013

final parameters. We used the following criteria to select them: (a) there was an effect on our preliminary assessment; and (b) based on the radiant system models described in the radiant system standards (ISO: 11855-2012), guidebooks (REHVA guidebook 7-2007) and engineering manuals, and based on relevance in practice application. The analysis of the following seven impact factors on calculated response time for Type E will be taken as an example:

(1) Room set-point operative temperature in cooling mode (°C): 23, 24.5, 26;
(2) Water temperature (°C): 14, 16, 18;
(3) Pipe spacing (mm): 150, 200, 250, 300;
(4) Pipe outside diameter (mm): 16, 19, 22;
(5) Water flow pattern (Reynolds number): 3000, 6000, 9000;
(6) Concrete type: light weight, medium weight, heavy weight;
(7) Concrete thickness (mm): 150, 200, 250, 300.

We can see for each factor, three to four levels are taken into account. This needs $3^5 \times 4^2 = 3888$ simulations in total, which requires a lot of computing memory. We used Matlab to process the calculations. Thanks to the efficiency of the SSM, the computation time is less than one hour for the 3888 calculation cases. Fig. 5 shows the analysis of the impact factors on the response time based on the calculation results from the 3888 cases.

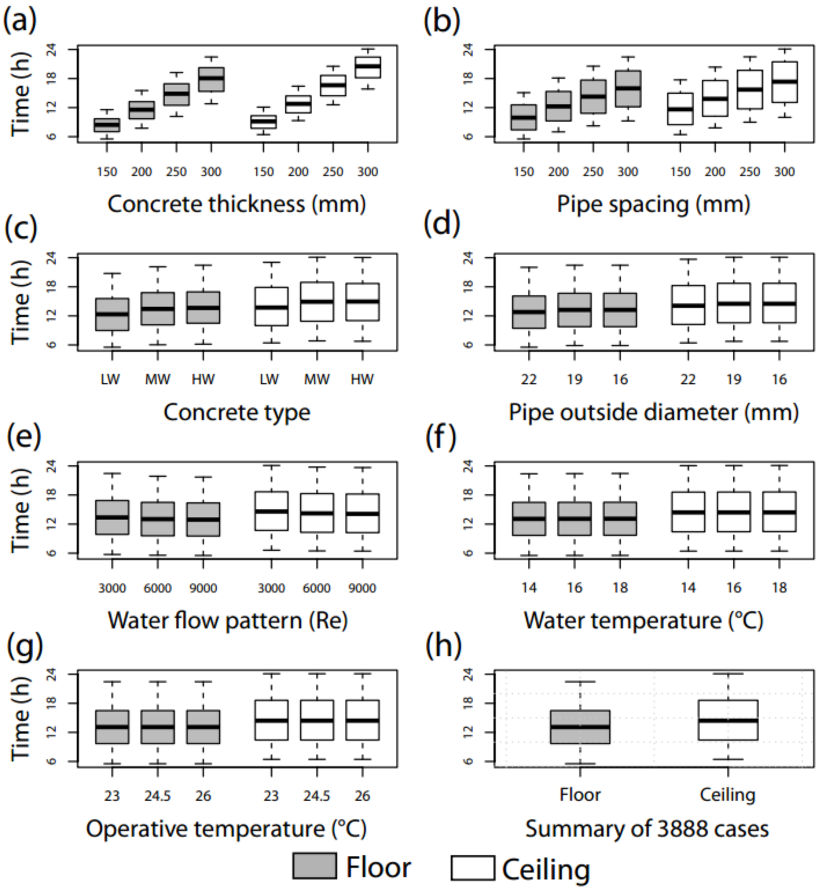


Fig. 5. Response time for different impact factors on TABS in cooling mode.

We can conclude from Fig. 5 that concrete thickness, pipe spacing, and to a lesser degree, concrete type, have a significant effect on response time, while room operative temperature, water temperature, water flow Reynolds number and pipe diameter do not.

From Fig. 5 we can see that the average response time of TABS is 13.1 h for floor side and 14.4 h for ceiling side; and the minimum to maximum response time range is 5.5-22.4 h for floor side, 6.4-24.1 h for ceiling side. In addition, the range from the lower quartile to upper quartile are 9.7-16.5 h for floor side, and 10.4-18.6 h for ceiling side. The difference in response times for floor and ceiling are due to the following: they have different heat transfer coefficients with room thermal environment, and the pipe-embedded position has impact on the response time for floor and ceiling side. In this study, we take the average value and the lower quartile to upper quartile range as the most important values. This is because the average value represents a general evaluation, and the lower and upper quartile range represents the response time for most radiant system types. These data are reported in the format of 13.1 (9.7-16.5) h for floor cooling, and 14.4 (10.4-18.8) h for ceiling cooling. We merge these data using the minimum and maximum value of the lower and upper quartile range, and the response time range for the TABS is 9.7-18.8 h in cooling mode. We will use the three values to have a general evaluation for other radiant systems.

4.3 Response time for other radiant system types

The input parameters for radiant system Type A to G with a variety of impact factors can be found in *Supplementary material, Part 3*. Since Type A and Type C are both radiant systems with pipes embedded in the screed, we only calculate the response time for Type A in this study. We conduct the calculations using the above-mentioned adapted SSM method for both cooling and heating mode. The calculated response time dataset for all the radiant system types is available in *Supplementary material, Part 4*. The average, minimum, maximum and the lower and upper quartile value of the calculated response time using SSM are summarized in Table 3. In addition, to provide more information for design, testing and control of radiant systems, the $\tau_{63.2}$ and cooling or heating capacity at steady-state condition are also calculated and presented in *Supplementary material, Part 4*.

Table 3. Summary of response time (τ_{95}) for different radiant systems

Modes	Types	RCP	Type A		Type B		Type D	Type E		Type F	Type G
	Floor or ceiling	Ceiling	Floor	Ceiling	Floor	Ceiling	Floor	Floor	Ceiling	Ceiling	Floor
	Units	min	h	h	h	h	h	h	h	h	h
Cooling mode	Case numbers	6	8748	1215	8748	729	2187	3888		1215	2187
	Min value	2.0	3.0	1.2	2.3	0.5	0.8	5.5	6.4	4.4	0.6
	Lower quartile	2.3	5.6	2.3	4.5	0.8	1.7	9.7	10.4	8.7	1.5
	Median value	4.3	7.0	2.8	5.6	1.0	2.4	13.1	14.4	11.6	1.9
	Upper quartile	6.5	8.7	3.3	7.2	1.4	3.1	16.5	18.6	14.8	2.3
	Max value	6.9	13.0	4.1	11.0	1.8	4.7	22.4	24.1	20.1	3.6
Heating mode	Case numbers	6	8748	1215	8748	729	2187	3888		1215	2187
	Min value	1.6	2.9	1.4	2.2	0.6	1.0	5.5	6.6	5.5	0.6
	Lower quartile	1.8	5.1	2.8	4.0	1.1	2.0	9.7	10.7	10.4	1.5
	Median	3.7	6.3	3.5	5.1	1.4	2.7	13.0	14.6	13.2	1.9

value										
Upper quartile	5.6	7.8	4.1	6.4	1.8	3.5	16.4	18.8	16.3	2.3
Max value	6.0	11.8	5.2	10.1	2.4	5.7	22.7	24.4	21.9	3.3

From Table 3, we found the response time varies with the types of radiant systems. The response times in cooling and heating mode are also different, which is mainly because the heat transfer coefficients between the radiant surface and room thermal environment are different. We summarize the response time for each radiant system type to have a general evaluation; the results are expressed with boxplot in Fig. 6. In addition, we also have the analysis for $\tau_{63.2}$ to provide more information for design, testing and control of radiant systems; detailed results are presented in the *Supplementary material, Part 5*.

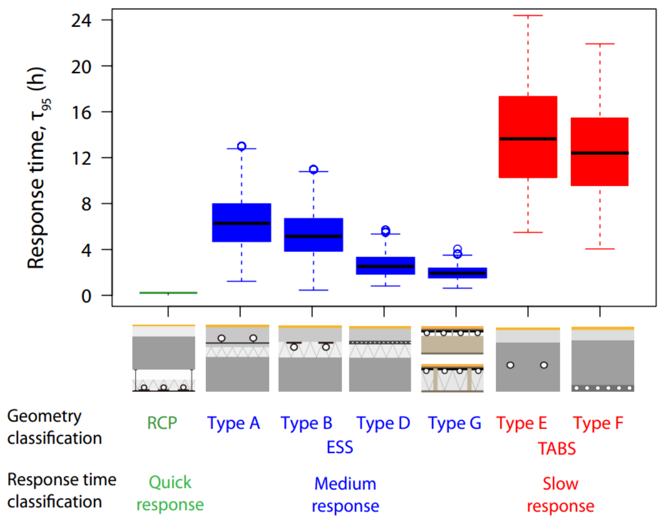
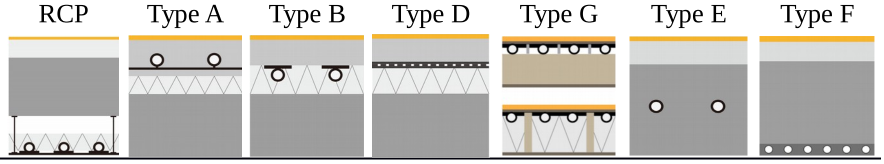


Fig. 6. The response time for different radiant system types.

The quantitative description of the average response time and the lower and upper quartile range are shown in Table 4.

Table 4. Average and the range of response time (τ_{95}) for different radiant systems

Radiant system types		Quick response	Medium response				Slow response	
Structure name		RCP	Type A	Type B	Type D	Type G	Type E	Type F
Sketch drawing								
Unit		min	h	h	h	h	h	h
Average response time		4.0	4.9	3.3	2.5	1.5	13.8	12.4
Response time range	Lower quartile	1.8	2.3	0.8	2.0	1.9	9.7	8.7
	Upper quartile	6.5	8.7	7.2	3.5	2.3	18.8	16.3

From Fig. 6 and Table 4 we can see that the response time for RCP is in the range of 1.8-6.5 min, and for ESS, in the range of 0.8-8.7 h, and for Type E of TABS, in the range of 8.7-18.8 h. We found the radiant systems can be classified as quick response (RCP), middle response (Type A, B, D, and Type G), and slow response (Type E and Type F) types.

4.4 Limitations

It should be noted that the calculation of response time in this study is based on the assumption that the room thermal conditions are constant. In reality, many room conditions like room geometry, internal heat gain, building envelope type and solar radiation can impact the response time. These factors are not taken into account in this study. Moreover, although the calculation of response time using the adapted SSM is close to the CFD method, an experimental verification is needed for the calculation model. To our knowledge, there are no publically available data to verify these results. This may be due to the fact that is hard to do dynamic tests of radiant systems. In addition, this study gives an approximate result of response time for radiant floor and ceiling. Radiant system types like radiant walls and electric heating system are not covered in this study.

5. Conclusions

Through the comparison of time constant and response time, we found that response time (τ_{95}) can provide a more consistent metric of long-term thermal response of the full range of radiant system types. This finding allowed us to apply our calculation method to evaluate the dynamic thermal performance of radiant systems, leading to the proposed classification scheme. During the course of this study, we realized that some radiant systems that involve larger amounts of thermal mass may have a behavior different from the one of a first-order model and will require more information than just response time to address effective control solutions. For this reason, it will be important to define response time data (for example: τ_{25}, τ_{50}, $\tau_{63.3}$, τ_{80}, *etc.*) for a particular system that is relevant for the application.

In this study, to distinguish different types of radiant systems based on their thermal parameters, the response time (τ_{95}) for a radiant system is defined as "*The time it takes for the surface temperature of a radiant system to reach 95% of the difference between its final and initial values when a step change in control of the system is applied as input.*".

We calculated the response time for radiant systems with different combinations of geometric parameters and thermal parameters. We found that concrete thickness, pipe spacing, and to a less degree, concrete type have significant impacts on the response time of Type E of TABS; while pipe diameter, room operative temperature, supply water temperature, and water flow regime do not.

We performed 56,874 calculation cases using CFD simulation, and state space and thermal resistance models. By using response time, the radiant systems can be classified into fast response (τ_{95}<10 min, like RCP), medium response (1 h< τ_{95}<9 h, like Type A, B, D, G) and slow response (9 h< τ_{95}<19 h, like Type E and Type F). This is a preliminary radiant system classification scheme and it helps to more clearly describe the dynamic thermal performance of radiant systems.

Acknowledgments

This study was supported by the China Scholarship Council (NO. 201406130019). Additional support for this work was also provided by the Center for the Built Environment at the University of California, Berkeley.

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