Optimum Comfort Limits Determination through the Characteristics of Asymmetric Thermal Radiation In a Heated Floor Space, “Ondol”

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This study was undertaken to evaluate the effects of the asymmetric radiation on thermal comfort, and to suggest the optimum comfort limits in a radiant heating space. The index of V.R.T. (Vector Radiant Temperature) was used to describe the environmental quality of the heated floor space. Optimum comfort limits of this space were suggested through both theoretical and empirical studies. It is recommended to use not only man’s sensation of the ambient air but also that of the floor surface for the determination of the optimum comfort limits on the heated floor space such as an “Ondol” in Korea.

In the present study the optimum comfort limits were suggested in terms of the V.R.T. The optimum limits obtained were as follows:

Key words: Thermal Comfort, Asymmetric Radiant Field, Optimum Comfort Limits, Vector Radiant Temperature

It might be impossible to describe thermal environment at a point in the heated floor space using the concept of M.R.T. (Mean Radiant Temperature), where the effects of asymmetric thermal radiation and the directionality of the radiation are not considered. “Ondol”, a floor heating system, is the most common heating system used in the residential buildings in Korea. A person under that environment used to feel local thermal discomfort at some part of his body due to intense radiation from the heated floor. Therefore there are some problems in applying the comfort criteria which have been used in other countries to Koreans without adjusting them for the differences of heating methods and thermal sensation between Koreans and others.

This study was undertaken to suggest the optimum comfort limits in a radiant heating space. As it has been known that the V.R.T. (Vector Radiant Temperature) affects the perceived asymmetry in recent researches, it was used to describe the environmental quality of this space. The optimum comfort limits of this space were suggested through both theoretical and empirical studies.

METHODS AND PROCEDURES
The Experiments
The experiments have been carried out in an experimental house of KIER (Korea Institute of Energy Research) during the winter of 1990. There is a room which has a floor heating system in the house. The room dimension of the house is shown in Table 1. The size of the room is 3.2m wide, 2.4m
Table 2 Measuring method and instruments

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>UNIT</th>
<th>POSITION</th>
<th>INSTRUMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor Air Temp.</td>
<td>°C</td>
<td>1 point (center 60cm high above the floor)</td>
<td>Data Logger (Kaye Digitrip IV)</td>
</tr>
<tr>
<td>Outdoor Air Temp.</td>
<td>°C</td>
<td>1 point</td>
<td>Indoor Climate Analyzer (B &amp; K type 1213)</td>
</tr>
<tr>
<td>Surface Temp.</td>
<td>°C</td>
<td>floor 3, wall 4, 1</td>
<td></td>
</tr>
<tr>
<td>P.R.T.</td>
<td>°C</td>
<td>1 point (center 60cm high above the floor)</td>
<td></td>
</tr>
</tbody>
</table>

long and 2.3m high. Their envelopes with windows are thermally well insulated. The surface temperatures of the walls, the windows, the ceiling, and the floor were measured and recorded. P.R.T. (Plane Radiant Temperature) at the center of the room, which is 60cm high above the floor, was also measured. The height of the sensor for P.R.T. is the abdominal height of the seated subjects that is recommended by ISO 7730 (ISO, 1984). Measuring method and instruments are shown in Table 2.

In the present study experimental conditions were determined by the floor surface temperatures. The experimental conditions are shown in Table 3. Each condition continued for 24 hours. All parameters were measured by varying the floor surface temperatures at an interval of 5°C from 20°C to 45°C.

Table 3 Experimental conditions of the floor surface temperatures [°C]

<table>
<thead>
<tr>
<th>CASE</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor surface Temp.</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>45</td>
</tr>
</tbody>
</table>

The View Factor

The view factors to calculate the P.R.T. were determined using the chart by Raber and Hutchison (Hutchison, 1962). Fig.1 shows the correlation between room and a small plane element. The height of an element is 60cm which is equal to the abdominal height of seated subjects recommended by ISO. The view factor of each surface can be simplified as

\[ \varphi_{P-w} = 1 - \varphi_{P-f} \] (or, \( \varphi_{P-c} \))

where, \( \varphi_{P-w} \) : the view factor in the case of a small plane element perpendicular to the walls

\( \varphi_{P-f} \) : the view factor in the case of a small plane element parallel to the floor

\( \varphi_{P-c} \) : the view factor in the case of a small plane element parallel to the ceiling

The view factors are determined using the chart of Ref. 7 and Fig.1.

The view factors for upper space are

\( \varphi_{P-c} = 0.45 \), \( \varphi_{P-wui} = 1 - \varphi_{P-c} = 0.55 \)

The view factors for lower space are

\( \varphi_{P-f} = 0.86 \), \( \varphi_{P-wui} = 1 - \varphi_{P-f} = 0.14 \)

where, \( \varphi_{P-wui} \) : the view factor in the case of a small plane element perpendicular to the walls for upper space

\( \varphi_{P-wui} \) : the view factor in the case of a small plane element perpendicular to the walls for lower space

P.R.T.

The P.R.T. is the temperature of a uniform hemi-
sphere which produces the same irradiance as exists in the real environment. It is easily visualized as the 'average' temperature of the half of the room. (McIntyre, 1976)

The formula to calculate P.R.T. is:

\[ T_{pr1} = \varphi_{p-R} T_r + \varphi_{p-w1} T_{w1} \]

\[ T_{pr2} = \varphi_{p-c} T_c + \varphi_{p-wu} T_{wu} \]

where, \( T_{pr1} (T_{pr2}) \) : P.R.T. for lower (upper) space of a room

\( T_r \) : floor surface temperature

\( T_c \) : ceiling surface temperature

\( T_{w1} (T_{wu}) \) : wall surface temperature for upper (lower) part of a room

V.R.T.

The radiation vector is a measure of the asymmetry of the radiation field. The radiation vector is the difference between the irradiance on opposite sides of a small plane element; the equivalent definition of vector radiant temperature is the difference in the plane radiant temperatures seen by opposite sides of a plane element. (McIntyre, 1974)

V.R.T. can be simplified as

\[ T_v = T_{pr1} - T_{pr2} \]

where, \( T_v \) : Vector Radiant Temperature

RESULTS

Indoor air temperatures that resulted from the variation of the floor temperatures from 20°C to 45°C were also measured.

P.R.T. was calculated by the theoretical formula and the measurement by the Indoor Climate Analyzer (B & K type 1213). Results are shown in Fig. 2 and 3. In Fig. 2 the calculated values for the floor (lower space; \( T_{pr} \)) are compared with the measured ones (\( T_{pr} \)). The difference between the calculated values and the measured ones increased with increasing P.R.T.. Since the transducer of the instrument was installed too low from the floor, effective measurements of the radiative heat from the floor surface were not able to be taken. However, in Fig. 3 the calculated values (\( T_{pr} \)) are nearly in accordance with the measured ones (\( T_{pr} \)). These results are regarded as the view factors of walls which are similar to that of the ceiling. Therefore, in the present study the calculated P.R.T. were used to calculate the V.R.T..

Fig. 4 illustrates the average values of P.R.T. (\( T_{pr1}, T_{pr2} \)), V.R.T. (\( T_{vr} \)) and floor surface temperatures (\( T_{f \text{avg}} \)) for six different floor surface temperatures. The variation range of P.R.T. decreased with the upper surface temperatures of the floor. In this case V.R.T. varied between 3.1~15.5 K.

Fig. 5 is the scatter diagram of the correlation between the V.R.T. and the floor surface temperatures. The regression equation can be obtained using the correlation between the V.R.T. and the floor surface temperatures. The equation is

\[ T_{vr} = -4.4 + 0.5 \times T_{f \text{avg}} \]

Since the optimum floor surface temperature range of the heated floor space (ondol) has been known as 30.6°C~38.8°C in recent research, the optimum V.R.T. range for the floor surface temperature can be obtained from this equation. (Yoon et al., 1985)
Thus, $T_{\text{vrt}} = 11.0 - 15.0$ (K)

The hatching area of Fig. 5 presents the optimum V.R.T. range in a floor heated space.

**DISCUSSION**

Table 4 shows the standards and results by some studies on floor surface temperatures, V.R.T. and indoor air temperatures during the heating season for reference to explain the our results on V.R.T.

The optimum comfort range of the floor surface temperatures by Viesmann and Yoon et al. was obtained under the condition which the occupants were seated on the heated floor. On the other hand, other results on the floor surface temperatures were obtained under the condition which the indoor air was convectively heated and the occupants were seated on the chair. Therefore the lower limits of the floor surface temperature in our results are much higher than other results for the occupants' thermal sensation by direct contact with the heated floor.

In Table 4, the V.R.T. is the upper limits except our results. The lower limits and the upper limits were determined simultaneously in our results. That reason is that man's thermal sensation on cold or hot floor and the difference between floor surface temperature and indoor air temperature play an important role to his comfort sensation in floor heating system.

The terms of 'Horizontal' and 'Vertical' in the column of V.R.T. indicate the direction of heat source in Table 4. 'Horizontal' is the condition...
Table 4 Standards and results on optimum comfort limits

<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>Nevins et al.</td>
<td>23.7-37.8</td>
<td></td>
<td>23.7</td>
<td>(Nevins et al., 1964)</td>
</tr>
<tr>
<td>Viesmann</td>
<td>29.4-32.2</td>
<td></td>
<td>15.6-21.1</td>
<td>(Nevins et al., 1964)</td>
</tr>
<tr>
<td>McIntyre</td>
<td>29.5</td>
<td>20</td>
<td>(optimum value: 10)</td>
<td>(McIntyre, 1976)</td>
</tr>
<tr>
<td>Olesen et al.</td>
<td>10</td>
<td></td>
<td>20</td>
<td>nude 0.7 clo (Olesen, 1985)</td>
</tr>
<tr>
<td>Yoon et al.</td>
<td>30.6-38.8</td>
<td>11-15</td>
<td></td>
<td>floor heating</td>
</tr>
</tbody>
</table>

which the heat source is on the wall, and 'vertical' is the condition which heat source is on the ceiling or on the floor.

In the case of horizontal direction, almost of the upper limits of V.R.T. was 10 (K). However, Olesen et al. suggested 20 (K) under the condition which the surface temperature of a wall was controlled higher than the opposite side and the clo value of occupants was 0.7 (clo). ISO and ASHRAE suggested 5 (K) for the upper limit, and McIntyre suggested 10 (K) for the optimum value and 20 (K) for the upper limit of V.R.T..

In the experiments of the present study the heat source was directed vertically. All the V.R.T. for vertical direction expressed the effects of the ceiling heating, but our results expressed that of the floor heating.

Discomfort sensation near the occupants' head by ceiling heating might be increased according to the increase of surface temperature of the ceiling. Because this sensation is more sensitive than the thermal sensation for the floor, the upper limit of V.R.T. is lower than that of the floor heating.

On the contrary, man's thermal sensation by conduction heat from the floor has an important effect upon his comfort sensation in the floor heating system. In addition to the floor surface temperature, the difference between floor surface temperature and indoor air temperature caused occupants to feel discomfort sensation. The V.R.T. is useful to express that differences. So it is recommended to determine the optimum range of V.R.T. including the lower limit as well as floor surface temperature in floor heating system.

In this study, the optimum comfort range of V.R.T. was determined and its range was 11.0-15.0 (K). These results are regarded slightly high rather than other results which were obtained in the ceiling heating system.

In conclusion, it is necessary to establish the lower limit as well as the upper limit on optimum comfort range of V.R.T. in asymmetric radiant field such as an ‘Ondol’ for these reasons.

CONCLUSIONS

The present experiments have been carried out to investigate the optimum comfort limits of the heated floor space. It is recommended that men's thermal sensation of ambient air and floor surface must be considered together to determine the optimum comfort limits on the heated floor space such as an “Ondol” in Korea.
Both the upper limit and the lower limit of V.R.T. should be defined to determine the optimum comfort limits on the heated floor space. It is also recommended that 11.0~15.0 (K) in the V.R.T. be regarded as the optimum limits.

REFERENCES
International Standard 7730, 1984 : Moderate thermal environments-Determination of the PMV and PPD indices and specification of the conditions for thermal comfort, International Organization for Standardization : p.5
Olesen, B.W. et al., 1985 : Comfort limits for asymmetric thermal radiation, Energy and Building, No. 8 : p.225

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