A Review of Floor Heating Research in Japan

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(received on April 16, 2001; accepted on Aug. 16, 2001)

Abstract

Floor heating systems have been recently become popular in Japanese houses. Many researchers have conducted their researches on floor heating from the viewpoint of creating a comfortable living environment in winter. They have gotten valuable information for architects, engineers and occupants. The objective of this paper is to review the previous studies on the effect of floor heating systems on human thermal comfort in Japan. Aims and findings of each research group are summarized based on research papers presented from 1975 to 1997 in Japan. Comfort zones, recommended conditions and limit conditions for humans using the floor heating system proposed by each researcher were illustrated in the charts consisting of air temperature and floor surface temperature. This review will contribute to the progress of future floor heating research.

Key words: review, floor heating, comfort zone, human body, Japan

Introduction

Recently, floor heating systems have been become popular in Japanese houses. Generally, the floor heating system is recognized as providing a high amenity environment in rooms in Japan because the vertical air temperature difference is small and occupants feel it comfortable to receive thermal radiation from the heated floor and conductive heat from the contacted floor surface. Many researchers have carried out research on floor heating from different points of view, i.e. determining the thermal comfort zone, numerical simulation for evaluating the system efficiency, system development of floor heating and so on. Consequently, they have provided valuable information for architects, engineers and occupants. Although similar researches have been conducted in Europe and America, their findings do not necessarily applying to Japan because the life styles in both areas are different. People in Japan and Korea are used to sitting on a floor. This study reviews papers on floor heating presented in Japan from 1975 to 1997. The important point of this paper is to summarize the progress of floor heating research by each research group. Comfort zone, recommendations and limit conditions for the floor heating are illustrated in the charts which show with air temperature and floor temperature.

Trend of Floor Heating Research

The following sources were used as review materi-

als: 1) Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan (AIJ), 2) Journal of Architecture, Planning and Environmental Engineering (Transactions of AIJ), 3) Transactions of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan (Transactions of SHASE), 4) Summaries of Technical Papers of Annual Meeting the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan (SHASE), 5) Japanese Journal of Biometeorology, 6) Proceedings of Symposium on Human-Environment System. The original papers and reports submitted to the literature from 1975 to 1997 were investigated. The number of papers regarding floor heating is 131. Figure 1 shows the number of papers with passage of the year. Although the number of papers doesn't always mean the progress of the research, it may indicate the degree of the interest. Though the researches on floor heating were also reported before 1975 in domestic and overseas, papers after 1975 were investigated in this review for the reason to obtain easily. A lot of researches regarding the amenity of floor heating have been performed since the beginning of 1980's. In 1989, the SHASE set up "Research Committee on Amenity Evaluation of Floor Heating". In 2000, the Society of Human-Environment System held a symposium "International Standards for Non-Uniform Thermal Environments—With Respect to Floor Heating Systems".

Fig. 1. Number of papers concerning floor heating.

Fig. 2. Comfort zones, recommendations, and limit conditions of the floor heating (Tokyo Metropolitan University).

Features and Progress in Each Research Group

In order to clarify the aims and features of each research group, the papers are analyzed. Comfort zones, recommended conditions and limit conditions, which can be expressed in the combination of air temperature and floor temperature, are illustrated in the charts. The legends in the charts show the following: author(s), published year, body posture of subject, thermal insulation value of clothing (in clo unit) and heat source (electric or hot water). Since all papers except one are written in Japanese, the terminology in this review refers to original titles and abstracts written in English.

1) Tokyo Institute of Technology and Toyohashi University of Technology

This group has carried out a continuous series of subjective experiments in order to clarify the effect of air temperature, air flow, humidity and thermal radiation upon the human body using an artificial climatic

wind tunnel. In 1975, the first paper on the effect of floor temperature on the human responses was presented by Inoue et al. (1975). Maintaining the operative temperature at 23°C, 25°C and 28°C, the influence of asymmetric thermal radiation fields on the human body was examined by Kurazumi et al. (1985) and Kobayashi et al. (1986). Hirayama et al. (1984) reported that the clothed subject felt thermal neutrality when the operative temperature was 23°C and mean skin temperature was 33°C. Yamaguchi et al. (1985) studied the effect of shielding of radiant heat due to a desk in office space. Hirayama et al. (1985) developed a modified operative temperature including the effect of heat conduction between human body and floor surface.

2) Tokyo Metropolitan University (See Fig. 2)

This group has conducted comprehensive research concerning the effect of asymmetric radiation on thermal comfort (Ito et al., 1985; Ito et al., 1986a; Ito

Fig. 3. Comfort zones, recommendations, and limit conditions of the floor heating (Nara Women's University).

et al., 1986b; Ito et al., 1987a; Ito et al., 1987b; Ito et al., 1989). An experimental study for floor heating was performed in 1976. Ito et al. (1976) reported that the subjects voted thermal neutrality when the combination of floor temperature was 30°C and air temperature was 16°C in a room with floor heating. This group conducted subjective experiments to clarify the amenity of floor heating under various combined conditions of floor temperature and air temperature. Sunaga et al. (1992) obtained tolerance limits and comfort zone in the combination of air temperature and floor temperature from analysis of previous studies in Japan. Based on the experimental data, comfort condition for clothed person sitting on a chair (27.5/23.5°C floor/air temperature) and comfort range for clothed person sitting on a chair (26–28/22–24°C floor/air temperature) were proposed (Ito et al., 1993a; Ito et al., 1993b). Ito et al. (1994a) examined the relationship between thermal sensation of whole body and local thermal sensation, and pointed out that local thermal sensation at head, arm and back affects thermal sensation of the whole body in a hot environment, while that the sensation at arm, back and foot affects the whole body sensation in a cold environment. Ito et al. (1994b) discussed the equivalent thermal comfort line by the combination of floor temperature and air temperature. Ito et al. (1995) proposed two comfort ranges; 25–30/22–25°C floor/air temperature for sitting on a chair, 23.5–28.5/20.5–24°C floor/air temperature for sitting on a floor. Hori et al. (1997) proposed to predict the thermal comfort condition using the local thermal sensation based on the experiments in which over 700 subjects participated. Kabata et al. (1993) clarified that the optimum

condition depends on the heating system, e.g. convective heating or radiant heating. Ito et al. (1989) also dealt with radiant cooling. The effect of posture (Kato et al., 1995) and the effect of the installation site of radiant panels on thermal comfort (Kato et al., 1994) were also examined.

3) Nara Women's University (See Fig. 3)

Research on floor heating started from the viewpoint of design for the sleep environment. Okada et al. (1981) reported comfortable floor temperature (29.5–32.5°C) in the bed with the air temperature at 23.5°C. Isoda (1982) carried out experiments in which subjects could choose the preferred floor temperature and air temperature. Isoda et al. (1986a) investigated the effects of the floor and air temperatures on physiological and psychological responses experimentally. Comfort conditions for the subject sitting on a heated floor (combination of air temperature 15–18°C and floor temperature 27–32°C), lower limit of air temperature of 18°C for sitting on a chair, upper limit of floor temperature of 30–33°C were proposed as shown in Fig. 3. Researches on the amenity of the floor heating were carried out from the following viewpoints; difference of posture (Isoda et al., 1986b; Lee et al., 1997a), direct or indirect exposure to heated floor (Kim et al., 1987; Kim et al., 1990), difference of finishing materials of floor (Kim et al., 1989), radiant heating or cooling (Lee et al., 1997b; Mitsuda et al., 1997) and difference of heating system (Isoda et al., 1996). Enomoto et al. (1994) conducted an experimental study of the effect of radiant heating on the elderly. This research is remarkable, since many research groups mainly used young sub-

Fig. 4. Comfort zones, recommendations, and limit conditions of the floor heating (The University of Tokyo).

jects.

4) Yokohama National University

Kawashima et al. (1982) investigated physiological and psychological effects of floor heating systems using electric panel heaters and hot water panel heaters. Fukai and Emura (1996) reported that the thermal sensation of the contacted part and thermal comfort depend on the different thermal resistance of floor materials. The skin temperature in contact with the floor rose and subject felt warm, when the heat source temperature became higher or the thermal resistance of floor material was higher, even though floor and air temperature conditions were same (Fukai and Emura, 1997). Fukai (1997) also studied the effect of floor cooling on the physiological and psychological responses, and clarified that subjects felt the thermal neutrality when the skin temperature in contact with the floor was approximately 32°C.

5) The University of Tokyo (See Fig. 4)

This group has carried out a series of research projects regarding the effect of thermal variables such as air temperature and thermal radiation on thermal comfort (Tanaka et al., 1984; Mitsumine et al., 1985; Shimizu et al., 1986; Mitsumine et al., 1986). This group participated in the 'Research Committee on Amenity Evaluation of Floor Heating' after the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan in 1989, and through the activity of the research committee the following results were obtained: comfort condition for sitting on a chair was 29/22°C floor/air temperature (Tan et al., 1990), comfort range for sitting on a chair was 27–31/20–23°C

floor/air temperature (Tan et al., 1991), lower limit of air temperature was 21°C at floor temperature of 30°C (Tan et al., 1993). Tan et al. (1994) indicated a thermal neutral range based on the thermal sensation of the contacted segment, thermal sensation of the whole body and comfort votes as shown in Fig. 4. Tan et al. (1995) also studied the tolerance of cold draft in relation to floor heating from subjective experiments.

6) Osaka City University (See Fig. 5)

Emura and Saito (1985) examined the effect of the heating of the sole of the foot on the physiological responses by subjective experiments. They concluded that the rectal temperature did not drop when the sole of the foot was heated. This group participated in the 'Research Committee on Amenity Evaluation of Floor Heating' after the SHASE, and performed remarkable research. Emura (1990) surveyed the permissible surface temperatures for floor heating as reported by previous researches over the world. The threshold of the moderate temperature burn can be estimated in the relation between contact surface temperature and contact time. In order to prevent the moderate temperature burn, Emura recommended that the floor temperature should be set less than 40°C. Yagou et al. (1991) proposed thermally neutral conditions and limiting conditions based on subjective experiments in which subjects were exposed for 4 hours; thermally neutral condition for sitting on a chair was 30/22–23°C floor/air temperature, thermally neutral condition for sitting on a floor was 25.5/20°C floor/air temperature, lower limit of air temperature was 20–21°C, upper limit of the floor

Fig. 5. Comfort zones, recommendations, and limit conditions of the floor heating (Osaka City University).

temperature was 32°C. Oyama and Emura (1992) indicated that the local thermal sensation of peripheral parts such as arms, legs and ankles affected the thermal sensation of the whole body. Oyama et al. (1993a) proposed the optimum ranges of floor temperature, globe temperature and mean skin temperature; 27.85–33.23°C, 23.28–25.46°C, 32.65–33.7°C, respectively. A database obtained from subjective experiments through the research committee activities was constructed (Emura, 1993; Emura et al., 1993; Oyama et al., 1993b). Zheng et al. (1995) studied the floor heating safety by investigating the contact temperature through experiment and heat transfer analysis using the model of contact body position. Based on previous domestic and overseas researches, Zhang et al. (1996) statistically investigated the recommended conditions and tolerable floor surface temperature for both the young and the elderly.

7) Building Research Institute (See Fig. 6)

This group has carried out a series of researches to clarify the effect of floor heating on thermal comfort. Based on domestic and overseas studies, Bogaki (1985) outlined allowable limits and comfortable conditions for floor heating systems. Bogaki (1986) concluded that the combination of the floor surface temperature range from 25 to 30°C and air temperature range from 18 to 20°C gives a thermally neutral and comfortable zone for floor heating especially when the persons were sitting on the floor or a chair with no slippers. This author compared the influence of age between elderly and young, and pointed out that the elderly would wear 0.4–0.5 clo clothing more than the young. This group participated in the ‘Re-

search Committee on Amenity Evaluation of Floor Heating’ after the SHASE, and through the activity a series of subjective experiment was carried out. Bogaki and Osawa (1990) proposed the combination of floor temperature of 24°C and air temperature of 19°C as a permissible condition for the elderly and the young. Bogaki (1991) proposed a goal condition combining of floor temperature from 25 to 27°C and air temperature from 19 to 20°C through subjective experiments using the elderly and the young, in the posture of sitting on a chair and a floor. Bogaki (1994) showed the optimum zone and goal condition for designing floor heating shown in Fig. 6 by experiments using college aged subjects.

8) Waseda University

Kimura et al. (1987) carried out subjective experiments using floor heating panels. By calculating the modified temperature (MT) from the measured data, thermal comfort in the room with floor heating system was evaluated. MT was defined as the air temperature of 50% rh, 0.1 m/s mean air velocity, 0.6 clo, 1.0 met and mean radiant temperature equaled to the air temperature, which would provide the same thermal sensation as under the actual thermal condition and was calculated by Fanger’s comfort equation (Tanabe and Kimura, 1986). Kimura et al. (1988a) measured the energy consumption necessary for maintaining PMV=0 in the occupied zone using radiant panel heating, hot air heating and floor heating, respectively. The effect of the difference of heating system on the thermal comfort was examined by subjective experiments (Kimura et al., 1988b, 1988c). Subjective experiments focused on the amenity of floor

Fig. 6. Comfort zones, recommendations, and limit conditions of the floor heating (Building Research Institute).

Fig. 7. Comfort zones, recommendations, and limit conditions of the floor heating (Nagoya Institute of Technology).

cooling were also conducted (Kimura et al., 1988d).

9) Nagoya Institute of Technology (See Fig. 7)

Choi (1990) reported a field survey on thermal environments in a Korean apartment house fitted with Ondol floor heating system. In order to clarify the effect of floor heating on the human body from the physiological and psychological viewpoints, a series of experiment using unclothed subjects was carried out (Choi and Horikoshi, 1991; Sakai et al., 1992; Choi et al., 1996). Based on the obtained data, upper limit of floor temperature and optimum temperature condition were proposed as shown in Fig. 7 (Choi,

1995). Effective radiation area factors and configuration factors between the body and its surroundings should be known to estimate radiative heat exchange. By a photographic method with a special fisheye lens, these factors for males and females sitting on a floor were measured and diagrams of configuration factors were presented (Miyamoto et al., 1996; Miyamoto et al., 1997). Choi et al. (1991) calculated the modified operative temperature including the effect of heat conduction between the human body and a heated floor. Miyamoto et al. (1994) extended the modified operative temperature to include the effect of inter-reflection radiation and the blocking effect of

Fig. 8. Comfort zones, recommendations, and limit conditions of the floor heating (Kinki University).

Fig. 9. Comfort zones, recommendations, and limit conditions of the floor heating (Hokkaido University).

the human body on it.

10) Kinki University (See Fig. 8)

Kajii (1990) developed a measuring instrument which used a heat flow meter to evaluate thermal sensation on the body part in contact with an object. Kajii (1992) conducted subjective experiments using panel heaters with circulating hot water, electric heaters and non-heated tatami mats. Thermal comfort of the floor heating system was examined from the physiological and psychological viewpoints (Kajii et al., 1993).

11) Hokkaido University (See Fig. 9)

This group carried out subjective experiments on a floor heating system from the viewpoint of energy saving and human acceptability in 1996. The lower acceptable limits of air temperature and floor surface temperature in a room fitted with a floor heating system in a cold region were approximately 18°C and 22°C, respectively (Ochifuji et al., 1996).

12) Other research groups

Narumi et al. (1996) examined the effect of body posture under floor heating on the physiological and psychological responses by subjective experiments.

Haccho (1983) focused on thermal comfort at the part of the body in contact with a floor. Narasaki and Iida (1985) discussed local thermal sensation under a non-uniform radiant field. Yamada et al. (1990) theoretically investigated the possibility of thermal injuries from the heat transfer point of view.

Conclusions

This paper has reviewed experimental researches regarding floor heating and its amenity using papers presented from 1975 to 1997 in Japan. Aims and findings of 12 research groups were presented. In addition, comfort zones, recommendations and limit conditions for the human body using floor heating were compared under the combination of air temperature and floor temperature. The next step is to integrate the above mentioned research findings for the benefit of architects, engineers and occupants. However, it is difficult to determine one comfort zone for floor heating because the experimental conditions (body posture, clo value, heat source) in each study are different. Therefore, a thermal index for floor heating fitted to any conditions is desired. The development of the index requires a theoretical approach based on the heat balance between human body and its environment. The index suitable for evaluation of floor heating is the modified operative temperature proposed by the Nagoya Institute of Technology group, which involved the effect of thermal radiation from a heated floor surface and heat conduction from a contacted floor. To apply the modified operative temperature to any conditions, it is necessary to prepare various values concerning the human body on each posture, namely, contact areas between human body and a floor, configuration factors between human body and its surroundings, and effective radiation area ratios. It is a way for establishing one comfort zone for floor heating to evaluate previous research results using the modified operative temperature as a scale. The index based on the heat balance can be applied to not only floor heating but also asymmetric and non-uniform thermal environment. Finally, culture and life style of people who use floor heating system should be considered, when these research findings are applied to the practice.

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