HYDRONIC RADIANT FLOOR FOR HEATING AND COOLING COUPLED WITH AN UNDERGROUND HEAT EXCHANGER: MODELING APPROACH AND RESULTS

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ABSTRACT

This paper explores the simulation of the thermal performance of a radiant floor for heating and cooling that is connected with an underground heat exchanger installed under the concrete floor of a house. In the heating season, an electric boiler is used to maintain the operative temperature at the set point value by varying the supply water temperature to the radiant slab. In the cooling season, the water from the radiant floor is circulated through an underground heat exchanger installed under the concrete slab. This water is then mixed with the return water, and it is supplied to the radiant slab. The system does not use energy for mechanical cooling. The paper presents also the sensitivity analysis of the model to the efficiency of underground heat exchanger and the mixing ratio between the water flow rate circulated through the underground heat exchanger and the water flow rate circulated through the radiant floor.

KEYWORDS

Simulation, radiant floor, heating, cooling, heat exchanger, underground.

INTRODUCTION

The designer of new multi-unit residential buildings in Lyon proposed the use of the radiant cooling floor to remove the heat from rooms in the summer. The cooling water is circulated through an underground heat exchanger that is installed in the soil under the basement floor. The heat removed from rooms by the radiant floor is rejected to the cooler soil. The designer had to prove by computer simulation that the indoor air temperature does not exceed 28ºC for more than 40 hours in one year. This approach is expected to satisfy the indoor thermal confort conditions in the summer without using energy for the mechanical cooling.

Several computer models were developed in the past for the simulation of a ground-coupled heat exchanger of geothermal heat pumps (e.g., Moujaes and Crowley 1988, Mohammad-zadeh et al. 1989, Hellstrom 1989, Safemazandarani et al. 1990, Deerman and Kavanaugh 1991, Lei 1993,Yuill and Mikler 1995, Muraya et al. 1996). Hollmuller (2002) developed a model for the simulation of the so called “Canadian well”, which brings outdoor air through an underground duct for preheating or precooling purposes, before the ventilation air is supplied in the house. In those models, the heat exchanger is assumed to be isolated from the underground floors or walls of the house under study.

Other models were developed in the past for the evaluation of heat transfer through the below-grade building components (e.g., Sullivan et al. 1985, Mitalas 1987, Bahnfleth and Pedersen 1989, Krarti et al. 1994, Beausolei-Morrison et al. 1995). Those models were not designed to include the interaction between the underground components of a house and a heat exchanger installed in the soil near the house.

Starting from this design approach, the authors explored the modelling of such a system in the TRNSYS environment. The modelling approach is presented in this paper. The thermal performance of such approach is estimated by using as a case study a typical house construction in Montreal.

CASE STUDY HOUSE

The model of the case study house is developed based on the form and dimensions of an existing house in Montreal area (Table 1). The thermal characteristics of exterior envelope are defined in such a way to comply with the prescriptions of the Model National Energy Code of Canada for Houses (MNECH 1997) (Table 2). The natural air infiltration rate was assumed equal to 0.15 ach on the ground floor, 0.05 ach in the basement. These values correspond, on average, to about 3 air changes per hour (ach) measured at 50 Pa pressure difference with a blower door. This is the average value of air leakage for new houses built in

Montreal area. The natural air infiltration rate in the attic is estimated at 0.3 ach.

Table 1 Surface area of building envelope of the case study house

Components	Area [m^2]
Walls above grade	170
Walls and floor below grade	142
Ceiling	93
Windows	15.7
Doors	8.2

The system operates in the heating mode between October 15 and April 30 to maintain the operative temperature of the ground floor space near the set point value of 20ºC. The system operates in the cooling mode between June 1 and September 30. There is neither heating nor cooling between May 1 and 31, and between October 1 and 14.

Table 2 Thermal resistance of different components of the building envelope

Components	Thermal resistance (m^2·K/W)
Above-grade walls	4.1
Walls in contact with ground	3.1
Intermediate floors	4.6
Floors in contact with ground	1.1
Attic-type roof	7.0

SIMULATION APPROACH IN THE TRNSYS ENVIRONMENT

Overall approach

The house is simulated, by using the TRNSYS environment (TRNSYS 2006), as a multi-zone building (Type 56) with the radiant floor defined as an active layer of the floor between the ground level and basement zones. The plastic pipes are embedded in the concrete layer, spaced at 150 mm on centers. A constant speed pump (Type 114) of 500 W is used for circulating the water to and from the radiant floor. The constant water floor rate and variable supply temperature to the floor are inputs to the active layer. Supply and return pipes are defined by using TYPE 31 (Pipe-Duct) to reduce fast variations in supply water temperature entering the radiant floor.

Type 701 (Basement conduction) is used to simulate the heat transfer between the basement floor/walls and the soil surrounding the house. The temperature of the inside surface T_{is} of each basement wall/floor in contact with the soil, as calculated by the TYPE 56, is input to TYPE 701, while the temperature of the outside surface $T_{out,surf}$ of each basement wall/floor, as calculated by TYPE 701, is input to TYPE 56. In the cooling mode only, the inside surface temperature of the basement floor, as calculated by TYPE 56, is first modified as presented in following section, and then becomes an input to TYPE 701.

In order to reduce the energy use for cooling in the summer, the water from the radiant floor is circulated through the heat exchanger under the concrete slab, it is mixed with the return water and then it is supplied to the radiant slab. In the heating mode, an electric boiler heats the water.

The model is developed using some available TYPES (14h, 16g, 23, 31, 56, 69b, 89e, 93, 114, 515, 701) plus a few new equations for calculations outside the available TYPES such as the control of supply water temperature entering the floor (T_{sup}, $T_{sup\text{-}cool}$, $T_{sup\text{-}heat}$) and the correction of the inside surface temperature of the basement floor in the cooling mode ($T_{is\text{-}new}$).

Simulations are carried out for three identical years, by using the weather data for Montreal in the EPW format (EnergyPlus 2006), in order to eliminate the impact of initial temperatures of the near-field, before results are recorded.

Heat transfer through basement floor and walls

Type 701 calculates the temperature of the nodes of a mesh that describes the near-field earth in contact with the house. At the boundaries between the near- and far-fields, the soil temperature is calculated, by using the Kusuda's correlation, in terms of the earth surface conditions (e.g., surface absorptance=0.5, annual mean surface temperature=6ºC, and amplitude of surface temperature=11ºC), the soil thermal properties and the depth. The following thermal properties of soil are used: the thermal conductivity is 1.5 W/(m·ºC), the density is 1800 kg/m^3 and the specific heat is 2.0 kJ/(kg·ºC).

The temperature at the earth surface is calculated from the heat balance at each node. The initial ground temperature at every node in the near-field is also calculated using the Kusuda's correlation. The soil in the near-field under the basement floor is simulated as being composed of seven layers. For instance, the first layer of soil under the concrete slab is composed of 25 control volumes, each one having the following dimensions: 3 m (length), 1 m (wide) and 0.1 m (height). The following layer has the height of 0.2 m, and the third layer the height of

0.4 m. The last layer (the seventh) has the height of 3 m and reaches the far-field boundary at the depth of 9.0 m.

The near-field is discretized as follows:

Nx-ext=4, Nx-adj=5, Nx-total=13,
Ny-ext=4, Ny-adj=5, Ny-total=13, and
Nz-ext=7, Nz-adj=3, and Nz-total=10.

The temperature distribution in the ground at the end of the first year is extracted from the output file *.Soil_out and copied on the input file *.Soil_in, which is then used for the simulation of the second year. The procedure is repeated for three identical years, and only the results for the last year are presented. Therefore the long-term influence of the heat added to or extracted from the ground on the soil temperature is taken into account.

Supply water temperature to the radiant floor

The supply water temperature to the active layer of the radiant floor is controlled as follows:

a) In the heating mode:
$T_{supply} = T_{s,heating}$ (1)

b) In the cooling mode:
$T_{supply} = T_{s,cooling}$ (2)

c) When there is neither heating nor cooling provided by the floor system:
$T_{supply} = T_{s,noHC}$ (3)

The required supply water temperature in the heating mode is calculated as follows:

$T_{s,\ heating} = T_{sH} \cdot operath \cdot OnOffHeat$ (4)

In order to prevent that the supply water temperature, in the heating mode, is lower than the return water temperature, the following condition is defined:

$T_{sH} = \max(T_{return}, T_{s,control})$ (5)

T_{return} = the return water temperature from the radiant floor; it is obtained from TYPE 56 as TOFL 39 (fluid outlet temperature);
$T_{s,control}$ = the supply water temperature (the controlled variable) simulated by TYPE 23 (PID Controller); it has values between 30ºC and 40ºC; $T_{s,control}$ is calculated in terms of the set point of operative temperature T_{op} for heating (e.g., 20ºC) and the calculated operative temperature of the ground floor zone, as estimated by TYPE 56. The TYPE 93 (Input Value Recall) is used to add one hour delay to the controller (TYPE 23):

$T_{op}(k) = T_{op}(k-1)$ (6)

operath =hoursch·seasonheat; it is equal to 1 if the system is in the heating mode, and 0 if it is not; in a similar way, *operatc* is equal to 1 if the system is in the cooling mode, and 0 if it is not;

hoursch indicates the hourly schedule, as defined in TYPE 14h (Time Dependent Forcing Function);

seasonheat indicates those days, over a 12-month period, as defined in TYPE 515 (Heating and Cooling Season Scheduler), when the system is in the heating mode; *seasoncool* indicates those days when the system is in the cooling mode;

OnOffHeat = (1-*hoursch·seasoncool*)·LE(T_{op}, 20); it is equal to 1 when the system is in the heating mode and the indoor operative temperature is less than 20ºC; it is equal to 0 when the system is in the heating mode and the operative temperature is equal to or greater than 20ºC, or when the system is in the cooling mode.

The supply water temperature in the cooling mode is calculated as follows:

$T_{s,cooling} = T_{sC} \cdot operatc$ (7)

In order to prevent that the supply water temperature, in the cooling mode, is greater than the return water temperature, the following condition is defined:

$T_{sC} = \min(T_{return}, T_{sCool})$ (8)

T_{sCool} = the temperature of mixed water between the water leaving the underground heat exchanger and the water returned from the radiant floor:

$T_{sCool} = \alpha \cdot T_{sCHEX} + (1-\alpha) \cdot T_{return}$ (9)

α = ratio between the water flow rate circulated through the underground heat exchanger and the water flow rate circulated through the radiant floor;
T_{sCHEX} = the water temperature leaving the underground heat exchanger; it depends on the temperature of water entering the heat exchanger (T_{return}), the soil temperature (T_{soil}) around the heat exchanger, and the average sensible efficiency (e.g., η=0.4) of the heat exchanger:

$T_{sCHEX} = T_{return} - \eta \cdot (T_{return} - T_{soil})$ (10)

The supply water temperature during those days when the system is neither in the heating nor in the cooling mode is calculated a follows:

$$T_{s,noHC} = T_{return} \cdot (1\text{-}operath \cdot OnOffHeat\text{-}operatc) \quad (11)$$

Soil temperature around the underground heat exchanger

In this study, a simplified approach is used to estimate the soil temperature T_{soil} around the underground heat exchanger. The calculations are performed using only the outputs from TRNSYS, without changes to the source code of available TYPES or the development of a new type. Under these conditions, the temperature of the first layer of soil under the basement floor, where the underground heat exchanger is installed, is assumed to be almost equal with the average outside surface of the concrete slab:

$$T_{soil}(k) = T_{out,surf}\,(k-1) \quad (12)$$

$T_{out,surf}$ is calculated by TYPE 701 from the heat balance at the outside surface of the basement floor by considering the heat loss from the basement, and the heat transfer between all layers in the near-field. In addition, the heat balance must include the heat released in the first layer of soil by the underground heat exchanger (Q_{water}). Since the heat flow rate removed from the water circuit cannot be numerically added to the control volumes of the soil, without changing the code, the following approximation is used in this paper. The inside surface temperature (T_{is}) of the concrete slab, which is calculated by TYPE 56 at time k, is modified by taking into account the increase of temperature of the soil due to the heat lost by the circulating water in the heat exchanger:

$$T_{is}(k)^* = T_{is}\,(k) + \Delta T_{is} \quad (13)$$

$$\Delta T_{is} = Q_{water}/(m_{soil} \cdot c_{p,soil}) \quad (14)$$

$$Q_{water} = m_{water} \cdot c_{p,water} \cdot \eta \cdot (T_{return}(k-1) - T_{out,surf}\,(k-1)) \cdot operatc \quad (15)$$

$c_{p,water}$ = specific heat of water, J/(kg·°C);
$c_{p,soil}$ = specific heat of soil, J/(kg·°C);
m_{soil} = mass of the first layer of soil under the basement floor, in kg;
m_w = mass flow rate of water circulated through the underground heat exchanger, in kg/s;

$$m_w = \alpha \cdot m_{w,floor} \quad (16)$$

$m_{w,floor}$ = mass flow rate of water circulated through the radiant floor, kg/s; it is also equal to the pump water flow rate.

The new temperature T_{is}^* will affect the temperature of the outside surface of the floor $T_{out,surf}$ and the soil temperature T_{soil}, which finally will affect the heat exchange between the heat exchanger and the soil.
The modified temperature (T_{is}^*) is input to TYPE 701, where the outside surface temperature and the corresponding soil temperatures are estimated.

DISCUSSION OF RESULTS

Some results of the simulation are presented as examples in this section. In the base case scenario, the average sensible efficiency η=0.4, α =0.4, the mass flow rate of water circulated through the radiant floor $m_{w,floor}$=0.17 kg/s, and the simulation time step Δt=0.25 hr.

The operative temperature T_{op} is above 20ºC most of time in the heating mode, while in the cooling mode is kept below 28ºC without mechanical cooling (Figure 1). The maximum supply water temperature in the heating mode is 40ºC, while in the cooling mode is between 16.1ºC and 19.6ºC.

For comparison purposes, it is now assumed that the water is not circulated through the underground heat exchanger (α=0), however, the same water flow rate (as in Figure 1) is circulated by the pump through the radiant floor. As expected, the operative temperature exceeds the maximum value set at 28ºC (Figure 2).

The supply water temperature, in the cooling mode, is 27.8±1.5ºC when there is no water circulated through the underground heat exchanger (α=0), and it is 16±0.4ºC when α=0.7. In the base case scenario (α=0.4), the supply water temperature is 18.3±0.5ºC.

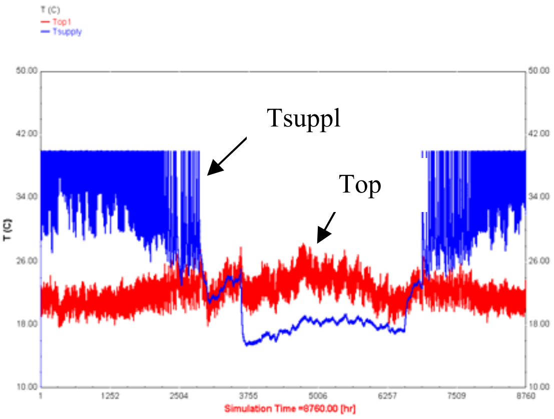

Figure 1 Supply water temperature to the radiant floor versus operative temperature of the ground floor zone (η=0.4 and α =0.4).

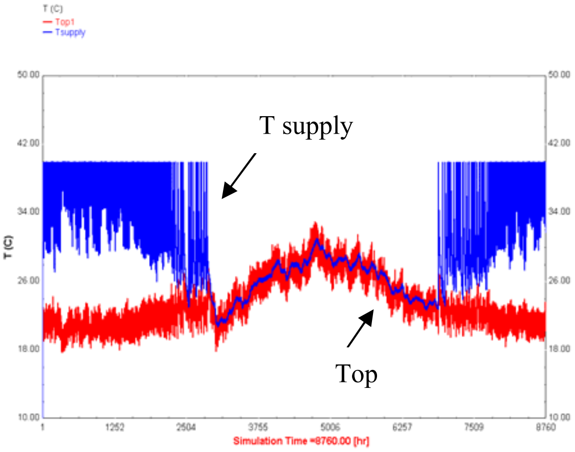

Figure 2. Supply water temperature to the radiant floor versus operative temperature of the ground floor zone (η=0.4 and α =0).

The following figures present only the simulation results during the cooling mode, that is, between hour 4300 and hour 6300 of the annual simulation.

The water mass flow rate circulated through the underground heat exchanger, in the cooling mode, has a significant impact on the operative temperature of the ground floor zone. When α=0, the operative temperature is 27.7±2.1ºC (Figure 3), while the operative temperature is 22.8±1.7ºC when α=0.7. In the base case scenario (α=0.4), the operative temperature is 23.8±1.7ºC.

As expected, the model is sensitive to the average sensible efficiency (η) of the underground heat exchanger (Figure 4). The increase of the efficiency η leads to the decrease of temperature of the water supplied to the radiant floor. The supply temperature is 18.3±0.5ºC at η=0.4, and 16.9±0.4ºC at η=0.6, both estimated at α=0.4.

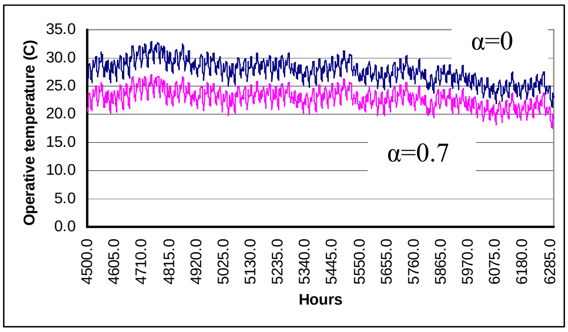

Figure 3. Operative temperature of the ground floor zone in the cooling mode (η=0.4, and α=0 vs α=0.7).

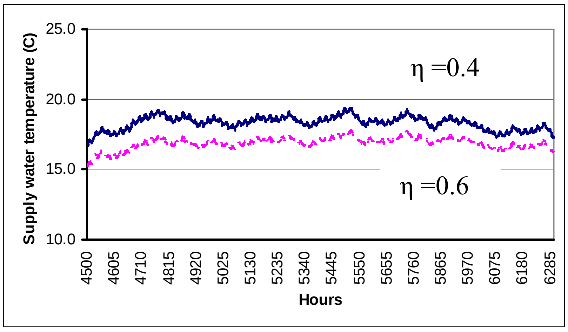

Figure 4. Supply water temperature in the cooling mode (α=0.4, and η=0.4 vs η=0.6).

The difference between the water temperature that is supplied to the radiant floor, over the whole the cooling season, and the temperature of the outside surface of the basement floor is 4.3±0.5ºC for the base case scenario (Figure 5). The average difference between the outside surface temperature of the basement floor and the temperature of the first layer of soil under that floor is 0.33ºC (Figure 6). Therefore, the assumption used in the calculation of the underground heat exchanger is acceptable: the temperature of the first layer of soil under the basement floor is almost equal with the average outside surface of the concrete slab.

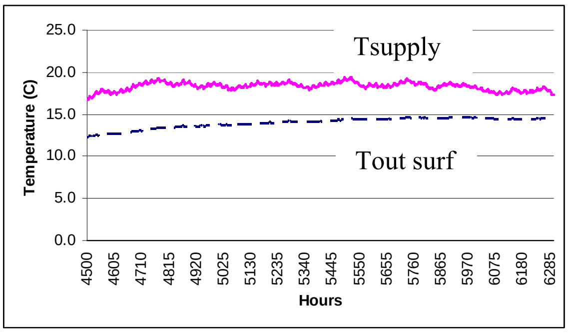

Figure 5. Supply water temperature versus outside surface temperature of the basement floor in the cooling mode (α=0.4 and η=0.4).

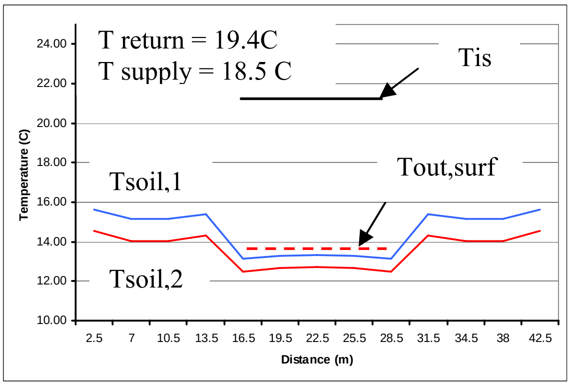

Figure 6. Comparison of the basement floor temperatures and the temperature of the first two

layers of soil under the floor at hour 5000 (α=0.4, η=0.4).

CONCLUSIONS

This paper presented the approach used for simulating in the TRNSYS environment of a radiant floor for heating and cooling coupled with an underground heat exchanger. The results indicated that it is possible to keep the operative temperature in the summer, in the case study house located in Montreal, within thermal comfort conditions without using energy for mechanical cooling.

The improvement of present model, for instance for the underground heat exchanger, will be the scope of future work. Future work will also explore the optimization in terms of energy consumption and cost of several design alternatives (e.g., air-to-water and water-to-water heat pumps, gas-fired boiler).

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