DYNAMICS OF THE THERMAL PERFORMANCE OF AN ELECTRIC RADIANT FLOOR WITH REMOVABLE CERAMIC TILES

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ABSTRACT

Energy efficiency and thermal comfort are two key features in the design of home heating systems. They allow greater thermal efficiency than conventional systems, because the heat is better distributed and the heating in the dwelling is more uniform. The systems based on radiant flooring provide a more hygienic, healthy and comfortable atmosphere.

In this study, in an initial stage, the temperature profiles that appear, in a steady state, in a radiant floor formed by several layers were analysed: insulation, an electric heating element, plastic substrate and a floor tile. In a second stage, an experimental study was done on the performance of radiant floors with different configurations, in all cases using electric sheet-type heating elements. In order to do this study, a prototype was designed that reproduced the different layers of a radiant floor, temperature sensors were placed on each one of the layers and, finally, an *all/nothing* controller was installed that allowed the surface temperature of the device to be adjusted. With the help of this assembly, the dynamic performance of the radiant floor was analysed: the time the floor takes to reach the set temperature, the range and frequency of the thermal oscillations produced during steady-state functioning and the system's energy consumption.

1. INTRODUCTION

Radiant floor heating systems are based on heating a room floor for it, in turn, to give out heat to the room. These systems allow more thermal efficiency than the conventional ones (radiators, heat pumps, etc.) due to the heat being better distributed and the heating of the home is more uniform, as well as the fact that draughts are eliminated [1,2].

There are two large families of radiant floors: radiant floors through accumulation and radiant floors with direct emission. In the first case, hot water is made to circulate through pipes located under the floor (with a thickness of 5-8 cm); this acts as an accumulator and the tile acts as an element that gives out the heat. In the second case, electric resistances are used for heating the floor [3]. These second systems are made up of the following elements: deck, thermal insulation, electric heating element, plastic substrate and flooring, as well as a control system for adjusting the temperature, which is used extensively in parquet floorings or plastic surfaces [4].

To improve the quality of life in public health environments, the German Allergy and Asthma Association carried out a study in which it was proven that radiant floor heating reduces the favourable conditions for the spreading of mites in comparison with other heating systems. It also causes less dust to move than the convection heating systems [1]. The local temperature of the floor can also have an influence on health. The previous study shows that acute chilling of the feet causes the beginning of cold symptoms in 10% of the people included in the study (180). Radiant heating can prevent bare feet from getting cold and, therefore, it can help to maintain the health of the room's occupants [6].

In this work, in a first stage, the temperature profiles, in a steady state, which appear on an electric radiant floor were analysed. This calculation allows the layers in which the highest thermal decreases (lower thermal transmittances) are produced and the factors that affect the thermal performance to be determined. In a second stage, an experimental study was done on the performance of these heating systems. In order to carry out this study, a prototype was designed that reproduced the different layers of a radiant floor. Temperature sensors were placed on each of the layers and, finally, an *all/nothing* controller was installed that allowed the surface temperature of the device to be adjusted. With the help of this assembly, the dynamic performance and the system's energy consumption were analysed. Different configurations were studied, changing the type of floor tiles, nature of the substrate, thickness of the insulation, type of deck on which it was installed, or location of the temperature control sensor.

2. HEAT TRANSFER IN A RADIANT FLOOR

In this section, the temperature profile developed, in a steady state, in a CIVIS' TERMIA® radiant flooring system was analysed. To do the calculations, an assembly made up of the following elements, in rising order, has been considered: an adiabatic floor (this represents the deck), a polystyrene substrate (thickness: 2.5 mm, thermal conductivity: 0.16 W/(m·K)), a heating element, an adapted plastic support from the Drysystem® dry installation system (thickness: 6.2 mm, thermal conductivity: 0.12 W/(m·K)), and a ceramic tile (thickness: 8.5 mm, thermal conductivity: 0.12 W/(m·K)).

Also, in order to obtain the thermal profile, the convection + radiation heat transmission factor must be known. For this, the UNE-EN 1264-2 standard on "*Radiant floor heating. Systems and components. Part 2: Determination of thermal output*" was consulted, which proposes a combined convection + radiation (h_T) factor which is determined by the expression:

$$h_T = 8{,}92(T_S - T_A)^{0.1}$$

Equation 1.

Where:

T_S: Floor surface temperature (K).

T_A: Room temperature (K).

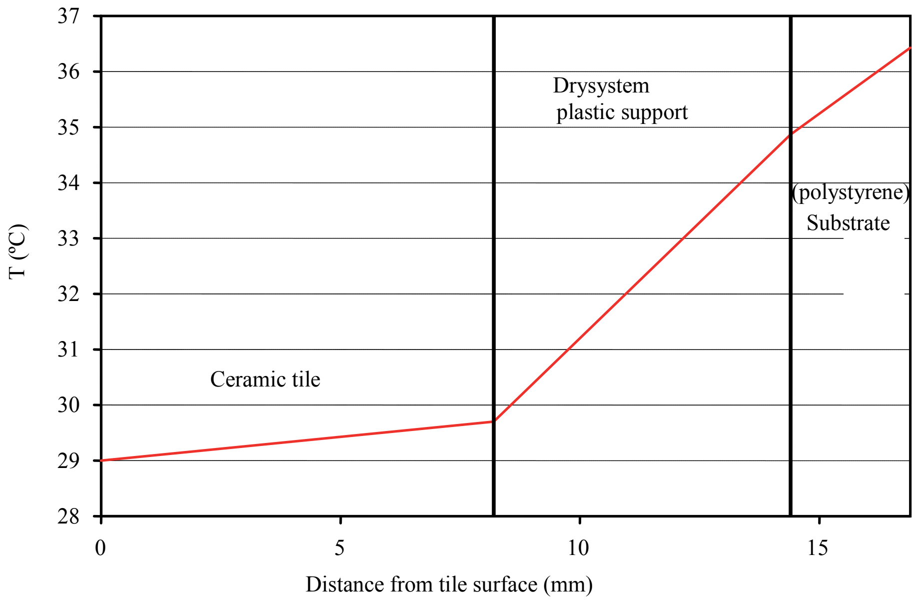

Figure 1. Temperature profile in the different layers that make up the radiant floor.

Equation 1 is simply an estimate of the hT value. A more detailed calculation would require knowing the floor surface's emissivity and the environment in which it is found (temperature of the walls, presence of windows, etc.).

Finally, the temperature of the tile surface and the atmosphere must be set. The values were established following the recommendation of standard UNE-EN 1264-2, T_S = 29 ºC and T_A = 20 ºC. Under these conditions, the heat flow density is totally defined: q_z = 100 W/m^2 and it is independent of the floor configuration (number of layers, thicknesses, and conductivities), as long as it is assumed that the floor is adiabatic, i.e. as long as the heating element is properly insulated with respect to the deck. The floor configuration will, however, have an influence on the temperature profiles obtained.

Figure 1 shows the temperature profile, in a steady state, in the different layers that make up the radiant floor. The temperature profile is linear in each layer, and it is seen that the highest thermal drop occurs in the plastic support. An extremely high thermal resistance of some of the layers could lead to excessive heating of the radiant element. However, the calculations indicate that the temperature of the radiant element reaches 36.4 ºC, which is perfectly admissible.

3. EXPERIMENTAL STUDY OF THE PERFORMANCE OF RADIANT FLOORS. GENERAL DESCRIPTION OF THE ASSEMBLY.

The prototype developed to characterize the radiant flooring systems considered is made up of the following elements (placed on top of each other):

- a thermal insulation panel.
- an electric heating element.
- a plastic substrate.
- a flooring sample.

The standard configuration is formed by a 20-mm-thick expanded polystyrene insulation, a 0.35-mm polyethylene substrate and flooring made up of a dry installation system (adapted and modified plastic support for the radiant floor application + a porcelain tile).

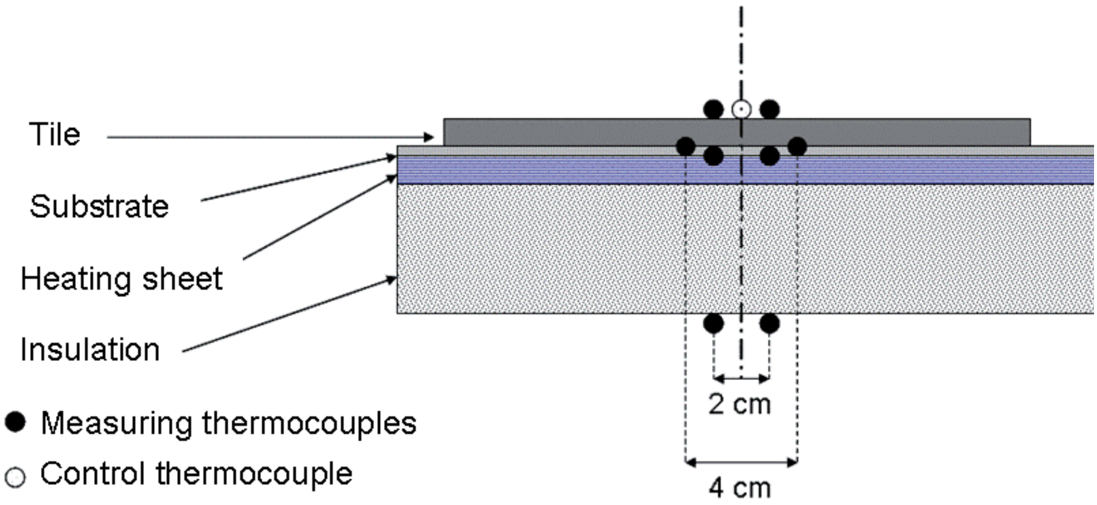

Figure 2. General diagram of the assembly used, indicating the installation of the thermocouples in the case of the standard substrate (polyethylene).

During the test, the temperature of each element was measured with two thermocouples with a T-type contact, as shown in figure 2. These thermocouples were installed near the centre of the system, as can be seen in figure 3. The heating sheet was regulated by an *all-or-nothing* controller, using the top surface temperature of the tile as a control variable. During the start-up period, the system heats the tile until it reaches 29 ºC. It then works in a steady state: the heating sheet switches on again when the control temperature drops to less than 28 ºC and it switches off when it reaches 29 ºC again, leading to heating and cooling cycles, as seen in figure 4. Strictly speaking, this is not a steady state, since the temperatures change with time as a result of the on-and-off switching by the *all/ nothing* controller.

Figure 3. Photos showing the installation of the measuring thermocouples on the heating element (left), the polyethylene substrate (centre), and the tile (right).

The major differences between the different floors analysed are in the time the system takes to reach a steady state, in the temperature that the element reaches, in the control system's on-and-off switching frequency, and in the range of thermal oscillation of the floor surface.

In the steady state, the electricity consumption is also an important variable. In this study, it has been evaluated based on the time the electric resistances are switched on. As a result, there may be a certain error in the average consumption measured due to the errors in the determination of the moment when they are switched on and off, which had an uncertainty equal to the sampling range (5 or 10 s, depending on the tests).

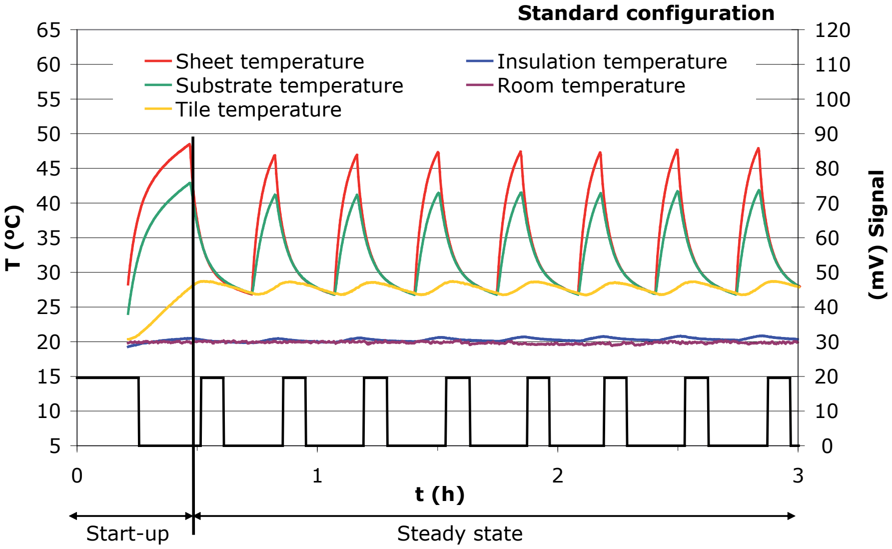

Figure 4. Temperature distribution during a typical test.

4. ANALYSIS OF DIFFERENT RADIANT FLOOR CONFIGURATIONS

4.1. Upper layers.

4.1.1. Effect of the type of flooring and nature of the substrate.

In the first stage of the work, the surfaces normally used on radiant floors were verified and different radiant floor configurations were studied, changing the substrate or the type of flooring (table 1) with respect to the standard configuration. In table 2, the different tested configurations and the variables that are characteristic of the start-up are shown: the maximum temperature reached by the heating element (T_{Max}) and the heating time needed to reach a floor surface temperature of 29 ºC (t_i). The variables that are characteristic of the steady state are also shown: the electricity consumption (Q), the heating element on-and–off switching frequency (f), the average flooring temperature (T_P) and its variation range (ΔT_P). Finally, the room temperature values (T_{amb}) during start-up and in the steady state are also shown.

Type of floor covering	Reference
CIVIS TERMIA®	CT
Parquet	PA
Carpeting	MO
Plasticised flooring	SP
Cork	CO

Table 1. Types of floor coverings tested with radiant floors.

The initial heating time varied from about 4 minutes (in the case of carpeting) to almost 30 minutes (cork flooring). There seems to be a correlation between the thickness of the "substrate+floor" system and the duration of the first heating cycle. In particular, we can divide the studied assemblies into three groups: the thickest (CO-SPo, CT-SPn, CT-SPa assemblies), which took between 20 and 30 minutes to heat, the intermediate assemblies (CT-SPo and PA-SPo), which reached 29 ºC in 10-20 minutes, and the thinnest (MO and SP-SPo), which took less than 6 minutes to reach the set temperature.

Substrate	Type of flooring	Start-up			Steady state				
		T_{amb} (ºC)	T_{Max} (ºC)	t_i (min)	T_{amb} (ºC)	Q (W)	f (ciclos/h)	T_p (ºC)	ΔT_p (ºC)
Polyethylene (SPo)	CT	18.7	47.1	18.5	18.7	13.4	3.2	27.5	1.8
Black plastic (SPn)	CT	19.9	48.1	21.5	18.8	14.3	2.1	27.1	1.7
Plastic with Al sheet (SPa)	CT	18.6	50.4	27.7	18.9	14.6	1.8	27.4	1.9
Polyethylene (SPo)	PA	16.1	46.2	17.2	18.3	14.6	3,3	27.6	2.5
Polyethylene (SPo)	MO	16.6	40.7	4.2	18.1	12.8	10.7	27.6	2.7
Polyethylene (SPo)	SP	17.3	41.4	5.8	18.0	11.1	9.5	27,6	2.0
Polyethylene (SPo)	CO	13.5	57.4	29.2	18.0	15.2	2.7	27.5	2.5

Table 2. Characteristic data of the studied systems.
Effect of the type of flooring and substrate.

The temperature of the heating element also changed significantly in the different floors analysed, ranging from 40 ºC in the cork to 31.2 ºC in the plasticised flooring. Under the test conditions used, it was seen that the heating element temperature was not too high, and the maximum temperature that the heating element could withstand was much higher than the one measured in the tests.

In the steady state, it should be noted that the average temperature of the tile was very similar in all the studied systems. Together with the plasticised flooring, the systems that used the CT system are those that had the most stable floor temperature, although among the floors analysed, the differences were not very significant. On the other hand, the control system on-and-off frequency displayed important variations among the analysed systems. This frequency is related to the thermal inertia of the floor, other parameters (like the configuration of the controller itself) being equal. The standard configuration had an intermediate thermal inertia.

Finally, the electricity consumption values showed some variation, although it is difficult to establish whether this variation is important within the experimental error of the measurement. There are basically two factors that can introduce errors into the measured consumption: the fact that the floors analysed did not all have exactly the same format (since some could not be cut), and the errors in the determination of the on-and-off switching moment, which had an uncertainty equal to the sampling range (10 s).

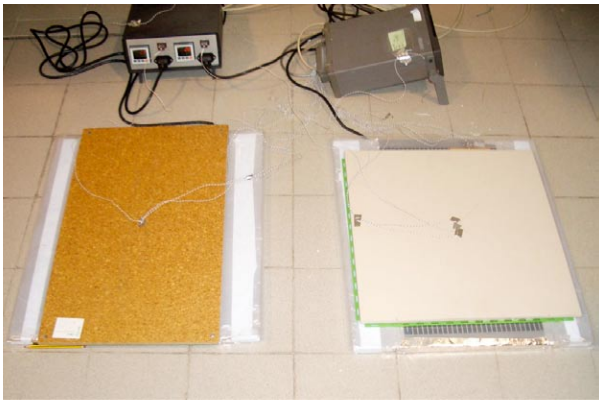

Figure 5. General photo of the assembly showing the difference in dimensions between the cork tile and the CT system.

Figure 5 shows the difference in dimensions between the cork tile and the CT system.

In principle, as mentioned in section 2, the consumption should be the same for all the analysed floors, and only the temperature profiles and the on-and-off switching frequencies should change. A more in-depth analysis indicates that there could be differences among the different floors, but these would be basically due to the emissivity of the external surface of the floor or to insufficient insulation.

In order to distinguish between the different systems from the point of view of consumption, the format (size) of the floorings would have to be kept strictly identical and the sampling range would need to be reduced. As a result, the tests presented below were carried out with a sampling range of 5 s.

4.1.2. Effect of the ceramic flooring colour.

The (light or dark) colour of a tile influences its absorptivity and could also affect its emissivity. As a result, the performance of a radiant flooring system could be different when the colour of the flooring changed. In order to assess this effect, the prototype designed for simultaneously testing two different floors was used: one white floor and the other one black.

When the results of the tests are compared, it is seen that, in general, there are almost no differences between the system consisting of the light-coloured tile and the one with the dark tile though the initial heating time is slightly longer in the case of the dark tile (table 3). The few differences that exist between the results obtained indicate that the emissivity values are practically the same.

Test	Colour	Start-up			Steady - state status				
		T_{amb} (ºC)	T_{Max} (ºC)	t_i (min)	T_{amb} (ºC)	Q (W)	f (cycles/h)	T_P (ºC)	ΔT_P (ºC)
A	White	17.8	51.2	22.3	17.8	16.0	3.0	27.2	1.8
	Black	17.8	50.6	24.5		16.6	3.1	27.6	1.6
B	White	20.6	51.3	18.0	20.7	10.9	2.4	27.7	1.8
	Black	20.6	50.0	16.5		10.3	2.5	27.5	1.8

Table 3. Characteristic data of the studied systems. Effect of flooring colour.

It should be pointed out that the emissivity can be very different from the absorptivity, and this is partly due to that fact that, when speaking of emissivity, the radiation "emitter" is the tile, which is at a temperature similar to the room temperature, and when we speak of absorptivity, we tend to refer to the solar radiation received, in which case the "emitter" is the sun. The wavelengths of both radiations are very different, and so are the performance reactions of the tiles to them. A light-coloured tile and another dark one placed in the sun will reach very different temperatures due to the difference in absorptivity, although their emissivity is identical.

In contrast, the results obtained show that the start-up time reduces significantly when the room temperature rises: when the room temperature is raised 3 ºC, the start-up time drops by about 25%. There is also a considerable difference in consumption between the two tests carried out: a drop in room temperature of 3 ºC corresponds to an increase in consumption that is close to 50%. When different configurations are compared, it is important to check that the atmospheric conditions in which the tests are carried out are similar.

4.2. Control system.

In this second experimental stage, the effect of the control system on the performance of the CT electric radiant floor heating system was studied. As mentioned, the heating element was regulated by an *all/nothing* controller. In this part of the study, tests were carried out using the temperature of the upper surface of the tile (conventional control) or of the heating element as a control variable. As indicated in table 4, three different tests were carried out. In the first one, the temperature of the tile was used to control the system. The last two tests were carried out using the temperature of the heating element to control the system. The control value was 29 ºC or 35 ºC. This second value corresponds to the average measured temperature of the heating element in the test carried out with conventional control.

Test	Control thermocouple location	T_{cons} (ºC)	Steady state				
			T_{amb} (ºC)	Consumption (W)	f (ciclos/h)	T_P (ºC)	ΔT_P (ºC)
A	Flooring	29	20.7	10.9	2.4	27.5	1.8
B	Heating element	29	21.4	4.4	29.3	25.0	0.2
C	Heating element	35	20.1	10.0	56.1	26.6	0.3

Table 4. Characteristic data of the studied systems. Effect of the control system.

In the tests carried out with the conventional control system, there was an initial start-up period in which the heating element heated up until the tile reached 29 ºC (figure 4). In contrast, in the case of the tests controlled by the temperature of the heating element, the floor does not reach the target temperature after one hour testing (the target temperature being 29 ºC in the centre of the tile, which corresponds to about 27.5 ºC in the position of the thermocouple). The tile progressively heats up while the temperature of the heating element oscillates slightly around the control value. After one hour of testing, the temperature reached by both tiles is about 25 ºC for a set temperature of 29 °C, and about 26 ºC for a set temperature of 35 °C (figure 6).

On the other hand, the performance of the system in a steady state is clearly different, depending on whether the assembly is controlled by the floor temperature or by the temperature of the heating element. In the first case, the floor temperature changes with time (figure 4). The on-and-off switching of the heating element lead to heating and cooling cycles that translate into oscillations of about 2 ºC in the tile surface temperature. When the temperature of the heating element is used as a control variable, a very stable temperature is obtained on the tile surface, though it is lower than in the previous case (figure 6).

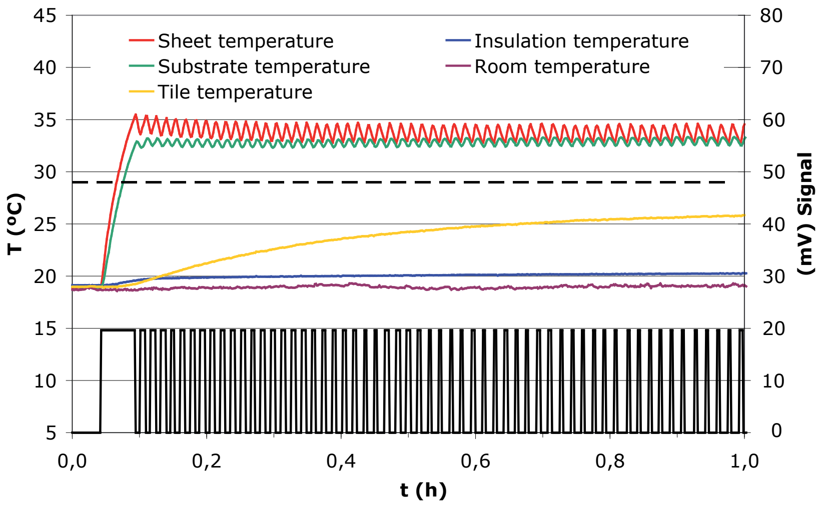

Figure 6. Temperature distribution during the first hour of testing in a test with control by heating element temperature (Tcons=35 ºC).

In the case of the systems controlled by the heating element temperature, the switch-on frequency was much higher than for the tests carried out with the conventional control method. The heating element switched on for very short periods of time (about 10 to 15 s) and they were similar to the sampling range (5 s), which could lead to considerable error in the consumption values obtained. When the consumption data are compared with conventional system data, no big differences are found between test A and test C. On the other hand, the consumption measured in test B is very low. This can be explained by a smaller difference between the tile temperature and the room temperature, in comparison with the difference that exists in the other tests.

4.3. Lower layers.

In the third experimental stage, the effects of the thickness of the insulation and of the type of floor on the performance of the radiant floor were considered, using the prototype for simultaneously testing two radiant floor configurations: one with a 5-mm-thick insulation and the other with a 20-mm-thick insulation. The tests were carried out by placing the prototypes on the two types of floor described in table 5.

Floor	Description of the floor (deck)
Type 1	Basement floor made up of ceramic tiles, a 20-cm H-200 concrete floor, a 2-mm polyethylene sheet and a 20 cm drainage fill.
Type 2	Deck floor made up of ceramic tiles, a 5-cm mortar base, a 3-cm decoupling, levelling and filling layer, joists, and 26-cm joist-to-joist filler blocks.

Table 5. Floors used as substrates for the radiant floor assembly.

As previously mentioned, room temperature has a significant influence on both the initial heating time and on consumption. Consequently, it was decided to increase the set temperature in some of the tests to obtain similar differences between the set temperature (T_{con}) and the room temperature and to be able to compare the results obtained on one type of floor with those obtained on the other. The test conditions and the results obtained are shown in table 6.

Floor	Insulation thickness (mm)	T_{cons} (ºC)	Start-up			Steady state				
			T_{amb} (ºC)	T_{Max} (ºC)	t_i (min)	T_{amb} (ºC)	Q (W)	f (cycles/h)	T_P (ºC)	ΔT_P (ºC)
Type 1	20	29	15.8	49.8	30	18.0	15.4	3.0	24.1	1.8
	5			44.7	41		21.5	3.4	26.5	1.5
	20	32	22.8	51.0	16	21.5	12.0	2.8	31.5	1.8
	5			47.6	23		20.2	3.3	30.6	1.6
Type 2	20	29	20.4	47.5	19	20.0	15.6	3.0	28.3	1.7
	5			41.2	19		16.5	3.3	27.0	1.4
	20	34	24.0	54.3	25	26.0	12.8	2.8	32.5	1.9
	5			47.9	28		16.5	3.2	32.3	1.5

Table 6. Characteristic data of the studied CT systems.
Effect of the insulation thickness and type of deck.

The results obtained in this part of this study cannot be immediately interpreted since the start-up time and the consumption depend on the insulation thickness and the type of floor, as well as on the difference between the set temperature and the room temperature. To identify which of the three above factors have a significant effect on these variables, it was decided to fit the results, assuming that they depended linearly on all the variables, using the following equations:

$$t_i = b_0 + b_1 \cdot \Delta T^* + b_2 \cdot A + b_3 \cdot S$$

Equation 2.

$$Q = c_0 + c_1 \cdot \Delta T^* + c_2 \cdot A + c_3 \cdot S$$

Equation 3.

Where:

t_i: Initial heating time (min).

Q: Electricity consumption (W).

ΔT^*: Difference between the set temperature and the room temperature (ºC)

A: Insulation thickness (mm).

S: Parameter, function of type of floor: S=0 if for floor type 1 and S=1 for floor type 2

b_n, c_n: Fitting parameters.

Parameters b_n and c_n were determined by using the least squares method, calculating the statistical error value (typical deviation) of each one of them. A high value of this error versus the value of the coefficient means that the corresponding variable has little effect on the heating time. On the other hand, a small error indicates that the variable has a significant effect.

	$t_i = b_0 + b_1 \cdot \Delta T^* + b_2 \cdot A + b_3 \cdot S$				$Q = c_0 + c_1 \cdot \Delta T^* + c_2 \cdot A + c_3 \cdot S$			
Parameter	b_0	b_1	b_2	b_3	c_0	c_1	c_2	c_3
Value	- 4.56	3.32	0.28	0.24	10.28	1.17	-0.31	-0.31
Statistical error	6.48	0.57	0.13	2.05	6.68	0.64	0.08	1.49
Relative error	-	17%	45%	600%	-	55%	25%	500%

Table 7. Fitting parameters of the start-up times.

Table 7 contains the fitting parameters of equation 1 and the error corresponding to each one. In view of these results, it can be seen that the difference between the set temperature and the room temperature, as well as the insulation thickness, are the variables that most influence the performance of the radiant floor. When the insulation thickness is increased, the CT system heats up more quickly and consumption is reduced as a result of smaller heat losses through the bottom of the radiant floor heating system. Finally, it should be pointed out that the type of deck has no significant effect on the heating time or the consumption, as the very high error values indicate on the corresponding parameters (b_3, c_3).

5. CONCLUSIONS

- Theoretically, the thermal calculations carried out with a floor consisting of the CT system (adapted Drysystem + polyethylene substrate + heating element + polystyrene insulation) indicate that the highest resistance to the heat flow lies in the plastic support of the adapted Drysystem. However, the temperature reached by the radiant sheet is not very high, which means that the system can carry out its function perfectly as a radiant floor.
- The influence of each of the layers on the performance of the CT radiant floor system has been experimentally evaluated using a prototype designed especially for this study. When the type of floor is changed, the initial heating time and the temperature of the heating element change significantly. However, in none of the floors analysed was the heating element temperature excessively high. On the other hand, it deserves to be noted that, together with the plasticised floor, the systems that use the CT system are the ones that have the most stable floor temperature.

- The studies of the heating time required to reach a steady-state surface temperature and the on-and-off switching frequency of the heating element indicate that the system has a significant heat accumulation capacity in comparison with other studied systems, and acts as a semi-accumulating radiant system.
- When the colour of the ceramic flooring is changed, the performance of the CT radiant floor heating system is not modified. On the other hand, the room temperature has a significant effect both in the steady state and during the initial heating.
- In the standard configuration, the heating element is regulated by an *all or nothing* type controller, using the tile upper surface temperature as a control variable. Tests have been carried out using the temperature of the heating element as control temperature; this enabled oscillations in the floor surface temperature to be eliminated, but the initial response time was much slower and more than 1 hour was needed to reach the quasi-steady state with a stable surface temperature. This change in the control system does not mean any substantial modification in system energy consumption.
- Finally, it has been confirmed that, under the same room temperature conditions and for the same set temperature, increasing the insulation thickness allows the initial heating time of the CT system to be reduced and the electricity consumption to be decreased. On the other hand, the performance of the radiant floor system is independent of the type of floor on which it is installed.

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