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Alternative Method to Integrate Electrically Heated Floor in TRNSYS: Load Management

Hélène Thieblemont^{#1}, Fariborz Haghighat^{#2}, Alain Moreau^{*3}, Arash Bastani^{#4}, Frederic Kuznik^{°5}

[#]*Department of Building, Civil and Environmental Engineering,
Concordia University, Montreal, Canada, H3G 1M8*

¹*h.thieblemont@gmail.com*

²*Fariborz.Haghighat@concordia.ca*

⁴*arash_bstn@yahoo.com*

[°]*INSA-Lyon, CETHIL, F-69621 Villeurbanne, France*

⁵*frederic.kuznik@insa-lyon.fr*

^{*}*Laboratoire des technologies de l'énergie d'Hydro-Québec, Shawinigan, Canada*

³*moreau.alain@ireq.ca*

Abstract

In a cold climate, electrical power demand for space conditioning during certain periods of the day becomes a critical issue for utility companies. Shifting a portion or all of it to off-peak periods can help reduce peak demand and to reduce stress on the electrical grid. Electrically heated floor systems consist of heating elements embedded in a material with a high thermal storage capacity. Electrically heated floors can store thermal energy in buildings during the off-peak periods and release it during the peak periods while maintaining occupants' thermal comfort.

TRNSYS is a powerful and flexible simulation software. Nevertheless, no model has been developed for the simulation of an electrically heated floor. This paper reports the development of an alternative method to integrate an electrically heated floor in TRNSYS and investigate the impact of floor assembly on the electrically heated floor performance. The results show that an electrically heated floor in a cold climate allows to completely shift the energy consumption.

Keywords: *Electrically heated floor, Control strategy, Load Management, Thermal storage, Modeling*

1. Introduction

Intense energy consumption periods during winter in cold climate [1] compels utility providers to use fossil fuel to generate the required energy. Thus, from both an environmental and economic point of view, it is necessary to shift the peak demand to the off-peak periods. This can be achieved by storing energy during off-peak periods to be utilized during peak ones. The building envelope, central heating system, and hot water tank have already can be used as thermal energy storage (TES) [2]–[6].

For resistive heating systems, the conversion efficiency is about 100, thus the heating system can be used to heat the building mass and store thermal energy during off-peak periods. Then, during peak hours, the stored energy can be released allowing the heating system to remain off. One possibility is the integration of the heating system in the floor assembly, based on the circulation of hot water (hydronic floor heating system), or with electrical wires (electrically heated floor - EHF). Benefits of EHF are numerous; first, heating elements are installed within the floor assembly that may be appreciated from an architectural point of view. Another advantage of such an approach is that thermal radiation could provide a better thermal comfort (TC) environment for the occupants.

For example, Kattan et al. [7] reported that a hydronic under-floor heating system composed of concrete and insulation could reduce the load by 26% during the peak periods and the total energy consumption by 30% in comparison to a conventional convective system. Li et al. [8] investigated a number of control strategies for shifting the peak demand while the heating system was allowed to operate between 22:00 to 6:00, unless the TC was jeopardized. Their results showed that there is an 80% load reduction during the peak period. Nevertheless, the simulation was carried out for an office. Consequently, the TC was studied only between 8:00 and 18:00. Moreover, the study did not report the floor surface temperature (FST). Lin et al. [9] carried out an experiment with an EHF accompanied with PCM in an environment with an average outdoor temperature of 13.6°C. Their control strategy was based on the heating element temperature (heaters stopped working when the heater temperature was over 70°C and worked again when it was below 55°C): the system did not have a good control over the room and FSTs, which resulted in high average indoor temperature (31°C) and FST (40°C). Cheng et al. [10] conducted simulations and experiments with an EHF with a shape-stabilized PCM. The heating time lasted 10 hours and the intermittent time lasted 14 hours, with outdoor temperatures between 0°C and 6°C. In comparison with other heating strategies (i.e. operating all day), the EHF with PCMs was able to completely shift the load from peak periods to off-peak periods. Nevertheless, average room temperatures were quite low (between 15°C and 16°C). Thus, the TC condition requirement was not met.

The results of the earlier investigations show that a floor heating system is able to shift part of or the entire space-conditioning load from peak periods to off-peak periods, but it may not be able to provide the required TC. Moreover, the effect of the outdoor temperature in cold climate regions has not been thoroughly investigated, and the majority of studies are conducted using hydronic floor heating systems. Therefore, further investigation is required for EHF with the objective of completely shifting the peak demand to off-peak hours while maintaining the occupants' TC. To realize it, the software TRNSYS will be used, to model the building. Nevertheless, the

existing models for an EHF in TRNSYS do not allow to take the thermal mass on the top of the EHF into consideration. Thus, a procedure will be developed for the integration of an EHF in TRNSYS. Then, the developed model will be used to study the ability of the EHF to shift part of or the entire load of the peak period in a cold climate. To have more information on the behavior of each layer, a parametric study will be realized.

2. EHF in TRNSYS

2.1. Existing Methodologies for EHF in TRNSYS

TRNSYS is the acronym for TRaNsient SYStems simulation program. This software is working with modules called “Type”. These types are mathematical models, in which users can choose to link inputs and outputs of different types together in order to study the performance of a system. The format of the program makes this software really flexible.

EHF in TRNSYS

For hydronic floor heating systems, two models were developed and implemented in TRNSYS: the Active Layer and the Type 653. For EHF, two methods can be used to approximate them in TRNSYS. The first method is the wall gain, which is analogous to defining a given heat flux on a surface and not within the layer. Another possibility is, by choosing a high flow rate, to assume a constant water temperature: it is possible to use the Active Layer to have a similar behavior to an EHF. Nevertheless, to use the Active Layer, it is required to determine the relationship between the parameters of the active layer and the power of an EHF. Moreover, because the Active Layer has to respect some hypothesis, the “wall gain” solution is more flexible.

2.2. Integration of EHF

Some modifications must be made in order to use the “wall gain” to model a building integrated with an EHF.

Creation of a fictitious zone

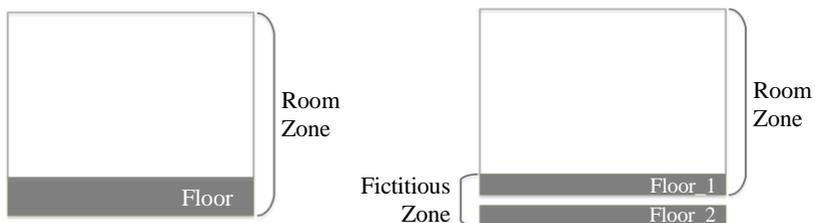


Figure 1: Conventional configuration of a room in TRNSYS (left) and configuration with the added fictitious zone in TRNSYS (right)

In an EHF, the heating element is uniformly placed within the concrete. Thus, the power is uniformly distributed and the concept of constant power gain can be applied to such system. Then, to model this heat flux, a "wall gain" will be used. To apply this surface gain for such application, a fictitious zone is created within the concrete floor. By having the size of this fictitious zone infinitesimally small and a high heat transfer coefficient for the fictitious layer, a perfect contact between two layers can be assumed. Also the perimeter heat losses are neglected since the volume of this fictitious zone is very small. This fictitious zone will have one floor (connected to the ground) and one ceiling (connected to the room zone). The modification of zones is represented in Figure 1. Coupled together, these two zones represent all layers of the desired assembly.

Implementation of the wall gain

Once the fictitious zone is created, the method of the "wall gain" to model an EHF, presented earlier, can be used. The wall gain, used as a surface gain to model the EHF, is added on the upper-surface of the lower-wall (on the top of the *Floor_2*, as shown in Figure 2).



Figure 2: Conventional configuration of a floor in TRNSYS (left) and configuration with the added fictitious zone and the wall gain (right)

Thus, the wall gain has been implemented inside the concrete layer. In this way, the modelling takes into consideration the concrete layer on the back of the EHF as it was before the modification of the building, but also the concrete layer on the top.

2.3. Validation of the Model

To validate this model, the main consideration is to be sure that the creation of a new zone is done properly and simulates the behavior of the system.

Validation of EHF model

To verify the validity of this approach, the temperature on the back of the *Floor_1* has to be the same as the temperature on the top of the *Floor_2*. These temperatures are available as outputs of TRNSYS. The temperature difference between the upper side of the *Floor_2* and the lower side of the *Floor_1* is calculated for 10 days, and only the last 8 days are taking for analysis: Results show an average error of less than 1%.

Whole model validation

The implementation of this model is realized in a residential building which was experimentally validated [11]. To validate the integration of the

fictitious zone, the wall gain is set to 0, and electrical baseboards are used to heat the buildings with the same control strategy as the one used earlier [11].

The simulations are performed for one month (in January), for the reference building [11] and the modified one (building with the fictitious zone). The energy consumption of the heating system is then compared: there was an excellent agreement. Results show a difference of 0.20%. This indicates that the EHF was modelled correctly and it correctly simulates the behavior of the building.

3. Application: Parametric Study

3.1. The Reference Case (Ref.) & Parameters

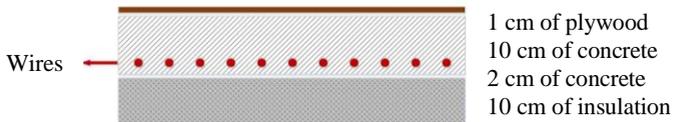


Figure 3: Electric floor heating system - Reference case

The building was modified to meet the requirements of this project: namely to have a floor consists of five layers: XPS (insulation of the ground), concrete on the top of the wires, concrete on the back of the wires, XPS (insulation between the screed and the covering floor), and plywood (floor covering). The configuration of the EHF for the reference case is presented in Figure 3.

Then, extensive simulation was carried out to study the impact of design parameters on the performance of the system for a cold climate. All the studies are conducted for Montreal (Canada) for the month of January. Results will be compared with the reference case (Figure 3). The simulation results are analyzed in terms of energy consumption, floor surface and room temperature, as follows:

Floor Surface Temperature (FST):

- Max $T_{\text{floor_surf}}$: Maximal FST.
- Daytime $T_{\text{floor_surf}}$: Daytime when the FST is at its maximal. For example, 7:00 means that the maximal FST appears generally at 7:00 on the morning every day and decreases after.
- $T_{\text{floor_surf}}$ at 20:00: FST at the end of the peak period (20:00).

Indoor temperature:

- Max T_{in} : Maximal indoor temperature.
- Daytime T_{in} max: Daytime when the indoor temperature is at its maximal. For example, 11:00 means that the maximal indoor temperature appears generally at 11:00 on the morning every day and decreases after.

- Daytime $T_{in} < 20^{\circ}\text{C}$: Daytime when the indoor temperature drops below 20°C . For example, 20:00 means that the indoor temperature is above 20°C until 20:00 on the evening and drops below 20°C after.

All the parameters are averaged for the month and for all the rooms.

E (kWh/day): Energy consumption of the EHF for all the rooms in kWh, averaged by day.

3.2. Results on the Parametric Studies

The parametric study is to investigate the impact of each layer thickness (thk) of the EHF on the thermal behavior of the building. In these studies, the EHF is heated from 20:00 (8:00 PM) to 6:00 AM at the rate of 120W/m^2 , and the heater is turned off when the FST exceeds 28°C or the indoor temperature is higher than 23°C .

Insulation on the back

Table 1: Results of the parametric study of the thickness of the insulation on the back

THK (m)	FST			Indoor Temperature			E (kWh/day)
	Max $T_{\text{floor_surf}}$ ($^{\circ}\text{C}$)	Daytime $T_{\text{floor_surf}}$ max (h:m)	$T_{\text{floor_surf}}$ at 20:00 ($^{\circ}\text{C}$)	Max T_{in} ($^{\circ}\text{C}$)	Daytime T_{in} max (h:m)	Daytime $T_{in} < 20^{\circ}\text{C}$ (h:m)	
0.075	26.64	7:25	22.07	21.71	11:36	19:23	114.64
0.100 (Ref.)	27.60	7:06	23.12	22.58	11:13	21:17	108.23
0.125	27.93	6:48	23.54	22.90	11:02	22:06	103.18
0.150	28.08	6:34	23.77	23.06	10:54	22:33	99.59
0.175	28.16	6:25	23.92	23.16	10:41	22:50	96.88
0.200	28.20	6:19	24.03	23.23	10:43	22:59	94.75

Table 2 shows simulation results. We can observe that the maximal FST, the FST at 20:00 and the maximal indoor temperature increase when the insulation thickness increases. Indeed, with the increase of the insulation thickness, loss to the ground decreases: a higher proportion of the heat flux ends up to the room, increasing the maximal FST and the indoor air temperature. Moreover, for the same reason, the maximal FST and indoor air temperature appear earlier, and the indoor temperature for a longer period is above 20°C . Finally, the energy consumption decreases significantly as the insulation thickness increases.

Thus, these results show that increasing the insulation thickness allows to reduce the building energy consumption. Therefore, a higher proportion of the heat flux is delivered to the building. Thus, the energy consumption decreases and the system can provide the required TC for longer period of the day.

Hence, a thicker layer of insulation between the ground and the concrete layer is desirable for an EHF.

Concrete on the back

Simulations results are presented in Table 3. One can observe that all the parameters can be considered as constant between 8 and 14 cm of concrete (with 10cm of concrete on the top of the EHF). Even for a concrete thickness of less than 8 cm, the energy consumption and the maximal indoor temperature can be considered as constant. Thus, the concrete thickness below the EHF has no impact on consumption and on the maximal indoor temperature.

Table 2: Results of the parametric study of the thickness of the concrete on the back

THK (m)	FST			Indoor Temperature			E (kWh/ day)
	Max $T_{\text{floor_surf}}$ (°C)	Daytime $T_{\text{floor_surf max}}$ (h: m)	$T_{\text{floor_surf}}$ at 20:00 (°C)	Max T_{in} (°C)	Daytime $T_{\text{in max}}$ (h: m)	Daytime $T_{\text{in}} < 20$ °C (h: m)	
0.02 (Ref.)	27.60	7:06	23.12	22.58	11:13	21:17	108.23
0.04	27.41	7:59	23.87	22.67	12:09	21:52	109.31
0.06	27.11	8:36	23.87	22.59	12:34	22:10	109.18
0.08	26.82	8:56	24.36	22.47	12:34	22:07	108.89
0.10	26.63	9:02	24.45	22.39	12:31	22:05	108.63
0.12	26.51	8:53	24.51	22.33	12:17	21:58	108.51
0.14	26.44	8:49	24.56	22.30	12:19	21:58	108.38

Between 2 and 6 cm of concrete, the maximal FST decreases while the FST-at-20:00 increases, the maximal FST and indoor air temperature appear later, and the duration with a good TC is extended: the storage capacity has increased. Thus, between 2 and 6 cm of insulation, one can observe a slight improvement of the performance of the system (especially almost one hour in addition to indoor temperature above 20°C). This is due to an increase of the storage capacity of the system.

Thus, we can conclude that a small increase of the concrete thickness allows the increase of the storage capacity, and thus provide the requirement for TC for a longer period of time. However, from 8cm, it appears that, with already 10cm of concrete layer on the top of EHF, increasing the concrete thickness below the EHF does not impact the system performance.

Concrete on the top

To investigate the impact of the thickness of the upper (screed) layer of concrete on the thermal behavior of the building further simulation was performed. Table 4 shows that as the concrete thickness increases the maximal FST slightly decreases and the maximal indoor air temperature slightly

increases: the concrete thickness has no significant impact on the maximal temperatures. Indeed, the chosen control strategy prevents overheating.

Table 3: Results of the parametric study of the thickness of the concrete on the top

THK (m)	FST			Indoor Temperature			E (kWh/ day)
	Max $T_{\text{floor_surf}}$ (°C)	Daytime $T_{\text{floor_surf max}}$ (h: m)	$T_{\text{floor_surf}}$ at 20:00 (°C)	Max T_{in} (°C)	Daytime $T_{\text{in max}}$ (h: m)	Daytime $T_{\text{in}} < 20$ °C (h: m)	
0.02	28.30	4:39	17.71	21.83	8:02	13:52	99.07
0.04	27.99	5:06	19.73	22.04	9:05	16:27	102.27
0.06	27.78	5:32	21.12	22.21	9:52	18:23	104.62
0.08	27.68	6:20	22.22	22.40	10:28	20:03	106.42
0.10 (Ref.)	27.60	7:06	23.12	22.58	11:13	21:17	108.23
0.12	27.45	7:42	23.74	22.63	11:53	21:45	109.43
0.14	27.17	8:30	24.08	22.55	12:28	22:02	109.82

Moreover, the maximal FST, the maximal indoor air temperature and its drop below 20°C appear significantly later, and the FST-at-20:00 is significantly higher with a thicker concrete layer. Indeed, the increase of the concrete layer on the top of the EHF, especially because there is only 2cm of concrete below the EHF, allows the storage capacity of the system to increase. Then, the EHF is able to store more energy without overheating, what involves an increase in energy consumption until provide enough energy to have an acceptable TC (8 cm of concrete). This energy is then stored on the concrete, to be released during off-peak: the indoor temperature is longer above 20°C.

In conclusion, the screed layer thickness has an important effect on the EHF performance. It allows more energy to be stored thus provide a longer period of acceptable TC for the occupants.

Table 4: Results of the parametric study of the thickness of the insulation on the top

THK (m)	FST			Indoor Temperature			E (kWh/ day)
	Max $T_{\text{floor_surf}}$ (°C)	Daytime $T_{\text{floor_surf max}}$ (h: m)	$T_{\text{floor_surf}}$ at 20:00 (°C)	Max T_{in} (°C)	Daytime $T_{\text{in max}}$ (h: m)	Daytime $T_{\text{in}} < 20$ °C (h: m)	
0 (Ref.)	27.60	7:06	23.12	22.58	11:13	21:17	108.23
0.01	25.47	9:45	23.18	21.35	12:32	19:04	112.02
0.02	24.08	10:58	22.38	20.29	12:29	17:21	114.10
0.03	22.65	11:32	21.25	19.10	12:08	-	116.45
0.04	21.14	11:49	19.89	17.80	12:04	-	118.03

0.05	19.70	12:09	18.53	16.54	12:05	-	118.03
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Insulation on the top

Table 5 gives the results of simulation. It shows by increasing the insulation thickness the maximal FST, the maximal indoor temperature, and the period during the day with an indoor air temperature above 20°C decrease. In addition, the electric consumption increases with the insulation thickness. This is mainly because as insulation thickness on the top increases the proportion of heat lost to the ground. Thus, the occupants' TC decreases significantly. Table 5 also shows that the electric consumption does not increase between 4 and 5 cm, because the EHF is already at 100% charged during the night.

Finally, this parametric study allows to show the importance of the concrete layer on the top of the EHF to store energy and consequently shift the consumption. Especially, in considering an off-peak period from 8:00 PM to 6:00 AM, this study shows that the EHF is able to completely shift the consumption of the day to the off-peak period from 8 cm of concrete. Moreover, the results show that the insulation thickness on the back allows to decrease the consumption and to have a longer acceptable TC. Thus, it may be possible to decrease the concrete thickness with an increase of the insulation thickness. Finally, it appears that the addition of a layer of insulation on the top increases significantly the proportion of heat loss to the ground.

However, it is important to notice that these results are only average in all rooms. Then, if one looks at the results room by room, one can see significant differences. Indeed, if the reference case is used, TC is provided without problems until around 23:00 in fact in 5 of 7 rooms. However, for two zones (both on corners so with a large amount of loss, one oriented in the north and the other in the east), an acceptable TC is provided only respectively until 18:51 and 16:00, because they have less solar gains than the other rooms. Thus, a control taking these losses and gains into considerations is required to achieve a better TC.

4. Conclusion

This paper investigates the possibility to shifting the load from the peak period to off-peak period in a cold climate using an EHF. To perform the simulations, a method to implement an EHF in TRNSYS is developed and validated. Then, an EHF is implemented in a typical residential house without basement. Parametric studies were performed to investigate the effect of the floor assembly on the EHF performance. Results show that:

- An EHF with the reference case is able to completely shift loads to the off-peak period.
- The insulation layer on the back allows to decrease loss to the ground, and then may allow to decrease the concrete layer thickness with the same TC.

- The concrete layer below the EHF does not have an impact on the system performance only until 6cm of concrete.
- The concrete layer above the EHF allows to store energy and to keep an acceptable TC during the day when the heating system is off.
- The insulation thickness on the top blocks the heat transfer to the room, thus increases loss to the ground

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