RADIANT PANEL FLOOR HEATING IN A NORTHERN CANADIAN CLIMATE

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The operating characteristics and energy efficiency of two versions of a hydronic radiant panel floor heating system and a forced air heating system were evaluated in a well instrumented passive test house. The panel systems studied consisted of two zones, main floor and basement, each controlled using an air temperature sensing thermostat. Both radiant panel systems as well as the forced air system utilized electricity as the primary energy source.

Based on total energy usage it was found that there was little measurable difference in the efficiency of the systems tested. Floor to ceiling air temperature profiles were found to be different with each system but the differences between systems were minor. Between 25 mm (1 in.) above the floor and 25 mm (1 in.) below the ceiling, temperature differences were less than 2°C (3.6°F) in all cases. One hour average globe temperatures were found to be higher with the hydronic radiant panel systems than with the forced air, 0.5°C (0.9°F) to 1°C (1.8°F) below air temperature. Globe temperatures during periods of panel operation were not high enough to lower air temperatures and maintain comfort conditions. Losses from the basement floor during periods of hydronic panel operation were found to be approximately 4 W/m^2 (1.3 Btu/hr-F), higher by 30% than when the forced air system was operated.

INTRODUCTION

Radiant floor panel heating systems are presently being installed in a number of new homes in Western Canada. The total number of installations is small by comparison with forced air, but interest in these systems appears to be increasing. Some information concerning the performance and comfort associated with radiant panel systems has been available from system manufacturers and installers, but few controlled studies have been undertaken to verify the information (Dale and Ackerman 1987). This study examines the performance of two commonly installed generic radiant panel systems in a well documented test house. The primary difference between the panel systems studied lies in the placement of the tubing used to carry heated water throughout each zone within the house. The first system studied utilized hot water tubes placed below the subfloor, between the floor joists, while the second had tubes laid over the subfloor and embedded in a gypsum based cement. The results obtained allow comparison of the performance of the systems with each other and against a conventional forced air heating system.

The radiant panel heating systems were installed in the passive test house at the Alberta Home Heating Research Facility. The research facility consists of six small uninhabited houses, each approximately 49 m^2 (528 ft^2) in main floor area with full concrete basements. Two of the houses, the Passive and the Reference house, were used in the evaluation of the radiant panel and forced air heating systems. The Passive house, as indicated in Table 1, is a well insulated structure with a south window area of 11 m^2 (118 ft^2), 22% of floor area. It was chosen for the present study because it represents the type of

Table 1. Test House Construction Details

Detail	Passive House	Reference House
Floor area (m^2)	49	49
Window Area (m^2)	12.3	5.7
South Window Area (m^2)	11.0	0
Full Basement	yes	yes
Insulation RSI (R)		
Ceiling	7.04 (40)	2.11 (12)
Wall	3.52 (20)	1.76 (10)
Basement Wall	1.76 (10)	1.76 (10) *
Basement Floor	0.88 (5)	none

* Insulated to 0.6m below grade

structure most difficult to control. Wide swings in internal energy requirements result from the large amount of south facing glazing. The insulation levels are similar to present Canadian building code requirements. In addition, one of the radiant panels incorporates a gypsum cement slab which would act as an energy storage medium within the passive structure. The Reference house is a moderately insulated structure which has not been modified since the construction of the facility in 1980. The use of a reference or control house is necessary as changes in energy usage of 20% on a seasonal basis have been observed when no modifications have been made to a structure. Details of the remaining test houses may be found in (Dale et al. 1980).

HEATING SYSTEM DESCRIPTION

The study was initiated with the installation of a simple two zone panel heating system shown in Figure 1. The main floor of the test house comprises one zone and the below grade basement area, the second zone. The upper zone panel was constructed using 12 mm (0.5 in.) polybutylene tubing, in three runs, each about 70 m (220 ft) in length. The tubes were placed in a serpentine design below the main floor, between the floor joists. The tubing was hung within the joist space and insulated from below using reflective foil and glass fiber insulation (RSI 2.11, R 12) as shown in Figure 2a. Two tubes were placed in each 400 mm (16 in.) joist cavity making the effective tube spacing about 200 mm (8 in.). Spacing was decreased to 150 mm (6 in.) under the south windows to offset increased heat losses in that vicinity.

The lower zone panel was also constructed using 12mm (0.5 in.) polybutylene tubing laid over RSI 0.88 (R 5) extruded polystyrene insulation and embedded in about 65-70 mm (2.5 in.) of self leveling gypsum based cement. A schematic of the installation is shown in Figure 2b. The tubing was installed over the insulation in order to reduce the back losses from the heated panel. Two runs of tubing, each approximately 70 m (220 ft) in length, were run over the floor in a serpentine fashion. Tube spacing was maintained at 300 mm (12 in.) over the entire floor by attaching the tubing to the insulation with plastic clips prior to embedment.

The initial system was operated for a heating season, after which the second variation of radiant panel system was installed. The second panel was installed by laying 12 mm (0.5 in.) polybutylene tubing over the floor and embedding in a 50 mm (2 in.) thick slab of gypsum cement as shown in Figure 2c. The tubing spacing was again maintained at 200 mm (8 in.), but reduced to 150 mm (6 in.) below the south windows.

The two radiant panel systems differ from one another only in the installation method for the upper zone tubing. All other components such as the electric boiler, pumps and zone controls were left unaltered. It was felt that embedding the tubes in gypsum cement would result in faster system response to changing loads due to better thermal coupling between the heated panel and the room air. It was also felt that increased amounts of

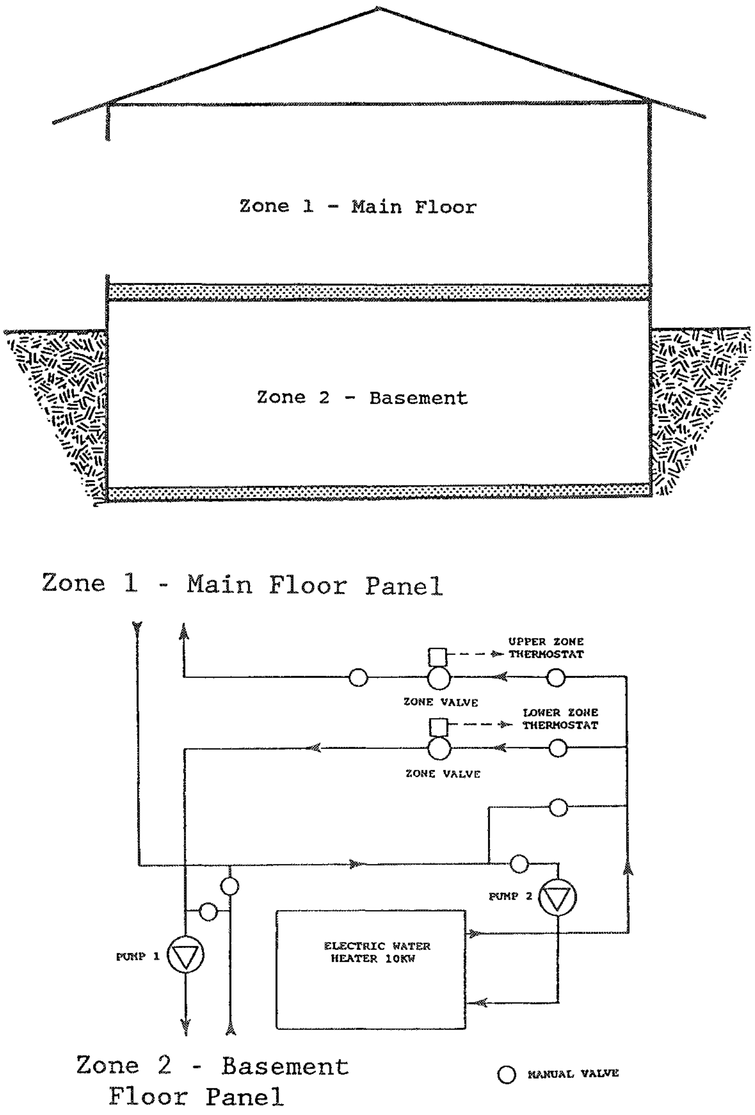


Figure 1. Schematic of Two Zone Radiant Panel Heating System

distributed mass in the form of a floor panel would result in reduced energy usage and fewer hours of overheat due to increased thermal mass. The reduction in overheat would be a very desirable result as excess energy must be either stored or removed from the structure to maintain comfort conditions.

The forced air heating system used for comparison purposes consisted of a fan unit, a conventional duct distribution system with floor diffusers and a 7.5 kW (25000 Btu/hr) electric duct heater.

Controls for both panel systems were basic, consisting of two air temperature sensing thermostats, one in each zone, and two zone valves as shown in Figure 1. Circulation was not maintained through the panels when the heating requirement, indicated by the thermostats, was zero. No attempt was made to minimize energy usage through night setback or control optimization as the objective was to evaluate the operation and performance of the generic panel systems relative to a conventional forced air heating

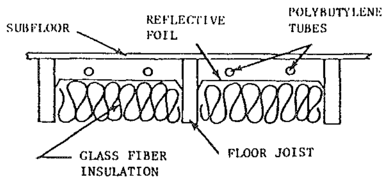


Fig. 2a Tubing Installation - Upper Zone

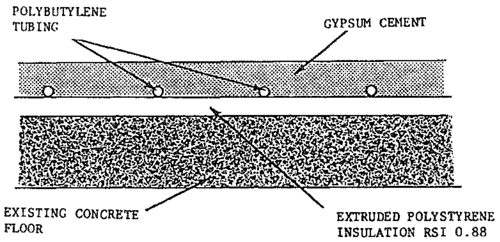


Fig. 2b Tubing Installation - Lower Zone

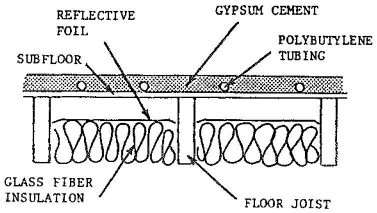


Fig. 2c Tubing Installation - Upper Zone, Embedded

Figure 2. Panel Construction for the Two Systems Evaluated

system. Control of the forced air system was accomplished using a single air temperature sensing thermostat. The circulation fan was left running continuously during periods of forced air operation to allow measurements of air infiltration rates using a constant concentration tracer gas system.

EXPERIMENTAL RESULTS

Total Energy Usage

Since both panel system variations utilized an electric water heater and the forced air system utilized an electric duct heater, measurement of total energy usage in the structure was straight forward. Electrical energy measured included heaters, lights, pumps and the computer system used to monitor the test houses. Normalization of the energy usage with integrated indoor-outdoor temperature difference and also with the energy usage of the reference house over identical time periods allowed direct measurement of the performance of each heating system. Normalization with the reference house, shown as Equation (1), eliminates seasonal variations which might otherwise bias the results towards a single heating system.

Relative Usage =

$$\frac{\left[\dfrac{\text{Energy usage of the Passive house}}{\text{Integrated indoor - outdoor temperature difference}}\right]}{\left[\dfrac{\text{Energy usage of the Reference house}}{\text{Integrated indoor - outdoor temperature difference}}\right]} \qquad (1)$$

Table 2 shows the results obtained with each heating system in operation. The first column in the table shows under what condition the testing was performed; which heating system was in operation and whether solar gains were allowed or excluded. Solar gains were excluded during parts of the testing by shading the south facing windows in order to change the load characteristics of the building. The remaining columns show the energy usage relative to the reference house during daylight periods, night periods and over the total test period. The data was split into day and night periods to assess the effectiveness of the 50 mm (2 in.) layer of gypsum cement added with the second panel configuration as a thermal storage medium.

During the first test period, the house was operated with the radiant panel heating system (tubes suspended under the subfloor) and solar gains were admitted to the structure. The day and night time energy requirements were 38% and 61% of the Reference house requirement and the overall usage was 52% of the Reference house. When the solar gains were excluded, both the day and night time energy usage increased quite dramatically. Day time energy usage rose to 82% of the Reference house while night time usage was 71% resulting in an overall energy usage increase of approximately 40%.

Operation of the forced air heating system with solar gains excluded led to results similar to those obtained with the initial panel system. Day, night and total energy usage were all lower than that obtained with the initial radiant panel system. Reductions in energy usage were small, ranging between 3 and 10%.

Table 2. Overall Energy Usage in the Test House With Panel and Forced Air Heating Systems

House Configuration	Energy Usage Relative to The Reference House		
	Day	Night	Total
Radiant Panel Heating - tubes in floor joist - no added mass - solar gains allowed	38	61	52
Radiant Panel Heating - solar gains excluded	82	71	74
Forced Air Heating - solar gains excluded	81	68	72
Radiant Panel Heating - embedded tubes - added mass - solar gains excluded	74	71	72
Radiant Panel Heating - embedded tubes - added mass - solar gains allowed	34	61	50

When the upper zone tubes were embedded in gypsum cement it was not expected that the energy usage would be altered during periods when the solar gains were excluded. It was quite surprising to find the day and night time energy usage almost identical at 74% and 71% of the Reference house. Total energy usage was essentially indistinguishable from results obtained with the forced air system, 72% of the Reference. When solar gains were again admitted to the structure it was felt that the additional mass would lead to a reduction in relative energy usage and potentially reduce the number of hours of overheat in the structure. As indicated in Table 2, the day time energy usage appears to have been reduced by 10% (compared to the radiant system with no mass added) while the night time usage remained unchanged at 61% of the Reference house. It had been expected that the added mass would alter both the day and night time energy usage.

Although it is not obvious why relative energy usage has not responded to the additional mass as expected, one point is abundantly clear. Given that the primary energy source and conversion efficiency is the same for the forced air and radiant panel heating systems, it appears that neither system has a real advantage in terms of overall efficiency. As will be shown later, it does appear that basement floor heat losses and ceiling heat losses are both higher when the radiant panel systems are operating giving the forced air heating system slightly lower energy requirements.

Zone Air Temperatures

Radiant panel heating systems have been said to produce a more comfortable thermal environment while at the same time, reducing energy usage because of warm floors and cool ceilings. Comparison of vertical temperature profiles were made by placing shielded thermocouples in a vertical row from floor to ceiling on both the upper and lower zones of the test house.

Measurements in the upper zone averaged over several weeks, are shown in Figure 3. The figure shows the difference between the temperature measured at any height above the floor and the temperature measured midway between the floor and the ceiling. Note that during the period of forced air operation the fan was left to operate continuously and as such the extremes in the vertical profile may have been reduced due to enhanced circulation. During periods of radiant panel operation the vertical temperature profile is extremely uniform, varying by less than 0.5°C (0.9°F) from very near the floor to the ceiling. The ceiling surface temperature is less than 0.5°C (0.9°F) cooler than the midheight air temperature. The floor surface temperature was found to be on average 2.8°C (5°F) warmer than the mid height air temperature but this result would depend on the thermal envelope characteristics and resultant operation time of the panel system.

During periods of forced air operation, both the upper and lower levels were cooler than the mid-height. The ceiling was found to be almost 2°C (3.6°F) cooler while the floor was approximately 1°C (1.8°F) cooler. It is surmised that the higher ceiling temperature during radiant panel operation is a result of the enhanced radiant exchange between the ceiling and heated floor.

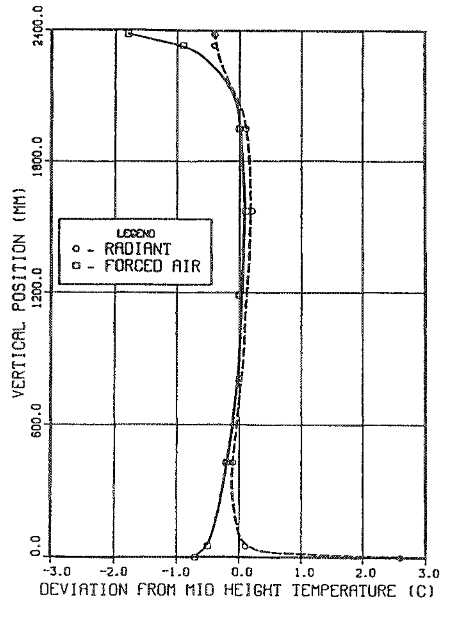
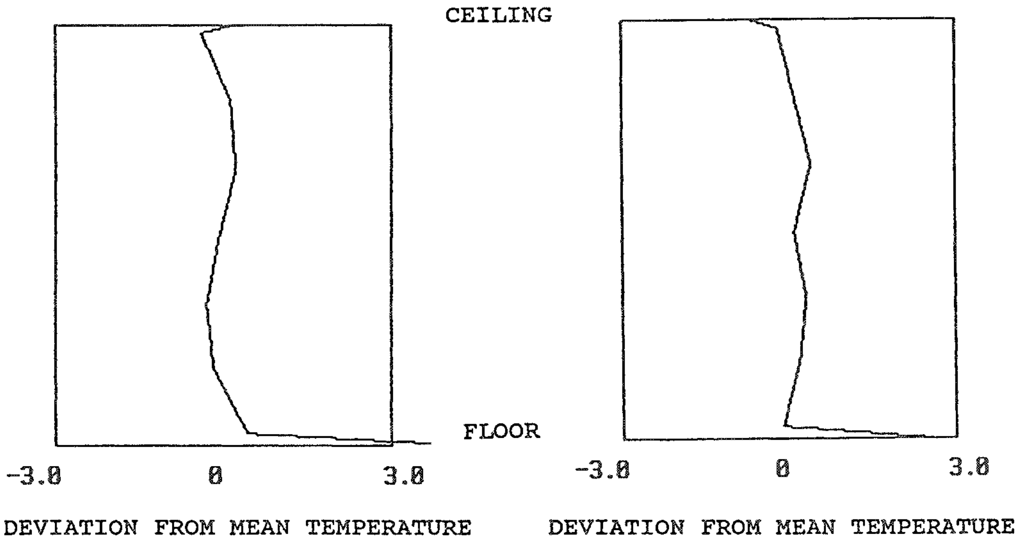


Figure 3. Air Temperature Measurements in a Vertical Floor to Ceiling Line, Radiant Panel and Forced Air Heating Systems

It was interesting to note that as the heating season progressed towards spring and the fraction of time that the panel system was in operation decreased, the on/off controls caused the temperature profiles to alternate between that obtained with the forced air system and that obtained with the panel system, both shown in Figure 3. Figure 4 shows the progression through one day. When the structure demand is satisfied and the heating system is off, the vertical profiles look very much like those obtained with the forced air system. When the thermostat calls for heat, hot water circulated through the slab raises the panel temperature resulting in the profile shown in Figure 4a. This profile is maintained over the system on period; during winter periods essentially throughout the night. When demand is satisfied the hot water circulation is stopped and the temperature profile changes to a more typical day time shape, Figure 4c. The period over which the change in profile occurs depends on the amount of radiation transmitted to the room during the day. In early evening, Figure 4d, the profile again changes shape due to a drop in the mean air temperature, as the house cools, while the slab remains warm with stored energy. Later in the evening the room air has cooled enough so that the thermostat calls for heat and the profile goes back to the typical shape seen during continuous system operation, Figure 4a.

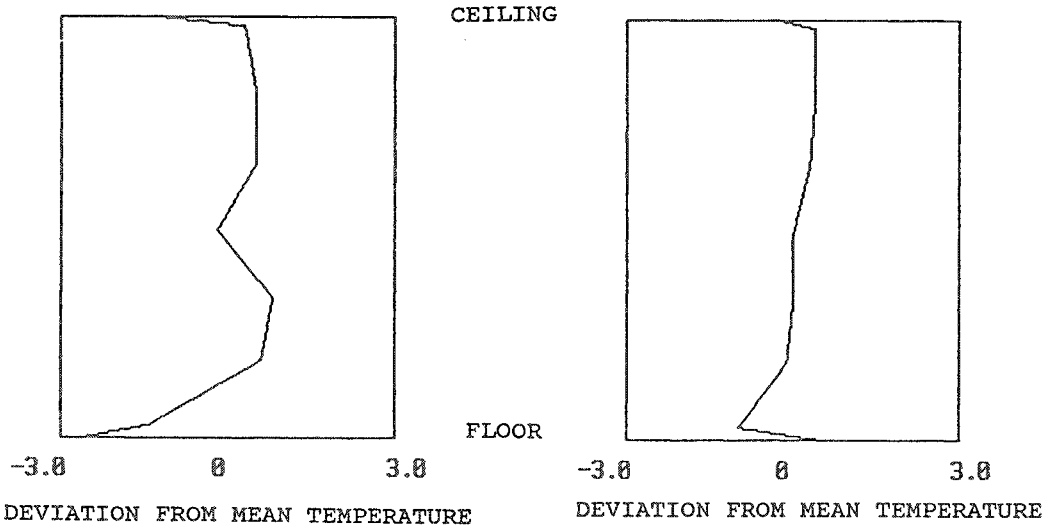
Vertical Air Temperature Profiles Near Windows

Forced air heating systems in Canada are generally installed with one floor diffuser located beneath each window in the house. The placement of the air outlets serves to keep windows free of excessive condensation during periods of cold ambient temperatures. Since the interior surface temperature of most windows is lower than room air during periods of cold weather, air near the window cools, moves down the wall below the window, and out across the floor. During periods of furnace operation, warm air exiting the diffusers in the vicinity of windows can



(a) Night - Early Morning

(b) Mid Morning



(c) Mid Afternoon

(d) Early Evening

Figure 4. Progression of Floor to Ceiling Air Temperature Profiles Over a Typical Day in March for a Radiant Floor Panel System

partially counter these cold air currents which might otherwise produce feelings of discomfort in occupants near the windows. Since the radiant panel systems have no air circulation fan, increased heat losses in the vicinity of the windows is compensated for by decreasing tube spacing below windows and it turn increasing panel output. Measurements of air temperature at locations very near the floor to a height of 350 mm (13.8 in.) were made using a string of 0.75 mm (.030 in.) diameter thermocouples. Measurements were made at 10 mm increments to a height of 50 mm (2 in.) and thereafter at

30 mm (1.2 in.) increments to a height of 350 mm (13.8 in.). Measurements were made using a computer controlled data acquisition system so that the 16 thermocouples could be sampled nearly simultaneously. The "rake" of thermocouples was placed at locations 300 mm, 600 mm and 900 mm (12 in., 24 in. and 36 in.) away from the window and measurements of vertical temperature profile made with either forced air or radiant panel systems operating. The location of the "rake" was chosen so that the plume of cold air falling off the window would not be actively mixed by flow from the diffuser but would only be mixed by bulk circulation within the room.

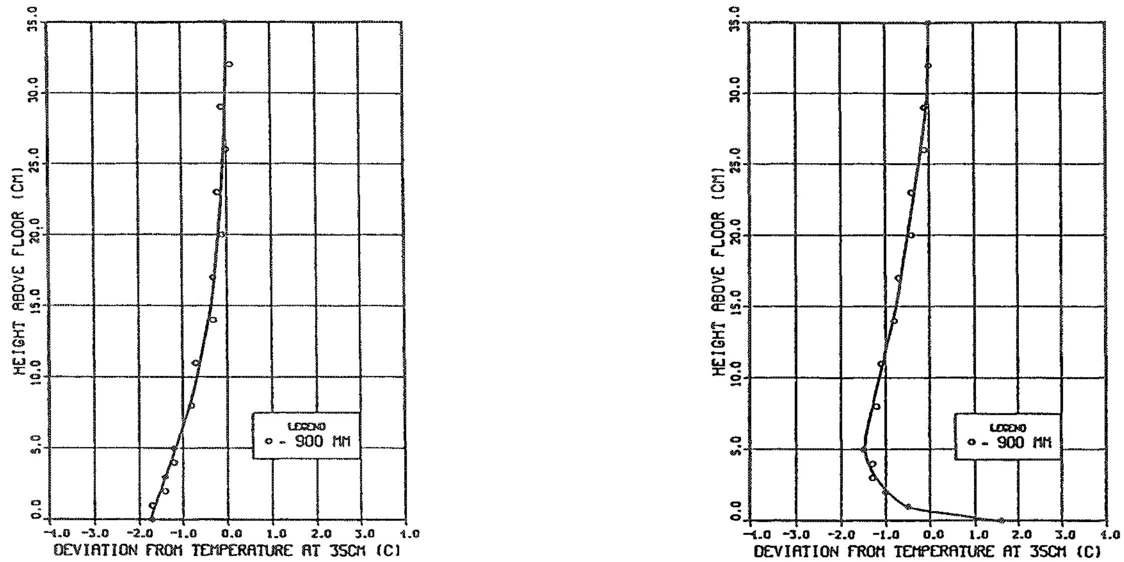
Figure 5a shows one week average vertical air temperature profile obtained at a distance of 900 mm (36 in.) from the window with the forced air system in operation. The average floor surface temperature near the window was significantly below the temperature at the 350 mm (13.8 in.) level of the rake with the effect only slightly less pronounced at a distance of 900 mm (36 in.) from the window. This would tend to indicate that the bulk flow within the room is not very effective in mixing the higher density cold plume produced by the windows. During the testing the furnace fan was allowed to run continuously.

Figure 5b shows measurements made at 900 mm (36 in.) from the window with the radiant panel system in operation. Again the measurements were collected for a period of approximately one week and the data used to calculate an average temperature profile. Although the profile shape is quite different near the floor due to the elevated floor surface temperature, above about 100 mm (4 in.) the profiles produced by both systems are very similar.

A closer examination of Figure 3, shown previously, indicates that the vertical temperature variation was reduced to less than 0.5°C (0.9°F) at 3.25 m (10.7 ft) from the window when the radiant panel system was in operation but was still very much in evidence when the forced air system was operated. This indicates that the radiant panel system was more effective in countering the cold plume from the window than the forced air system.

Basement Floor Losses

As was previously stated, the lower zone radiant panel was installed over RSI 0.88 (R 5) rigid polystyrene insulation to minimize losses from the back side of the panel. Since the floor is heated in a panel system, it was expected that back losses would



(a) Forced Air, 900mm from Window

(b) Radiant Panel, 900mm from Window

Figure 5. Vertical Air Temperature Profiles Near a Window With Forced Air and Radiant Panel Heating Systems

be somewhat higher than those measured with a forced air system in use. During the installation of the lower panel, a number of thermocouple pairs were placed to allow measurement of the temperature difference across the insulation and indirectly measure heat losses to the ground below the floor. The thermocouple pairs were arranged to monitor heat losses in a line from the south basement wall to the north basement wall. The locations were chosen so as to obtain a representative picture of losses over the entire basement floor. Figure 6 shows the distribution of losses for a section across the basement floor with both the radiant panel and forced air system in operation.

As expected, the basement floor losses were found to be a minimum in the center of the floor and increase towards the edges of the floor. Heat losses measured near the edge of the floor were approximately 50% higher than center losses indicating that the insulation level used was somewhat ineffective in preventing losses from the edge of the panel. Average measured losses over the floor showed that heating the floor increased back losses by 45% compared to the same floor unheated. Integration of average measured heat flows indicated that the basement floor losses accounted for 5% and 10% of the total energy usage in the structure during periods of forced air and radiant panel heating respectively.

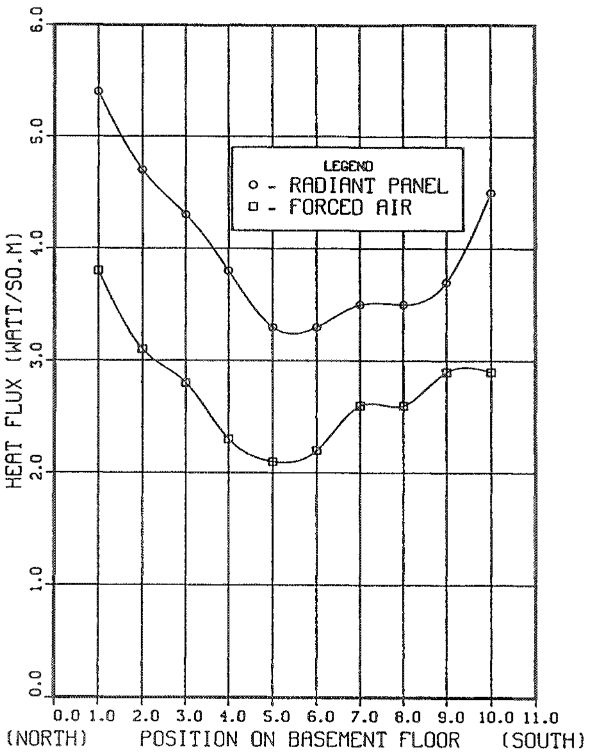


Figure 6. Measured Basement Floor Heat Losses with Radiant Panel and Forced Air Heating Systems

Globe Temperatures

Passive solar structures with large amounts of south facing windows may create unfavorable conditions in some living areas during cold winter temperatures due to the strongly asymmetric radiant fields produced. The asymmetric field may lead to discomfort for occupants due to heat loss by radiation from a person to a cold surface such as a window. Heat loss to a cold surface may produce a feeling of discomfort even in an environment where the air temperature may be quite high. To determine the possible benefits of using a heated floor panel to counter the asymmetric radiant field produced by the south window, globe and air temperature measurements were taken in the test house. Two locations were chosen for the measurements; the first 1 m (3.25 ft) away from the south windows, the second 3.25 m (10.7 ft) away. Comparison of the measured results showed that the forced air system produced the largest difference between globe temperature and air temperature. Globe temperatures were approximately 1°C below air temperature in both locations during periods with ambient temperatures ranging between 0°C (32°F) and -17°C (1°F). The use of the heated floor panel reduced the difference between globe and air temperature to near zero at the location 4 m (13.1 ft) from the windows and to about 0.5°C (0.9°F), 1 m (3.25 ft) away from the windows. Ambient temperatures during the latter testing ranged between 0°C (32°F) to -25°C (-13°F). Given the results obtained, the question of why the panel system never produced average globe temperatures significantly higher than air temperature must arise. The answer appears to be that the system was installed in a modern moderately well insulated structure in which the total energy requirement is quite low. To satisfy demand, the operation time of the heating system is quite short and floor surface temperatures as a result are only 3-5°C (5-9°F) above room temperature. This low temperature difference is insufficient to produce globe temperatures or mean radiant temperatures much above air temperature. This in turn means that air temperatures cannot be lowered below those used in a forced air heating situation and that the energy savings attributable to lowered indoor temperature are not realized.

CONCLUSIONS

Based on results obtained and observations made during testing, several conclusions may be made concerning the characteristics and operating efficiency of the three heating systems.

1. Based on overall energy usage in the test house there were no differences in the operating efficiencies of the three heating system configurations tested. Over relatively short periods, differences of approximately 5% were noted but were considered within normal experimental variation.
2. Measurements of vertical air temperature profiles and globe temperatures were made in order to estimate occupant comfort with each system. Vertical floor to ceiling temperature profiles were different shapes with forced air or radiant systems, primarily very near the floor and the ceiling. The radiant panel system was found to be more effective than the forced air system in countering the cold air plume falling off the windows and moving out across the floor. Floor surface temperatures were higher, on average by 2.8°C (5°F), when the panel system was operated. Globe temperatures were higher when the panel systems were in operation, but barely enough to measure accurately, and certainly not enough to allow lowering of the air temperature set point.
3. Precautions were taken to reduce back losses from the basement floor radiant panel by using under floor insulation (RSI 0.88, R5). Back losses averaged approximately 4 W/m^2 (1.3 $Btu/hr\text{-}ft^2$) when the radiant panel system was operated, and less than 3 W/m^2 (1 $Btu/hr\text{-}ft^2$) when the forced air system was operated.

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