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SIMULATION STRATEGY AND SENSITIVITY ANALYSIS OF AN IN-FLOOR RADIANT HEATING MODEL

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ABSTRACT

Heating Canadian homes is an energy intensive endeavour. Factors such as the northerly climate and dispersed population cannot be avoided but inefficiencies with heating system design can. The mismatch between the grade of heat required to heat a home and that produced by conventional heat sources results in large amounts of wasted energy and exergy. Low–grade heating sources, such as ground source heat pumps, when combined with low-temperature distribution systems offer a more suitable and efficient means of heating homes. Using whole building simulation to analyse the feasibility of in-floor radiant heating for use with a low-grade heating system is the focus of this study.

The goal of this research was to create and verify a means of modelling in-floor, radiant heating within the building simulation program ESP-r's building thermal domain, and to utilize this model to provide a sensitivity analysis comparing the temperature and end-use energy requirement profiles of in-floor radiant and forced air systems under various control scenarios. The findings show that an approximate procedure for modelling in-floor radiant heating is an effective tool for residential heating system comparison as well as for studying the feasibility of a low-temperature residential HVAC system.

INTRODUCTION

Due to its northerly climate and the prevalence of single-family dwellings, the Canadian residential sector is responsible for as much as 20 percent of the national end-use energy consumption, and 18 percent of greenhouse gas (GHG) emissions. More than 80% of this consumption is for space and domestic hot water heating, and fossil fuel (primarily natural gas and oil) based combustion systems or electricity are commonly used for these purposes (NRCan 2003). Conventional combustion-based technologies that utilize fossil fuels to condition homes emit GHGs, as well as generating high combustion temperatures (e.g. 2000°C for natural gas). These temperatures are excessive for residential energy demands that require heat at temperatures of 60°C or less. The large discrepancy between the temperatures of heat supply and demand results in high exergy losses and thus, wasted potential. Because the demand for heat in buildings is in the low temperature range, low-grade heat sources are thermodynamically adequate to supply heating to buildings. The use of low temperature heat generation and supply systems integrated with renewable energy generation present an opportunity for low exergy and emission energy supply for the residential sector, resulting in end-use energy conservation and GHG emission reductions. To assess the technical feasibility and performance of such integrated systems, a whole building simulation is necessary.

The work described here is a component of a larger project that will assess the feasibility of a proposed low emission residential energy system. The system has been designed to provide residential heating (both space and DHW preheating) via a ground source heat exchange loop and heat pump which is then distributed by radiant heating (see Figure 1).

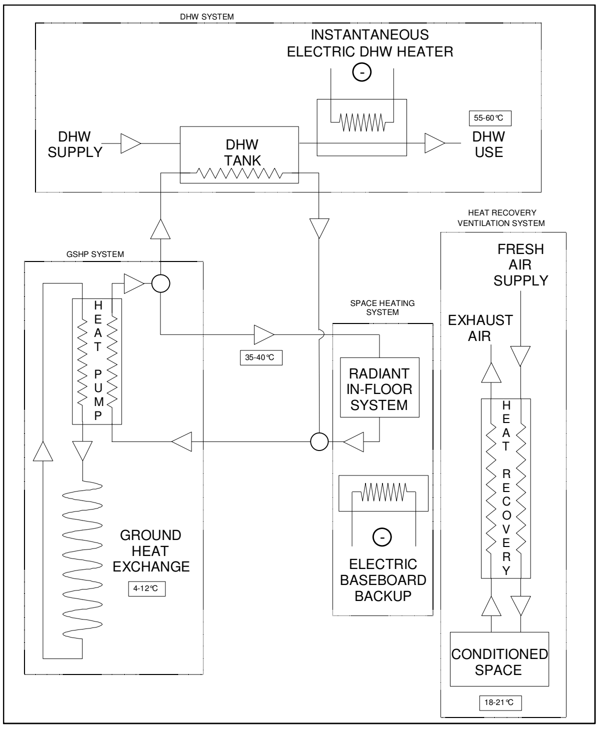

Figure 1: Schematic of Proposed Hybrid HVAC System

An essential component of the low exergy and emission HVAC system is the hydronic, in-floor radiant energy distribution system. The in-floor radiant system provides a means of supplying low-grade heat to the conditioned spaces via a network of pumps and nested tubing, and may offer improved thermal comfort and potentially lower overall end-use energy requirements.

This paper discusses the procedure that was developed to model an in-floor radiant heating system within a whole building environment. A sensitivity analysis was performed to assess the impact of various construction parameters and control strategies on the comfort and heating requirements of a residential building.

SIMULATION DESIGN

The in-floor heating system modelling procedure described in this work was created within a developmental version of CANMET Energy Technology Centre's (CETC) ESP-r/HOT3000 building simulation program. The HOT3000 software developed for the modelling and design analysis of the Canadian housing market uses ESP-r as its simulation engine (Haltrecht et al. 1999). This platform was chosen as a result of its powerful energy flow modelling capabilities. Through a series of finite-difference nodes representing air volumes, solid-fluid interfaces (such as wall and window constructions) and plant components, the simulation engine is capable of solving the heat balance and flows throughout an entire building. The zones are linked with a series of networks describing individual domains (i.e. plant, building, flow). This multi-domain approach allows the modeller the freedom of varying the level of complexity of both the model and the solution. As well, ESP-r offers the modeller improved freedom and flexibility in building design by way of its open source code. The evolving code continues to expand ESP-r's modelling capabilities from the original kernel developed by ESRU (Energy Systems Research Unit) at the University of Strathclyde. This development has been extensively documented and validated (ESRU 2000, Strachan 2000, Clarke 2001).

Residential Building Model

The residential building model used for this analysis is based on the Canadian Center for Housing Technology (CCHT) test houses in Ottawa. The houses were built according to R-2000 design standards and replicate common occupancy schedules. For a more thorough description of the construction and operation of the CCHT houses refer to Swinton et al. (2001). The CCHT test house was used in the simulations to assess the feasibility of in-floor radiant heating systems because it accurately represents a commonly encountered, modern, energy efficient Canadian home successfully modeled within ESP-r (Purdy & Beausoleil-Morrison 2001). The version of the model used for this analysis partitioned a set of zones representing a basement, main-floor, garage, second-floor, and attic totaling 210 m^2 of livable area. A skeletal model of the house is shown in Figure 2.

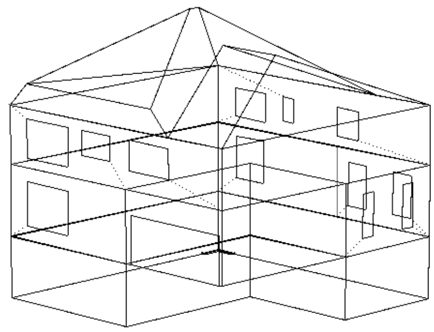

Figure 2: ESP-r Model of CCHT Test House

The occupied zones (main and second floor) were ideally controlled to achieve a set-point temperature of 21°C during the day (8am to 8pm) with a night temperature setback to 18°C. The remaining zones in the model were left to react uninhibitedly (free float) with the adjacent zones and exterior environment. The original HVAC system for the house comprised of a natural gas fired, high efficiency (91%) furnace system with a forced air, ducted distribution system supplying warm air directly to the conditioned zone. This configuration was used as the base case for which the low-temperature radiant in-floor model could be compared.

In-Floor Radiant Heating Model

Many models have been developed that successfully simulate radiant heating, ranging from detailed descriptions of piping networks and flow characteristics to generalized approximations. Elaborate models have been developed for the design and analysis of radiant heating system construction and control (see Athienitis & Chen 1993, Kilkis et al. 1995, Simmonds 1996). Although powerful for design, these autonomous models do not allow the modeller to monitor the performance of a radiant system when coupled with other HVAC systems, construction or control scenarios. For this type of analysis, coupling radiant models with whole building simulation software is necessary (see Stetiu et al. 1995, Strand & Pederson 2002). Within the ESP-r modelling environment, a two-dimensional analytical model developed by Laouadi (2004) has recently been incorporated into the plant modelling environment. This model, because of its inclusion in the plant network, was incompatible with other models essential to the design of the proposed energy system (ie. ground source heat pump) available only within ESP-r's building thermal domain. As a result a technique needed to be devised to simulate in-floor radiant heating that was compatible with the building thermal domain.

The method used to model the in-floor radiant heating system approximated the area occupied by the imbedded piping (the conduit for heated circulating water) with a thin, empty zone. This approximation permits heat to be injected into the air-point of the "fictitious" zone while being controlled by the heating requirements of the zone above. This approach allows for heat to be injected in a similar manner to typical in-floor heating systems as well as maintaining accurate floor construction and thermal mass characteristics to simulate appropriate time lag.

Chun et al. (1999) employed a similar technique for simulating radiant in-floor systems for a large, multi-unit apartment building. It was recommended by ESP-r modellers (Hand 2004) that similar success could be achieved for a residential building using ESP-r's existing heat transfer modules. The ability to simulate radiant heating within ESP-r's thermal domain was exemplified by Haddad (2003) upon successful completion of a series of radiant heating and cooling test cases (RADTEST) outlined by the International Energy Agency (Achermann & Zweifel 2001). The tests maintained imbedded zones at a constant temperature with ideal control and monitored the radiant heat transfer characteristics.

Unlike the constant temperature model, the modelling of the radiant in-floor heating system for this study required the development of an "injection zone" model as well as a control strategy that allowed for heat to be injected into the fictitious zones when required by the thermal comfort demands of the adjacent controlled zones.

Injection Zone Construction

Two fictitious zones were used to modify the simple floor model in order to incorporate the effect of in-floor radiant heating. The zones were inserted into the floor constructions below the main and second floors. The layer that typically consists of the heating coils was replaced by a separate thin zone of air. As the tubing for radiant heating is commonly encased in gypcrete (a gypsum-based, cement underlayment), the fictitious injection zone is thus embedded between two layers of gypcrete, each representing half of the 32 mm (1-1/4") thickness recommended by manufacturers (Maxxon 2004). Increasing or decreasing the thickness of the gypcrete layer above the injection zone allows the modeller to vary the thermal mass of the floor. The injection zone itself was set to a thickness of 10mm with the upper surface attribute representing half of the flooring construction and the bottom the other half as shown in Figure 3.

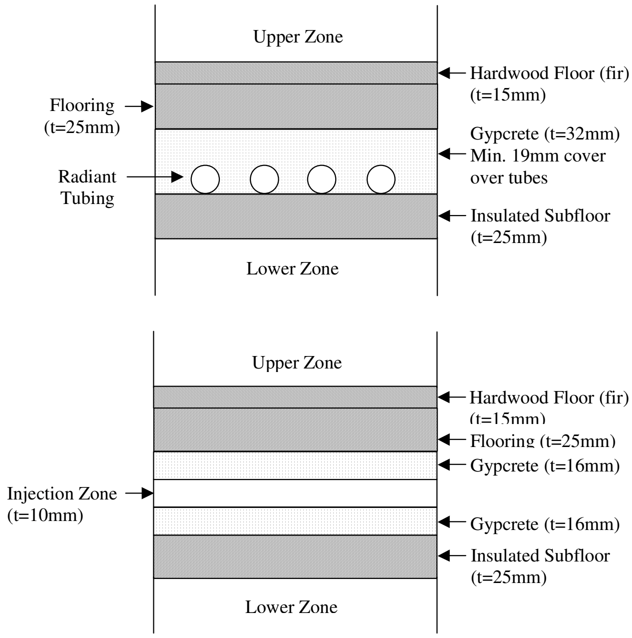

Figure 3: Common Wood Flooring Over Radiant Floor Heat Detail (top) and Diagram of Modelled Injection Zone and Flooring (bottom)

The edges of the zone were set to be adiabatic to eliminate heat loss to the exterior environment. Increased insulation values in the subfloor ensured that heat was transferred to the temperature controlled zone above.

Control Strategy

The ideal control law employed by both the base case scenario as well as Haddad's constant temperature radiant floor (Haddad 2003) were not applicable to the dual zone control required by the current model. An alternative control strategy was required that would allow heat to be injected into the fictitious zone as required by the separate controlled zone.

The proportional, integral, derivative (PID) control law within ESP-r allowed for the desired scenario where the control sensor is in a separate zone than the control actuator. In the case of this simulation, the need for heat injection was sensed in the air point node of the main and second floors, and the controller was actuated in the air point node of the corresponding fictitious injection zones located within the floor construction (see Figure 4). The sensor could be configured to monitor both the dry bulb temperature (DBT), the mean radiant temperature (MRT), or a combination of the two.

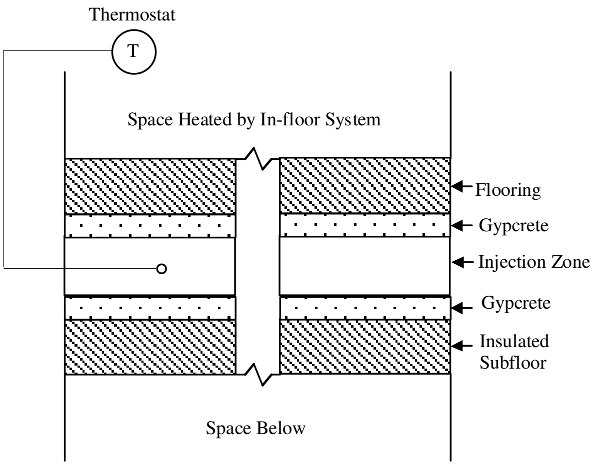

Figure 4: In-floor Heating Injection Control

PID Control

PID control is a feedback controller that determines an output based upon the error between a user-defined set point and a measured process variable. The PID controller was employed to provide faster response to the occupant thermal demands while reducing the amount of over and under heating. By manipulating or "tuning" the proportional band (PB), integral time (IT) and derivative time (DT) gains, the error can be reduced to better match the desired temperature profile in the controlled zone(s). Tuning a PID controller can be a non-trivial task, however, this task was simplified by following starting points and degrees of stability recommendations made by MacQueen (1997) for tuning ESP-r controllers.

In addition to manipulating the gain values, the PID control is also sensitive to the length of the simulation time step and width of throttling range. To operate the PID controller effectively, the simulation must operate on a short time step; otherwise overheating can occur. For this reason, a time step of one simulation per minute (the highest resolution possible within ESP-r) was chosen for this project. Both over and under heating are also possible if the throttling range is too wide or narrow. A sensitivity analysis revealed an acceptable width of 1°C. A complete list of the "tuned" PID control values is shown in Table 1.

Table 1: PID Controller Values

PID GAINS	
Proportional	0.5
Integral	200 sec.
Derivative	500 sec.
PID CONTROL VALUES	
Time Step	1 sim/min
Throttle Range	1 °C

Model Operation

To determine the accuracy of the proposed modelling approach, a simple control scenario was simulated for a typical week in the heating season to compare the forced air and in-floor radiant systems. With a temperature control scenario fixed at a zone dry bulb temperature of 21°C the end-use energy consumption for the radiant system (3230 MJ) was within 10% of that for the conventional furnace system with forced air heat distribution (2950 MJ). The accuracy is further validated by comparing the temperature control offered by the two systems, as shown in Figure 5 for a 24 hr period.

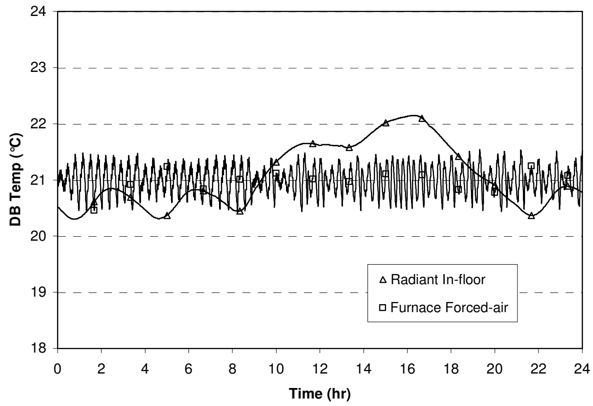

Figure 5: In-floor & Forced Air System Temperature Profiles for Constant Temp. Control Scenario (Ottawa, Jan 9th)

The radiant in-floor system offers a smooth temperature profile but is less able to respond to thermal gains (evident by the temperature rise between 10 am and 6 pm). When the thermal mass of the in-floor system is heated by thermal gains, a longer time lag is required for the heat to be dissipated than for the more responsive forced air system. Strategies will be explored throughout this paper to compensate for this lag using more complex control scenarios.

SIMULATION ANALYSIS

The degree of precision offered by the shortness of the simulation time step allowed the performance of the controlled zones to be closely monitored. With this information, a sensitivity analysis to control zone temperature and end-use energy consumption was performed.

Temperature Control

Achieving accurate zone temperature control with in-floor radiant heating systems is often difficult due to the inherent time lag between the time when heat is actuated and when it is sensed. Initial simulation results for a typical heating day in Ottawa with a night setback control strategy (Figure 6), show that over three hours elapse from the time the heating system has been initiated in the morning until the daytime setpoint temperature has been achieved.

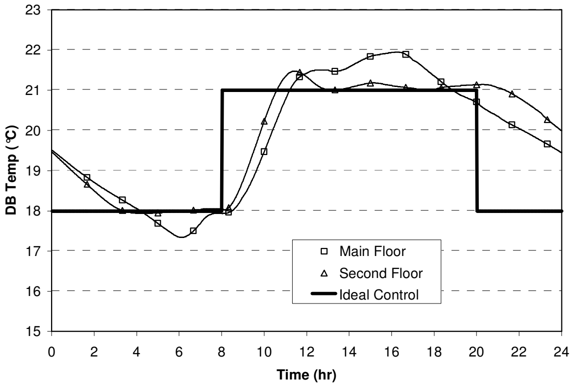

Figure 6: In-floor Heating for Main & Second Floors (Ottawa, Jan 9th)

This large time lag is a result of the thermal mass of the radiant heating system. This is clearly evident in the corresponding scenario in which the gypcrete layer is modified to alter the system's thermal mass. Figure 7 compares the temperature profiles of the original thermal mass (OTM) scenario with a high and low thermal mass scenario (HTM and LTM) in which the gypcrete layer was expanded to 100mm and contracted to 1mm respectively.

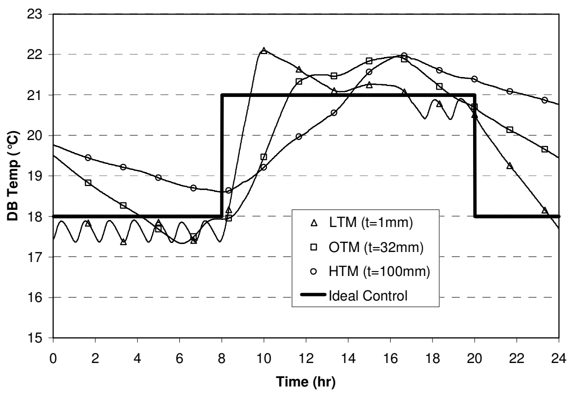

Figure 7: Low, Original, & High Thermal Mass Scenarios for Main floor (Ottawa, Jan 9th)

By decreasing the thermal mass, the response is increased to within an hour. The LTM scenario although quick to react, exhibits a much higher propensity for temperature oscillations. The OTM scenario displays the dampened temperature profile afforded by heating with a thermal mass avoiding hot and cold spots, a large part of the appeal for radiant heating.

Predictive Control

To achieve a temperature profile that coincides with the desired thermal comfort profile, the control for radiant in-floor heating systems often employ a learning algorithm to predict and anticipate heating requirements (see Chen 2002 and Cho & Zaheer-uddin 2003). This logic was artificially induced in the current simulation by shifting the heating systems actuation schedule ahead to better match the occupant driven set point temperatures.

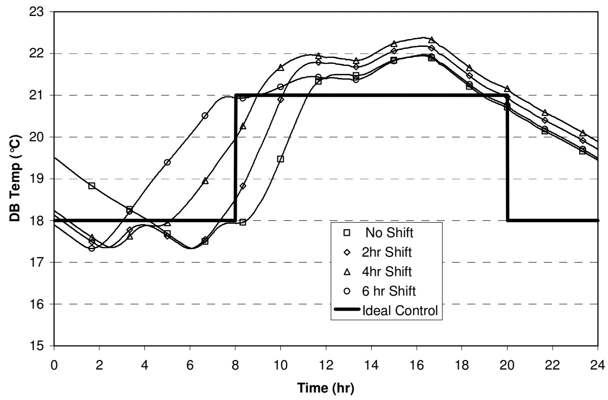

Figure 8: In-floor Heating Control Schedule Time Shift (Ottawa, Jan 9th)

In Figure 8 it can be seen that for a typical heating day the daytime setpoint temperature can be achieved at the desired time by shifting the control schedule ahead by four hours. The time shift does not significantly effect the setback phase (beginning at 8pm) as the simulated casual heat gains, representing occupant, lighting and equipment contributions, maintain an elevated temperature from 12 to 8pm regardless of control strategy.

Setback Control

Another technique utilized to avoid the time lag inherent with the heating of a high thermal mass system is to maintain the temperature of the zone at a constant level. To determine whether night setback control is feasible for the radiant system, the end-use energy savings afforded by lower setpoint temperatures at night must be weighed against the addition of an energy intensive reheat period. To determine the feasibility of this approach the zone temperature control (Figure 9) and the end-use energy consumption of the two techniques were compared.

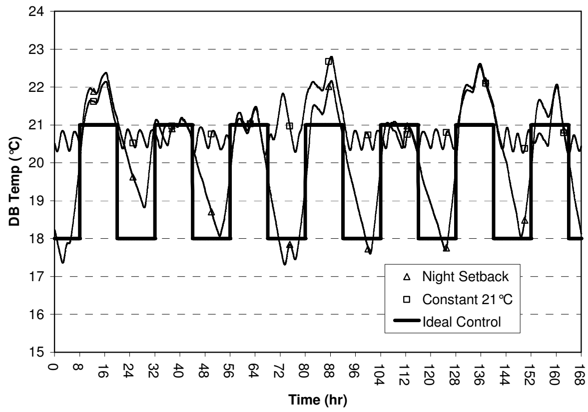

Figure 9: Temperature Profiles for Night Setback & Constant Control Schedules (Ottawa, Jan 9th-15th)

For a typical week in the heating season it was observed that the HVAC end-use energy consumption with night setback control was 3070 MJ, while the end-use energy consumption with the constant 21°C temperature control was 3230 MJ. These results show that even with a large thermal mass to reheat, the benefits of night setback still afford a modest end-use energy savings of 5 % when compared with the constant temperature control.

Floor Temperatures

To ensure that the temperatures of the injection zone do not rise to unacceptable levels the floor temperatures of the radiantly heated zones are monitored. ASHRAE (2000) recommends that floor temperatures do not exceed 29°C in order to maintain occupant comfort. It can be seen in Figure 10 that the floor surface temperatures for the proposed in-floor heating model are within the acceptable limits.

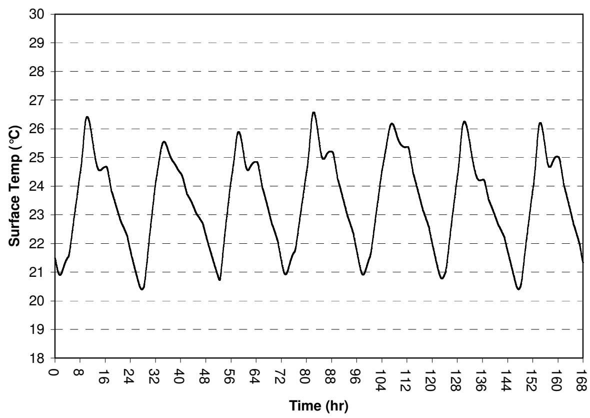

Figure 10: Surface Temperature of Floor for Second Level (Ottawa, Jan 9th-15th)

End-use Energy Consumption

A great divide exists in the literature determining whether in-floor radiant heat provides a means for reducing heating end-use energy consumption when replacing forced air systems (see Dale & Ackerman 1993, Carpenter & Kokko 1998, CMHC 2001, and Olesen 2002 for differing views). This study addresses the direct comparison of radiant and forced air systems. As well, methods were investigated for reducing radiant heating requirements such as including the sensing of MRT in addition to DBT.

Radiant vs. Forced Air Heating

To directly compare the performance of the in-floor radiant heating system with the CCHT base case scenario, the original forced air furnace system was modified to operate with an identical PID controller. Figure 11 illustrates the difference in zone temperature control for the two HVAC scenarios.

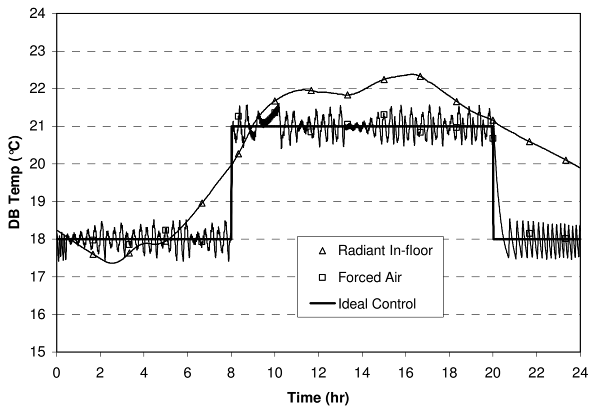

Figure 11: Forced Air & Radiant Temperature Profile Comparison for Mainfloor: DBT Sensed (Ottawa, Jan 9th)

Once again the radiant system offers a temperature profile with less oscillations, although it can also be seen in Figure 11 that even without cooling the forced air system is capable of maintaining a profile with little deviation from the set point temperature (particularly apparent at 12 and 5 pm). The zone temperature rise of approximately 1°C as a result of the building's evening casual gains highlight a concern of in-floor heating critics that the systems have a propensity for overheating because of the slower reaction times to mechanical, passive solar and occupant driven thermal gains.

The heating requirements of the two systems (including fan and pump power consumptions) for the duration of a typical heating week are shown in Table 2. Comparing the DBT sensor control it can be seen that the in-floor radiant system consumes 9.5 % more heating end-use energy than the base case.

Table 2: Comparison of Heating End-use Energy Consumption for Forced Air and Radiant Systems

HVAC TYPE	SENSOR TYPE	WEEKLY HEATING LOAD (MJ)	COMPARE TO BASE CASE (% DIFF)
Forced Air (base case)	DBT	2950	--
In-floor Radiant	DBT	3230	+ 9.5 %
	Operative	2620	- 11.2 %

DBT, MRT and Operative Temperature

For further analysis, this study also investigated the end-use energy consumption of both systems based on controlling the operative temperature. By sensing the operative temperature, importance for the level of thermal comfort is placed on both radiative and convective exchanges (ASHRAE 2001) and can be approximated for low air velocities by taking the average of the DBT and the MRT. Table 2 shows the results of this comparison. It can be seen that by considering the blackbody surface temperatures of a zone as well as the air temperatures, radiant systems can provide an end-use energy savings over forced air systems. By utilizing this practice for monitoring improved thermal comfort conditions in conjunction with the scenario outlined for this project a reduction in heating end-use energy requirements of more than 11.2 % was realized.

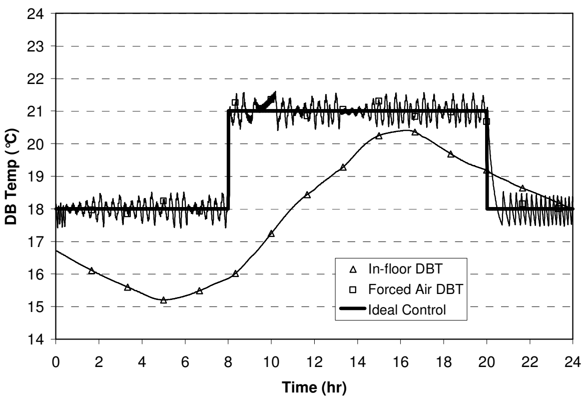

Figure 12: DBT comparison for Operative Temperature Sensed Scenario (Ottawa, Jan 9th)

As the MRT is a difficult indice to measure, and not often practicial for actual heating systems, the advantages of an increased mean radiant temperature are commonly realized by reducing the set point temperature. Therefore, a comparison of the corresponding DBTs for the two sensing indices is given. Figure 12 shows that when the comfort level of the in-floor system is simulated with the operative temperature indice, the air point DBT can be reduced by a few degrees celsius while still maintaining the same level of comfort as the forced air system.

CONCLUSIONS

This paper documents the implementation of a technique for simulating an in-floor radiant heating system within the building thermal domain of ESP-r. This model provides a good approximation of the thermal injection zone of floor embedded systems by utilizing the short time step and precise control of a powerful building simulation software.

This research was able to confirm some of the benefits of radiant heating such as its ability to provide an even temperature profile. It was also shown that a night setback control strategy can be utilized as a means of saving energy even with the thermal mass to reheat. Simulation of predictive control scenarios to compensate for the time lag caused by the inherent thermal mass of radiant systems were shown to be effective to more precisely meet the required thermal comfort levels. End-use energy consumption of the in-floor radiant and forced air system was found to be highly dependant on the environmental control indices. The forced air system required less heating energy under the dry bulb temperature control scenario but when the rationally derived indice, operative temperature, was sensed the opposite was found true. Despite the slight overheating due to slow reaction to thermal gains the in-floor radiant model exhibited an 11.2 % end-use energy savings over the base case scenario.

As well as for its comparative value, the model also establishes itself as a suitable simulation technique for low temperature HVAC applications. Monitoring of injection zone temperatures ensured that low temperature supply systems can be integrated with the in-floor radiant model as supply temperatures never exceed the capabilities of residential water-to-water ground source heat pumps. This estabishes the model's usefulness for future work with ground source heat pumps or other forms of low temperature heat generation aptly suited for residential heating.

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REFERENCES

Achermann, M., Zweifel, G. 2003. RADTEST – Radiant Heating and Cooling Test Cases, A

Report of Task 22, Subtask C Building Energy Analysis Tools Comparative Evaluation Tests, International Energy Agency, April 2003.

ASHRAE. 2001. 2001 ASHRAE Handbook – Fundamentals (Chapter 8).

Athienitis, A.K., Chen, T.Y. 1993. Experimental and theoretical investigation of floor heating with thermal storage. ASHRAE Transactions, v 99(1), p. 1049-57.

Carpenter, S.C., Kokko, J.P. 1998. Radiant heating and cooling, displacement ventilation with heat recovery and storm water cooling: an environmentally responsible HVAC system. ASHRAE Transactions, pp. 1321-26.

Chen, T.Y. 2002. Application of adaptive predictive control to a floor heating system with a large thermal lag. Energy and Buildings, v 34, pp. 45-51.

Cho, S.H, Zaheer-uddin, M. 2003. Predictive control of intermittently operated radiant floor heating systems. Energy Conversion and Management, v 44, pp. 1333-42.

Chun, W.C., Jeon, M.S., Lee, Y.S., Jeon, H.S., Lee, T.K. 1999. A thermal analysis of a radiant floor heating system using SERI-RES. International Journal of Energy Research, v 23, pp. 335-43.

Clarke, J.A. 2001. Energy Simulation in Building Design (2nd Ed). Butterworth-Heinemann, Oxford.

CMHC. 2001. Thermostat settings in houses with in-floor heating. Canadian Mortgage and Housing Corporation Research Highlights Technical Series, 01-106.

Dale, J.D., Ackerman, M.Y. 1993. The Thermal Performance of a Radiant Panel Floor-Heating System. ASHRAE Transactions, v 99, pp. 23-34.

ESRU. 2000. The ESP-r System for Building Energy Simulations: UserGuide Version 9 Series, ESRU Manual U00/1, University of Strathclyde, Glasgow UK.

Haddad, K. 2003. Modeller's Report: RADTEST – Radiant Heating and Cooling Test Cases, A Report of Task 22, Subtask C Building Energy Analysis Tools Comparative Evaluation Tests, International Energy Agency, April.

Haltrecht, D., Zmeureanu, R., Beausoleil-Morrison, I. 1999. Defining the Methodology for the Next-Generation HOT2000 Simulator. Proc. Building Simulation '99, Kyoto Japan, v 1 pp.61-68.

Hand, J. 2004. Personal communication forwarded by A. Ferguson, Aug. 13.

Kilkis, B.I., Eltez, M, Sager, S. 1995. A simplified model for the design of radiant in-slab heating panels. ASHRAE Transactions, v 99(2), pp. 210-16.

Laouadi, A. 2004. Development of a radiant heating and cooling model for building energy simulation software. Building and Environment, v 39, pp. 421-31.

MacQueen, J. 1997. The modelling and simulation of energy management control systems. PhD Thesis, University of Strathclyde, Glasgow.

Maxxon. 2004. Therma-Floor Data Sheet, Maxxon Canada. (http://www.maxxon.ca/product_detail)

NRCan. 2003. Energy Use Data Handbook, 1990 and 1995 to 2001. Cat No. M92-245/2001E. Natural Resources Canada, Ottawa.

Olesen, B.W. 2002. Radiant Floor Heating in Theory and Practice. ASHRAE Journal, July, pp. 19-24.

Purdy, J., Beausoleil-Morrison, I.. 2001. The Significant Factors in Modelling Residential Buildings, Proc. Building Simulation, 7th International Building Performance Simulation Association Conference, Rio de Janeiro, Brazil.

Simmonds, P. 1996. Practical applications of radiant heating and cooling to maintain comfort conditions. ASHRAE Transactions, v 102(1), pp. 659-65.

Stetiu, C., Feustel, H.K., Winkelmann, F.C. 1995. Development of a simulation tool to evaluate the performance of radiant cooling ceilings. LBNL-37300.

Strachan, P. 2000. ESP-r: Summary of Validation Studies, ESRU Technical Report, Energy Systems Research Unit.

Strand, R.K., Pederson, C.O. 2002. Modeling radiant systems in an integrated heat balance based energy simulation program. ASHRAE Transactions, v 108(2), pp. 1-9.

Swinton, M.C., Moussa, H., Marchand, R.J. 2001. Commissioning Twin Houses for Assessing the Performance of Energy Conserving Technologies. Proc. Integration of Building Envelopes, Performance of Exterior Envelopes of Whole Buildings VIII, Clearwater USA.