Development of Simple Commissioning Tools for Floor Heating Systems in Residences
-Performance Evaluation of Floor Heating Systems-

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Abstract
A method of evaluating the thermal performance of floor heating systems is examined as a commissioning tool. A simple method is needed to check a floor heating system while in use by residents, because evaluation currently requires significant time and effort. Therefore, a commissioning process consisting of three steps was proposed and applied to four residences. The performance of a floor heating system was estimated in these three steps: (1) efficiency was estimated from the room temperature and the energy consumption with the floor surface temperature kept constant, (2) crawl space temperature was compared with the system on and off (a hot-water floor heating system raised the crawl space temperature), (3) heat flow from the floor panel was analyzed by a one-dimensional heat conduction calculation using detailed measured data. The feasibility of estimating the thermal characteristics of the floor was shown by fitting the average and amplitude of the measured temperatures to the calculated value.

Keywords: floor heating; commissioning; energy consumption; crawl space; heat loss

1. Introduction
1.1. Background of the present study
Floor heating systems are widely used in today’s Japan because of the comfortable thermal environment they provide. However, if the system is not designed and constructed properly, it will not work as expected and will cause problems such as increased energy consumption due to heat loss to the crawl space, insufficient heating capacity, improper control of the heat supply rate and the surface temperature, and non-uniform surface temperature. Moreover, a health hazard may arise, such as the potential for a low-temperature skin burn.

When a floor heating system is planned and designed, it is important to consider the building structure, because the performance of the floor heating system depends profoundly on the building construction and design in addition to the heating system’s own characteristics. For example, inadequate insulation in the floor increases heat loss to the crawl space. When hot-water piping is insufficiently insulated, heat loss from the piping to the crawl space increases (Miura et al. 2002). In both cases, more energy is consumed than necessary. In addition to temperature unevenness due to non-uniform distribution of the hot-water pipes or electric heaters in the panel, temperature controllability is adversely affected by furniture on the floor and the floor structure above the heating panel.

To reduce energy consumption and improve the indoor environment, the floor heating system must be designed and constructed properly. It is very important to check its appropriateness, and match it to the floor structure and insulation. Commissioning is a useful and quite typical tool for this purpose (Annex 40 work program, ASHRAE Guideline 1-1996).

In the present study, commissioning is applied to a floor heating system used in residences, and a commissioning process consisting of three steps is proposed as a tool for checking the performance of the floor heating system. Case studies in which this tool was applied to actual residences are presented to demonstrate its effectiveness.

1.2. Commissioning of floor heating system (Fig. 1)
In order to apply commissioning to the floor heating system in a residence, which is usually designed under a variety of concepts and constraints, the occupant’s requirements for thermal characteristics such as heating capacity and floor surface temperature should be defined first. Then, the type of heating system is selected and designed in the planning and design phases. Next, whether the design performance is satisfied must be checked in the construction and acceptance phases. Furthermore, whether the floor heating system works in accordance with the occupant’s intent, and whether the residents use the system properly are checked after the residents move in. In this way, commissioning is carried out by evaluating the system's performance in various stages of its life cycle.
out continuously from the planning to the post-acceptance phases. Figure 1 shows the action list for commissioning.

When performance is checked in the acceptance and post acceptance phases, simplicity of making the measurements is very important because of time limitations and other constraints in actual residences, unlike in an experimental room.

| Project Process | Commissioning Action |
|-----------------|----------------------|
| Planning Step   | Check the selection process  
|                 | Have the characteristics of each heating method and system (air conditioner, gas fan heater, locomotive, etc.) been explained and understood?  
|                 | Have the characteristics of each floor heating system (electrical, hot water by boiler, hot water by heat-pump, etc.) been explained and understood?  
|                 | After having fulfilled the two steps above, have you confirmed whether the owner will introduce a floor heating system?  
|                 | List of the objective and evaluation methods of commissioning  
|                 | Commissioning subject  
|                 | Commissioning term (upward/downward heat flow, heat loss, controllability, heat capacity, floor surface temperature, etc.)  
|                 | Complete and verify an OP/CHIP owner’s project requirements document  
|                 | Create and obtain owner's agreement for commissioning plan  
|                 | Contract commissioning with the client |
| Working Design Step | Check the design process and documents  
|                   | Does the content of the contract drawings coincide with the Design Intent Summary?  
|                   | Have you checked whether the energy cost simulation had been performed?  
|                   | Check whether the construction schedule is proper for commissioning  
|                   | Revisit the commissioning plan |
| Elaboration Step  | Check the design documents  
|                   | Have you checked whether the design documents coincide with the design intent summary?  
|                   | Have you checked the design documents for later manual vs.  
|                   | Review the commissioning plan |
| Construction Step | Check the construction  
|                   | Is the construction being performed according to the design documents?  
|                   | Re-evaluate the performance if there are any changes in the construction plan |
| Acceptance Step   | Check the performance according to the design intent summary and the commissioning plan  
|                   | Upward/downward heat flow from the panel  
|                   | Heat loss of the system  
|                   | Controllability  
|                   | Heating capacity  
|                   | Floor surface temperature  
|                   | Check the maintenance document  
|                   | If performance is unsatisfactory, clarify the cause  
|                   | Calculate costs of any repair work  
|                   | Make the commissioning report |
| Post Acceptance Step | Check the performance, maintenance, and operationality  
|                    | Have you checked the periodic inspection or maintenance record to evaluate whether the maintenance quality is satisfactory?  
|                    | Have you checked how the system was used in winter? Has the system satisfied the owner's requirements?  
|                    | Have you checked the system's operability and controllability?  
|                    | If performance deteriorates, restore the intended performance  
|                    | Make commissioning report and submit it to the client |

Fig.1. Action List for Commissioning of Floor Heating.

1.3. Studies of floor heating

Many studies have been carried out on floor heating systems from the viewpoint of comfort, and Watanabe (2001) has reviewed the Japanese research.

Several studies have addressed the control and evaluation of heating load with thermal storage (Cho et al. 1998, Chen 2002, Lee et al. 2002 etc.), and floor heating with a solar collector (Alkhalaileh et al. 1999, Nakamura et al. 1999, Li and Okumiya 2001). However, heat loss and energy consumption are not evaluated in these papers.

Heat flow has been calculated with a simplified method that uses an approximation for two-dimensional heat transfer based on a one-dimensional calculation (Kollmar and Liese 1957, Udagawa 1986, Kilikis et al. 1995). Inoue (1997) proposed a one-dimensional method with high precision. Golebiowski (2002) showed an analytical solution to three-dimensional heat conduction in an electric floor heating system. Along with these, two dimensional calculation of a floor heating system with embedded piping coupled with heat balance calculation for the room (Ho et al. 1995), and solar radiation effects on thermal characteristics of floor heating (Athienitis 2000) have been reported. Although these studies dealt with calculations, measurement and evaluation methods for the performance of the floor heating systems were not provided.

Shimizu (1999) measured steady-state upward and downward heat flows from the floor heating panel in an experimental room. In his study, the ratio of the upward
and downward heat flows to the heat supply was shown to vary widely, depending on the floor structure. Heat flow was measured with several heat flow meters on the upper and lower surfaces of the floor. While this study evaluated the heat flow accurately with laboratory experiments, the objective of our research is to evaluate floor heating performance in the post-acceptance phase, which requires a simpler measuring method.

**1.4. Outline of the commissioning in this study**

In the commissioning process, the occupant’s performance requirements should be identified, and the design and construction of the system checked against them.

Figure 2 shows the performance required for a floor heating system. Although there are many requirements, the present study concentrates on thermal performance.

![Fig.2. Occupant’s Requirements for Floor Heating.](image)

**Table 1. Required Data for Measuring Heat Flow Rate and Efficiency of a Floor Heating System.**

| Requirement | Description |
|-------------|-------------|
| Heating Cost | Heat load, Heat loss from the piping (hot-water floor heating system), Boiler / heat pump efficiency (hot-water floor heating system) |
| Maintainability | Surface temperature, Water leakage |
| Controllability | Area, Floor heating material |
| Operability | Area, Floor heating material |
| Acoustic absorption | Initial Cost, Applicability, Panel area |

Heat losses should be measured to evaluate thermal performance. The main heat losses from a floor heating system are the downward heat flow from the panel and the heat flow from the hot-water pipe in a hot-water floor heating system. Therefore, the information listed in Table 1 is needed. Since a great deal of time and effort is required to measure these items, however, a simple method of evaluating thermal performance is needed. Therefore, a commissioning process consisting of the following three steps (Fig.3) is proposed in this paper.

The first step aims to detect floor heating systems with low efficiency based only on the energy consumption and room temperature, which can be measured easily. At the second step, heat loss to the crawl space from the floor and the piping (hot-water floor heating system) is evaluated by comparing the crawl space temperatures with the floor heating system on and off. The third step, based on detailed data, aims at clarifying the heat flow from the floor panel by calculation, using a thermal model.

Steps 1, 2 and 3 need increasingly detailed data in that order. First, step 1 is carried out. If the result is judged inadequate, the commissioning continues to step 2 and then step 3.

In this study, the effectiveness of this commissioning procedure is examined by application to existing residences.

![Fig.3. Three Steps for Evaluating the Performance of a Floor Heating System.](image)

**2. Outline of measurement**

Table 2 describes the houses and rooms to which these steps were applied.

House A has an electric floor heating system, while House B is heated by a hot-water floor heating system. House C is an experimental house, whose Rooms C1 and C2 have the same structure and thermal insulation. One of the rooms has an electric floor heating system and the other a hot-water floor heating system. Details of House B and House C are reported in Miura et al. 2002, and Kitagawa et al. 2003.

The operating mode of floor heating systems in House A and House B was selected freely by the residents. The floor heating systems in rooms C1 and C2 were controlled in the “strong mode” or “weak mode”.

**Table 2. Measured Houses and Rooms.**

| House | Room | Floor area of heated room | Insulation of the floor | Number of residents (Person) | Heating System | Year of Service |
|-------|------|---------------------------|------------------------|-----------------------------|----------------|----------------|
| House A | 100 | Polyurethane foam [62 mm] | 4 | Hot-Water Heating System at Confirmation | 2003 |
| House B | 100 | Polyurethane foam [80 mm] | 1 | Hot-Water Heating System | 1998 |
| House C | 100 | Polyurethane foam [60 mm] | 4 | Hot-Water Heating System at Confirmation | 2002 |

**3. Evaluation based on energy consumption for heating**

**3.1. Outline**

Given that the heat supplied to the room from the panel is measured, the efficiency of the floor heating can be evaluated. However, it is difficult to measure the supplied heat. Although the use of heat flow meters on the surface might be the simplest means, it requires a measurement
at many surface points because of the nonuniform temperature distribution. Also, as a practical matter it is also difficult to set up measuring equipment in a residence. Therefore, even a crude evaluation of the supplied heat by measuring only the room temperature is highly desirable. We will propose a new method and use it to make an estimate. If the proposed method is applicable, the efficiency of floor heating can be estimated by statistical means after accumulating sufficient data in residences.

3.2. Method

The heat flux from the floor is given by,

\[ q = h (T_{surf} - T_{room}) \]

- \(q\): heat supplied from the floor [W/m²]
- \(h\): heat transfer coefficient [W/m²K]
- \(T_{surf}\): floor surface temperature [°C]
- \(T_{room}\): room temperature [°C]

Usually a floor heating system controls the heat input to the panel so that the surface temperature is kept at a set point. Given that the floor surface temperature \(T_{surf}\) is maintained at the set point and the heat transfer coefficient \(h\) is assumed to be constant, the supplied heat can be calculated by only measuring the room temperature. Figure 4 shows the supplied heat with solid lines and an example of the energy consumption with circles. It is assumed that the value of the heat transfer coefficient is 7.5 or 10.0 and the surface temperature is 30 or 35 °C.

![Fig.4. Estimated Heat Supply and Energy Consumption.](image)

The measured periods were from 2003/2/1 to 2003/2/28 in House A, four days of 1998 (1/23, 1/30, 2/15, 2/22) in House B, and from 2003/1/17 to 2003/2/7 in both Room C1 and Room C2.

3.3. Results

Figures 5 to 8 show the correlation between room temperature and energy consumption when the floor heating is operated. In principle, the set point temperature of the floor surface should be defined in the design phase. However, the heat supplied to the room was estimated by assuming that the set point ranges from 25 to 30 °C and the heat transfer coefficient is 8.0 W/m²K.

1) House A (Elec. floor heating & air conditioner)

The living / dining room was heated. The air conditioner was also used as frequently as the floor heating. The energy consumption decreases with an increase in room temperature. The energy consumption of the floor heating shows no difference related to the operation of the air conditioner. The energy consumption approximately corresponds to the estimated heat supply.

![Fig.5. Energy Consumption vs. Room Temperature (House A).](image)

2) House B (Hot-water floor heating)

The heated room was the bedroom. The floor heating was used for almost the whole day. There was little correlation between the room temperature and the energy consumption. The energy consumption was more than the estimated heat supply by a factor of two.

![Fig.6. Energy Consumption vs. Room Temperature (House B).](image)
3) Room C1 (Elec. floor heating & air conditioner)

The data points are plotted with lines connecting them because the energy consumption is different depending on the operation mode. The energy consumed in "strong operation mode" is twice that in "weak operation mode". Since this floor heating system does not control the floor surface temperature, the energy consumption is constant and depends only on the operation mode.

![Image](image.png)  
Fig.7. Energy Consumption vs. Room Temperature (Room C1).

4) Room C2 (Hot-water floor heating)

The data points are plotted with a line because energy consumption is different depending on the operation mode in the same manner as in Room C1. Although energy consumption just after turning on was high (700-800 kJ/m²h), it was nearly constant after that regardless of the room’s temperature.

![Image](image.png)  
Fig.8. Energy Consumption vs. Room Temperature (Room C2).

3.4. Discussion

The efficiency of a floor heating system was estimated by comparing the energy consumption and the estimated heat supplied to the room.

In House A (Fig. 5), the energy consumption is nearly identical to the estimated supplied heat, which means the floor heating system operated at high efficiency.

In House B (Fig. 6), the energy consumption is double the estimated supplied heat. It seems that the efficiency of the heating system in this house is low, and a great deal of heat is lost to the crawl space and at the boiler.

In Room C1 (Fig. 7) and Room C2 (Fig. 8), the energy consumption was determined based on the operation mode, and thus there is no correlation between the energy consumption and the room temperature. Since the heat flow from the panel is constant, the floor surface temperature increases with the room temperature. When the energy consumption is much higher than the estimated supplied heat, it cannot be judged whether the efficiency of the system causes the difference, or too-high surface temperature causes the difference. Therefore, the efficiency cannot be estimated by using the method proposed in this section. Nevertheless, both the low efficiency and the high surface temperature require more energy than necessary. Therefore, it can be concluded that the floor heating system is not designed properly.

In Room C2 (Fig. 8), since the energy consumption is much larger than the estimated supplied heat, it can be said that the efficiency of the system is low, and that a great deal of heat is lost to the crawl space and at the boiler, as in the case of House B.

4. Evaluation based on crawl space temperature

4.1. Outline

The temperature of the crawl space is affected by the outdoor, room and ground temperatures, and the heat released from the floor heating system. The outdoor temperature influences this through ventilation and heat transmission via the foundation. If the heat loss from the heating panel and hot-water pipe is large, the crawl space temperature during operation must be higher than it is when the heating system is off.

Therefore, heat loss to the crawl space was evaluated by comparing the crawl space temperatures with the system on and off. The measured periods were from 2003/2/26 to 2003/3/6 in House A, 1998/2/1 to 1998/2/28 in House B, and from 2003/1/17 to 2003/2/7 in Room C1 and Room C2.

4.2. Measured results and discussion

Figures 9 to 12 show the results. In House B (Fig. 10), the floor heating was used almost the whole day. Therefore the number of system-off data points is small.

In House A (Fig. 9) and Room C1 (Fig. 11), the difference in crawl space temperature is quite small between system-on and off states. Therefore, the heat loss is judged too small to increase the crawl space temperature.

In House B (Fig. 10) and Room C2 (Fig. 12), the crawl space temperature when using floor heating is higher than when it is off. The heat loss to the crawl space seems to have affected the crawl space temperature. Additional measurements to discover the causes of the heat loss (Miura et al, 2002, Kitagawa et al. 2003) have discovered that the surface temperature of the piping was significant, resulting in heat loss from the piping to the crawl space.

Therefore, it can be concluded that the proposed commissioning tool, that is a comparison of the crawl space temperatures, can discover undesirable heat loss.
5. Evaluation based on a thermal model

5.1. Outline

More detailed information, such as the ratio of the upward and downward heat flows (the efficiency of the floor heating system), is usually difficult to obtain. In this section, a tool which makes use of a thermal model is proposed.

Measurement for this purpose was carried out in House A (electric floor heating) in November 2002. (Similar measurements in House B, Room C1 and Room C2 were reported elsewhere (Miura et al. 2002, Kitagawa et al. 2003)).

Temperatures were recorded every 15 minutes for the room, floor surface and crawl space, ground surface in the crawl space and outdoor air, with energy consumption measured each minute.

5.2. Measured result

Figure 13 shows the measured data. The floor heating was operated from 7 P.M. 11/6 to 8 A.M. 11/7. The on/off control was used to keep the room or floor surface temperature at the proper level. The floor surface temperature during operation shows a small fluctuation corresponding to on/off control.

5.3. Method of analysis

Upward and downward heat flows were estimated from the data gathered from 11/5 to 11/6 (Fig. 13). Transient heat conduction was calculated with the measured room and crawl space temperatures as boundary conditions (Fig. 14). Table 3 shows the thermal properties of the floor materials. Calculations were carried out with different parameter values such as plywood thickness and heat transfer coefficient, so that the calculated surface temperature approached the measured value.

| Material   | Thermal Conductivity [W/mK] | Heat Capacity [J/mK] |
|------------|-----------------------------|----------------------|
| Wood       | 0.1                         | 1128000              |
| Insulation | 0.035                       | 34100                |
5.4. Estimation of parameter values

1) Thickness of plywood on upper side (Fig. 15)

The floor surface temperature was calculated assuming a convective heat transfer coefficient of 5.0 W/m²K, radiant heat transfer coefficient of 1.0 W/m²K, insulation thickness of 62.0 mm, and upper side plywood 3.0, 5.0, and 8.0 mm thick.

The calculated floor surface temperature fluctuated due to the on/off control. The amplitude of the fluctuations in the calculated surface temperature with an upper side plywood thickness of 8 mm was less than the measured value. With 3 mm plywood, the surface temperature showed larger fluctuations than those measured. Thus, we estimated the thickness of the upper side plywood at 5 mm. As shown in this example, the characteristics of the upper side plywood could be estimated by making use of the amplitude of the fluctuation.

3) Heat transfer coefficient (Fig. 17)

The floor surface temperature was calculated assuming that the convective heat transfer coefficient was 5.0 W/m²K, radiant heat transfer coefficient 1.0 W/m²K, the insulation thickness 40.0, 62.0 and 80.0 mm and the upper side plywood thickness 5.0 mm.

Even if a quite different insulation thickness was used, a significant difference is not found for the calculated surface temperature. Therefore, it is difficult to estimate the thickness of the insulation. Since there is no significant difference in the ratio of the upward and downward heat flows, however, an estimate of the exact thickness of the insulation is not required. Therefore, the calculation was carried out by assuming that the insulation thickness was 62 mm, which is the design value.
5.5. Estimation of upward and downward heat flows from panel (Fig. 18)

Figure 18 shows the calculated result with a convective heat transfer coefficient of 5.0 W/m²K, a radiant heat transfer coefficient of 1.0 W/m²K, 62.0 mm of insulation and upper side plywood 5.0 mm thick. The calculated result agrees well with the measured. Figure 19 shows the cumulative value of the upward and downward heat flows.

5.6. Discussion

The heat loss and the efficiency of floor heating were examined using detailed measured data. The floor surface temperature was calculated using several values of convective and radiant heat transfer coefficients, and different thicknesses of upper side plywood and insulation. The characteristics of a floor can be estimated from its average measured surface temperature and the amplitude of its fluctuations.

6. Conclusion

Floor heating systems in four residences were commissioned. The commissioning process proposed in this paper consists of evaluations at three steps. At step 1, the performance of the floor heating system was evaluated based on the energy consumption for heating. If the energy consumption is greater than the estimated heat supplied, based on the room temperature, it should be considered that the efficiency of the heating system is low and that significant heat is being lost to the crawl space and at the boiler. At step 2, the heat loss from the floor heating system was evaluated by comparing the crawl space temperature with the system on and off. With hot water systems, the crawl space temperature was elevated during operation, indicating a significant heat loss to the crawl space. At step 3, the measured surface temperature was simulated by calculation, and the heat flow from the floor was evaluated. By making use of the fluctuation of the measured surface temperature, the thermal characteristics of the floor can be estimated.

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