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Modeling thermal comfort with radiant floors and ceilings

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ABSTRACT: The surface temperatures of radiant floor and ceiling systems should depend on the ambient air temperature, yet the surface temperature limits specified by current standards do not vary with air temperature. In addition, the limits for ceiling temperature are specified in terms of radiant temperature asymmetry, which is difficult to convert into surface temperatures. This paper provides graphs that allow designers to directly determine, for a representative room geometry, the acceptable range of floor- and ceiling surface temperatures as a function of air temperatures.

The graphs were generated using the Berkeley Thermal Comfort Model (BCM). Acceptable and optimal floor or ceiling temperatures were found for a range of air temperatures for normal office work activity level (1.2 met). Acceptability was defined as the absence of whole-body discomfort. Depending on the air temperature, the acceptable floor temperature range is 15-40ºC, wider than that specified in ASHRAE Standard 55 and ISO 7730 (19-29°C). The upper limit of 40ºC is based on avoiding discomfort through skin contact, supported by several studies showing that people are comfortable with floor temperatures near 40ºC. The 15ºC lower limit was chosen to avoid local foot discomfort as reported in a laboratory study. The acceptable ceiling temperature range is 10-50ºC, also wider than in Standard 55 and ISO 7730 (radiant asymmetry <5ºC for a warm ceiling, and <14ºC for a cool ceiling). The maximum temperature of 50ºC was chosen as a reasonable water temperature available from heat reclamation, and it was felt that temperatures below 10ºC were unlikely to be used in any climate because of the risk of moisture condensation on surfaces. The model simulation results were compared with published laboratory experiments on radiant floors and ceilings. The results are in generally good agreement, given a number of uncertainties in reproducing the laboratory conditions and matching a variety of different comfort voting scales.

Keywords: Radiant floors; Radiant ceilings; Local comfort; Overall comfort; Local sensation; Comfort modeling

1 INTRODUCTION

The ASHRAE 55-2004 and ISO 7730 comfort standards define temperature limits for floors and ceilings that are independent of the air temperature in the space. The limits were based on laboratory studies conducted under a small range of air temperatures. However, the acceptability of floor- and ceiling surface temperatures clearly depends on air temperature. This study uses a thermal comfort simulation model to examine surface temperature across a range of air temperatures. Surface temperatures that produce comfort at higher or lower room air temperatures may provide new options for energy efficient building operation.

2 BACKGROUND

Floors: Beginning in 1950, Kansas State University (KSU) carried out a series of experiments to determine the effect of heated and cooled floor surface temperatures on human thermal comfort (Nevins et al., 1958, 1964, 1967, Michaels et al., 1964, Springer et al., 1966). The subjects were males, females, and elderly (for the latter, only heated floors were tested). Activity levels ranged from sedentary to light work (for the cooled-floor and elderly-subjects, only sedentary activity was tested). Floor surface temperatures were tested in 5ºF (2.8 ºC) intervals, from 75ºF (23.9ºC) to 100ºF (37.8ºC) for heated floors, and from 75ºF (23.9ºC) to 60ºF (15.6ºC) for cooled floors. In most of the studies, the room air temperature was kept at 75ºF (23.9ºC), except for two heated floor tests of females and elderly, in which 80ºF (26.7ºC) was used.

The upper limit to heated floor temperatures was most constrained by seated women with bare legs, of whom 50% experienced foot discomfort at 90ºF (32.2ºC). Less than 20% of male subjects, and of women at the light-work activity level, experienced foot discomfort at this heated floor temperature. For seated men, less than 20% experienced foot discomfort at the floor temperature up to 100ºF (37.8ºC). The lower limit for cooled floors was determined by women (this time with trousers but bare ankles): 70% of females (and 10% of males) experienced foot discomfort at 60ºF (15.6ºC) whereas only 13% and 0% experienced discomfort at 65ºF (18.3ºC). Olesen (1977) fitted the KSU data to a predicted percent dissatisfied curve and recommended floor temperature limits of 19-30ºC (66 - 86ºF) for sedentary subjects and 17-28ºC for standing or walking persons. This has led to the ASHRAE Standard 55-2004 and ISO 7730 limits that define the allowable range of floor surface temperatures to be 19-29ºC (66.2-84.2°F).

One of the advantages of radiant floor heating systems is that they allow a lower air temperature than traditional convective systems, resulting in reduced heat loss from the building to the outdoors (Olesen, 1994, 2002). The KSU heating data were obtained at a relatively high room air temperature (23.9ºC). If a lower air temperature had been used, the acceptable floor temperature might have been higher than 29ºC. As an example, Zhang et al. (1998) suggested a permissible floor temperature range of 25-31ºC for seated Japanese test subjects at air temperatures of 21-23ºC. Song (2008) tested floor temperature on people with bare feet from 15 to 50ºC in 5ºC intervals at an air temperature of 20ºC. Defining foot thermal sensations between ‘slightly cool’ and ‘slightly warm’ as comfortable, the comfortable floor temperatures were from 25ºC to 40ºC. When using the whole body’s thermal sensation to define comfort, Song found comfortable floor temperatures were from 20ºC to 50ºC.

Ceilings: Because ceilings are further from the occupants than floors, standards set ceiling temperature limits in terms of radiant temperature asymmetry, defined as the difference between the temperatures seen by a planar element facing upward and downward at 0.6m above the floor. The planar element sees walls as well as ceiling, which under normal circumstances moderates the effect of the heated or cooled ceiling temperatures.

McNall et al. tested groups of seated male and female college-age subjects below a 4 x 8 m (12 x 24 ft) radiant ceiling (McNall & Biddison, 1970). They found that 79% of the 16 subjects felt no noticeable discomfort with a hot ceiling temperature of 54.4ºC (130°F) and air temperatures around 26ºC (79-80°F). They also found that 88% of the subjects felt comfortable with cold ceiling temperatures around 11ºC (51-52°F) and an air temperature of 26.1ºC (79°F). The radiant temperature asymmetries associated with the hot and cold ceiling temperatures in the KSU chamber tests were respectively 7.5ºC and 3.1ºC, as calculated from the center of the chamber.

Griffiths and McIntyre tested subjects sitting centrally under a 3.7 x 3.7 m heated ceiling with adjacent walls cooled to provide the subjects thermal neutrality. At a ceiling temperature of 45ºC and the air/wall/floor surface temperatures at 20ºC, they experienced a radiant asymmetry of 7.3ºC. This condition was acceptable to all 24 subjects (Griffiths & McIntyre, 1974). Fanger et al. performed a series of studies with 16 individual sedentary human subjects sitting centrally under radiant ceilings (Fanger et al., 1980, 1985, 1986). A 2.2 x 2.2 m suspended heated ceiling with a temperature of 34ºC (93.2ºF) produced a radiant temperature asymmetry of 4ºC (7.2°F), which was uncomfortable for one (5%) of the subjects (Fanger et al., 1980). This 4ºC value was recommended as the acceptable limit for heated ceilings. For cooled ceilings, a radiant asymmetry of 14ºC (25.2°F) was found to be acceptable to 95% of the subjects. This occurred at a test ceiling temperature of 9ºC (48.2°F) and an air temperature of 28ºC (82.4°F) (Fanger et al., 1985). Based on these Fanger's studies, ASHRAE standard 55 and ISO 7730 define the acceptable radiant temperature asymmetry as 5ºC (9°F) for warm ceilings and 14ºC (25.2°F) for cool ceilings. The limit for heated ceilings in the standards is conservative relative to the McIntyre and McNall results.

It is not easy to calculate radiant temperature asymmetry of spaces in order to obtain ceiling design temperatures. Designers might find it useful to have acceptable ceiling temperature limits directly specified, for a room large enough that the walls don't exert disproportionate influence on radiant temperature asymmetry.

3 SIMULATION APPROACH

We used the UC Berkeley Thermal Comfort Model (BCM) to predict thermal comfort for a wide range of environmental conditions. This multisegment model predicts skin and core temperatures, and thermal sensation and comfort, for the whole body as well as for 16 local body parts: head, chest, back, pelvis, left and right upper arms, lower arms, hands, thighs, lower legs, and feet. For more detailed description of how the BCM predicts physiological responses, sensation and comfort, see references (Zhang et al., 2001, 2004, Huizenga et al., 2001, 2004, Arens et al., 2006 a & b).

The BCM thermal sensation scale is similar to the ASHRAE 7-point scale except that it includes additional points for "very cold" and "very hot": -4 "very cold," -3 "cold," -2 "cool," -1 "slightly cool," 0 "neutral," 1 "slightly warm," 2 "warm," 3 "hot," 4 "very hot."

The comfort scale ranges from "just comfortable" (+0), to "comfortable" (2), to "very comfortable" (4), "just uncomfortable" (-0), to "uncomfortable" (-2), to "very uncomfortable" (-4). There is a gap between "comfortable" and "uncomfortable" to make a distinction between overall category of "comfortable" or "uncomfortable". The two scales are shown in Figure 1.

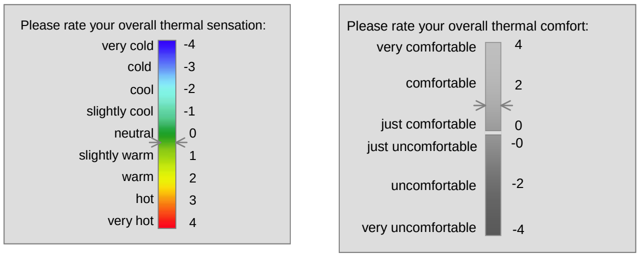


Figure 1. Thermal sensation and comfort scales

We conducted a series of comfort simulations within an 8 x 8 x 2.8 m (26 x 26 x 9.2 ft) room to establish acceptable ranges of surface and air temperatures that might be used directly by system designers and building operators. The relatively large size of this model room was chosen in order to represent open plan offices. Its view factor (from the center of the room and 0.6 m above the floor) is 0.424 for the floor, and 0.256 for the ceiling. Air velocity was constant at 0.1m/s (20 fpm), humidity 50%, activity level at 1.2 met, and clothing insulation 0.59 clo.

For our simulations we varied the air- and floor/(or ceiling) temperatures in tandem, keeping other factors constant. The remaining surfaces in the model room were set to be the same temperature as the air, which was uniform throughout the space.

In order to check the ability of the BCM to predict thermal comfort with radiant systems, we first compared simulated results with several previous human subject tests for which we simulated the published test conditions and chamber geometries.

3.1. Comparison of the model with measured data for radiant floors and ceilings

3.1.1 *Radiant floors*

We simulated a series of Nevins et al. studies of warmed (Nevins et al., 1964) and cooled floors (Nevins & Feyerherm, 1967). For the warm floors, Nevins conducted two series of tests, for seated (1.0 met) and standing light work (1.1 met) activities. Floor temperatures were increased as the air temperature was held constant. We modeled the subjects within the geometry of the Nevins test chamber, with the air and surface temperatures as measured. The subjects wore normal school clothing with approximately 0.7 clo insulation. The Nevins test footwear was estimated as 0.95 clo for the heated floor tests, with a floor-contact fraction of 0.4. This is an approximation; the comfort model requires a single value for foot insulation, while actual shoes presumably have different insulation values for shoe soles, shoe tops, and socks.

The overall (whole-body) thermal sensation scale used in these tests was the same as the ASHRAE 7-point scale, therefore, the test results could be directly mapped onto the BCM scale. Unfortunately, the tests' foot sensation scales were 3-point and 5-point scales, different from the BCM/ASHRAE scales. It is not possible to perfectly match these with the BCM's scale, so there are unavoidable uncertainties in the foot thermal sensation comparisons.

The warmed-floor scale used by Nevins et al. is a 3-point scale: 1-"cold," 2-"comfortable," and 3-"hot". We matched these values to their associated terms to the BCM/ASHRAE scales as follows: minus 3-"cold," 0-"neutral," and plus 3-"hot."

The comparisons for both series of warmed floor tests are presented in Tables 1 and 2.

In Tables 1 and 2, both measurements and simulations show an increase in thermal sensation vote with increasing floor temperatures. The predicted and simulated whole-body thermal sensations are very close. The differences for foot sensation are bigger. The predicted foot sensation votes are lower than the tested data for 1.0 met, and higher than the tested data for 1.1 met. This might be a scale resolution problem, if the subjects perceived Nevins' 3-point scale for foot sensation differently from its 9-point counterpart in the BCM.

Table 1. Warmed floors: comparison of measured and simulated thermal sensation (23.9 ºC air temperature, 0.7 clo, 1.0 met, (Nevins et al., 1964))

Floor surface temperature (ºC / ºF)	Overall sensation		Foot sensation	
	Nevins tested	BCM simulated	Nevins tested	BCM simulated
23.9 / 75	-0.36	-0.31	0.24	0.009
26.7 / 80	-0.27	-0.21	0.45	0.106
29.4 / 85	-0.25	-0.12	0.84	0.205
32.2 / 90	-0.10	-0.04	0.75	0.416
35.0 / 95	-0.06	-0.04	1.08	0.694
37.8 / 100	-0.05	0.02	1.02	0.994

Table 2. Warmed floors: comparison of measured and simulated thermal sensation (23.9 ºC air temperature, 0.7 clo, 1.1 met, (Nevins et al., 1964))

Floor surface temperature (ºC / ºF)	Overall sensation		Foot sensation	
	Nevins tested	BCM simulated	Nevins tested	BCM simulated
23.9 / 75	-0.12	-0.07	0.27	0.518
26.7 / 80	0.00	-0.01	0.78	0.840
29.4 / 85	-0.06	0.05	0.78	1.121
32.2 / 90	-0.07	0.18	0.72	1.396
35.0 / 95	0.08	0.32	1.08	1.636
37.8 / 100	0.43	0.45	1.65	1.746

The comparisons for cooled floors are presented in Table 3. In this series of tests, all subjects were seated (1.0 met). Subjects were clothed in cotton twill shirts and trousers, the standard 0.59 clo Kansas State University uniform, and shoes without laces (loafers for men, flats for women); we assumed those to be 0.7 clo at the foot, with the fraction contacting the floor equal to 0.4.

The overall (whole-body) sensation scale used by Nevins et al. in the cool-floor test could be directly mapped to the BCM scale because it is identical to the 7-point ASHRAE scale, with "neutral" representing the midpoint. The Nevins foot comfort scale in the cool-floor test is now however 5-points: 1-"cold," 2-"cool," 3-"neutral," 4-"warm," 5-"hot." We mapped Nevins' terms to the corresponding terms in the BCM scale, and used the BCM numbering. Thus the term ‘cool’ in Nevins represents both ‘slightly cool’ and ‘cool’ in BCM. The tested and simulated results for cold floors are listed in Table 3.

Table 3. Cooled floors: comparison of measured and simulated data (23.9 ºC air temperature, summer clothes, 1.0 met (Nevins & Feyerherm, 1967))

Floor surface temperature (ºC / ºF)	Overall sensation		Foot sensation	
	Nevins tested	BCM simulated	Nevins tested	BCM simulated
15.6 / 60	-0.42	-1.06	-2.34	-0.83
18.3 / 65	-0.34	-0.89	-1.62	-0.54
21.1 / 70	-0.17	-0.67	-1.13	-0.20
23.9 / 75	-0.59	-0.51	-0.30	-0.1

Both the simulated and tested overall (whole-body) sensation values are between neutral (0) and slightly cool (-1) under 4 tested conditions. The simulated sensation is generally cooler than the measured sensation, with the biggest difference at 15.6ºC floor temperature, when the simulation is slightly cool (-1.06), the measured at -0.42.

The simulated foot sensation values are considerably warmer than the test values, but all of the Nevins values are within the broad ‘cool’ category of this scale, making it difficult to interpret the differences. Even ‘slightly cool’ subjects are assigned a score of -2 (‘cool’) on the BCM scale because it was the only survey category available to them with the 5-point scale. In addition, it may be that the insulation value we assumed for female shoes in the simulations may have been too high.

3.1.2 *Radiant ceilings*

The comparisons for ceiling temperature are done with heated and cooled ceilings tests conducted by Griffiths and McIntyre (1974). The tests attempted to maintain a neutral thermal sensation throughout by changing ceiling, air and the rest of the surface temperatures simultaneously. The subjects were exposed to the test conditions for 15 minutes after arriving in a neutral state, a sequence which we duplicated in the simulations. The Bedford 7-point thermal sensation/comfort scale was used, which can be mapped onto the ASHRAE scale directly.

The comparisons under different test conditions are presented in Table 4. The measured and simulated sensations are slightly above neutral, very close considering the apparent noise in the experimental data. Griffiths and McIntyre also asked the question “Are you suffering any discomfort,” with 1 as ‘no discomfort,’ and 7 as ‘considerable discomfort.’ Votes ranged between 2.4 to 3.5. The BCM simulations show that comfort is maintained under all 4 conditions.

Table 4. Radiant ceilings: comparison of measured and simulated sensation and comfort (0.7 clo, reading or writing 1.1 met (Griffiths and McIntyre, 1974))

Ceiling temp. (ºC)	Air and rest surface temp.(ºC)	Overall sensation	
		Griffiths tested	BCM simulated
23	23	0.2	0.24
30	22	0.7	0.14
38	21	0.4	0.11
45	20	0.5	0.08

3.2 Conclusions to the test comparisons

In general the BCM model predicted sufficiently close to warrant using it to determine limits for floor and ceiling temperatures. The overall sensations for the whole body compared well for all the tests. The biggest mismatch occurs in the cooled foot test comparison, for which there are difficulties matching the tests’ subjective scales to the simulations. Because for the same degree of ‘cool’ sensation the numerical values for the tests are likely to be larger (in the cool direction) than those of the simulations, the differences in this comparison are probably exaggerated.

4 SIMULATION OF ACCEPTABLE SURFACE TEMPERATURE RANGES

A series of comfort simulations were performed to obtain the limits for ceiling or floor temperature for a range of air temperatures, and also combinations of radiant surface temperatures that would yield the highest overall comfort.

4.1 Predicting thermal comfort for radiant floors

To evaluate radiant floor temperature on comfort, we prescribed a maximum temperature of 40ºC for the simulations. This is a reasonable temperature to avoid discomfort through skin contact. Several human subject studies also showed that people felt comfortable with floor temperature near 40ºC (Nevins et al., 1964, Song, 2008).

Figure 2 shows the comfort zone for combinations of air and floor temperatures. Within the air temperature range (17-27ºC), the radiant floor is capable of providing comfort; beyond the range, radiant floor alone could not make occupants comfortable. The upper and lower curves represent the floor temperature boundaries for each air temperature, outside of which warm or cold discomfort will begin to occur (below 0 on a comfort scale of –4 to +4). The middle curve represents the optimum, following the highest comfort value observed for each air temperature. Typical maximum comfort values for radiant floors are around +1.7, and an example of the comfort distribution at 20ºC air temperature is shown in the figure. The distribution is broad-shouldered, indicating that there is a fairly wide range of floor temperatures around the optimal floor temperature which provides good comfort. This broad-shouldered feature was observed for all the air temperatures simulated.

The left side of the figure represents heated floors, and the right side of the figure represents cooled floors. When there is no radiant heating or cooling (represented by the line $T_{floor} = T_{air}$) the summer comfort zone ranges from 22 to 25.8ºC. This matches temperature values for uniform conditions given in the ASHRAE standards.

For heated floors, it is likely that people will be wearing winter clothing and that the acceptable air temperatures will therefore be cooler. We have used 0.9 clo in the left part of the figure (replacing the summer clothing of 0.59 clo). The comfort zone extends down to 17ºC air temperature, a reduction of almost 4ºC below the uniform condition comfort zone for 0.9 clo in the standards.

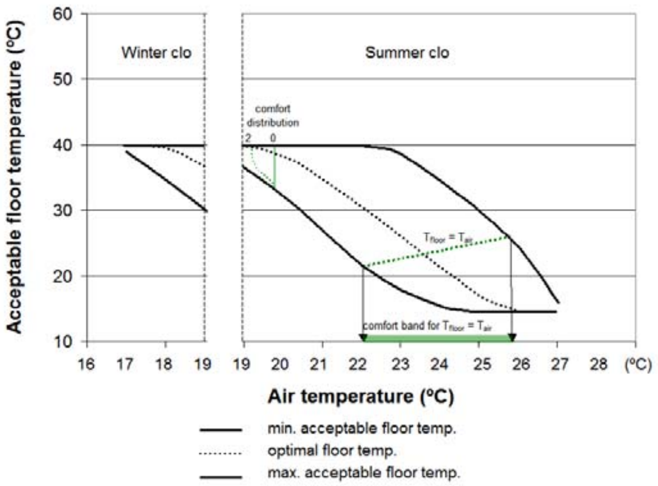


Fig. 2. Comfort zone for radiant heated/cooled floors, light office work (met 1.2, summer clo 0.59, winter clo 0.9, RH 50%).

From the figure, it is obvious that the acceptable radiant floor temperature decreases as air temperature increases. An increase of 1°C in air temperature can be offset by about a 5°C reduction in floor temperature. Though air temperature influences comfort more than floor surface temperature, thermal comfort can be obtained for a wide range of air temperatures when using an appropriate floor temperature. Outside the floor temperature boundaries, the model predicts local thermal discomfort occurring first because of warm feet on the warm boundary, and because of cool hands on the cool boundary.

4.2 Predicting thermal comfort for radiant ceilings

A maximum ceiling temperature of 50ºC is chosen for evaluating comfort with radiant ceilings. This value seemed reasonable for hydronic systems using reclaimed heat. Figure 3 shows the comfort zone for combinations of air and ceiling temperatures, the upper and lower boundaries, and optimum ceiling temperatures for each air temperature. As with floors in Figure 2, radiant ceilings can provide comfort for the air temperature range between 17-27ºC. An example of the comfort distribution is again given for 20ºC air temperature. The distribution was found to be fairly broad-shouldered for all the air temperature simulated. That means that comfort is close to the optimum value over a wide range of ceiling temperatures.

As with radiant floors, when there is no radiant heating or cooling (represented by the line $T_{ceiling} = T_{air}$) the summer comfort zone also ranges from 22 to 25.8ºC, matching the comfort zone for uniform conditions given in the ASHRAE standards. Again, 0.9 clo is used in the left part of the figure, and the comfort zone extends down to 17ºC air temperature, again almost 4ºC below the uniform-condition comfort zone for 0.9 clo given in the standards.

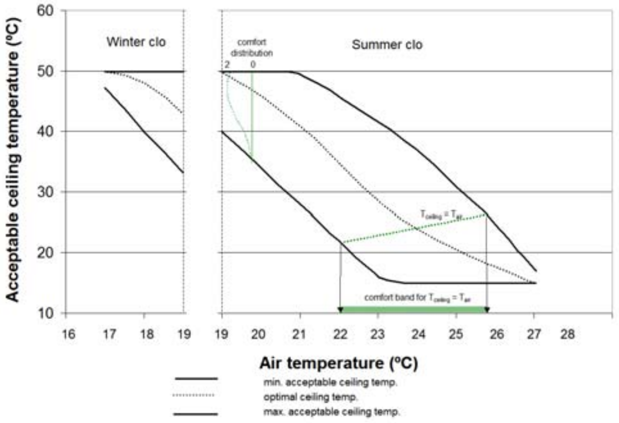


Figure 3. Comfort zone for radiant heated/cooled ceilings, light office work (met 1.2, summer clo 0.59, winter clo 0.9, RH 50%).

The acceptable radiant ceiling temperature decreases as air temperature increases. A 1°C increase in air temperature can be offset by a 3 to 5°C decrease in ceiling temperature. Beyond the comfort zone boundaries, local thermal discomfort is caused by warm head or hands under warm-ceilings or warm-air conditions. Cool feet or hands cause the discomfort with cool ceilings or cool air.

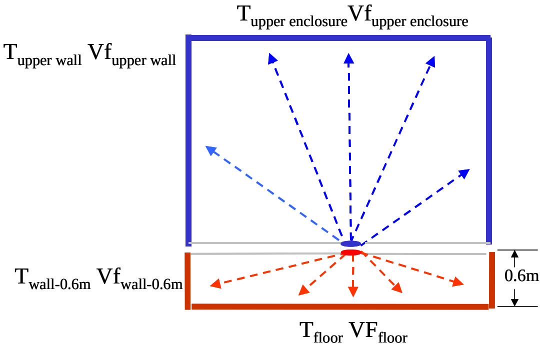
Comparing Figure 2 for radiant floor and Figure 3 for radiant ceiling, we see that when the air temperature is warm (e.g. 25ºC), optimum comfort requires a lower surface temperature on the floor (around 17ºC) than on the ceiling (around 21ºC). When the air temperature is cool (e.g. 20ºC), we need a higher ceiling temperature (around 46ºC) than floor temperature (around 38ºC) to provide optimal comfort. That means cooling the ceiling is more effective at cooling occupants in warm environments, and warming the floor is more effective at warming occupants in cool environments.

5 DISCUSSION

(1) A 1°C increase in air temperature is offset by about 5°C decrease in floor temperature, or a 3-5°C decrease in ceiling temperature. This is similar to results given by McNall et al. (McNall & Schlegel, 1968) and Olesen (1997, 2002).

(2) There is an advantage to specifying limits in terms of ceiling temperature instead of radiant temperature asymmetry, as in the standards, in that designers can directly use the results to design surface temperatures. However, unlike the radiant temperature asymmetry metric, the value of the acceptable ceiling temperature depends on the room geometry.

The radiant temperature asymmetry calculation uses view factors and surface temperatures, as shown in Figure 4 and its associated equation. The space is divided into two spaces, above and below 0.6m height. The radiant temperature asymmetry is the difference between the two plane temperatures of the two spaces, which equals the Mean Radiant Temperature (MRT) difference of the two spaces. The view factors and surface temperatures for each of the two spaces are presented in the figure.



Radiant temperature asymmetry = $MRT_{above\ 0.6m} - MRT_{below\ 0.6m} = (T_{upper\ enclosure}Vf_{upper\ enclosure} + T_{upper\ wall}\ Vf_{upper\ wall}) - (T_{floor}Vf_{floor} + T_{wall\text{-}0.6m}\ Vf_{wall\text{-}0.6m})$

Figure 4. Calculating radiant temperature asymmetry

(4) The recommended surface temperatures are based on thermal comfort analysis only. There is no consideration of other aspects, such as possible

health influences of high or low skin temperatures, as discussed by Song and Seo (2008).

6 CONCLUSION

The influence of air, floor, and ceiling temperatures on comfort and sensation were evaluated for a typical office activity level (1.2 met) using the BCM. Plots of acceptable and optimal surface temperatures are provided for a large range of air and surface temperatures.

Comfort can be provided with radiant floor temperatures of 15-40°C, which is a wider range than that specified in ASHRAE Standard 55 and ISO 7730 (19-29°C). Comfort can also be provided with ceiling temperatures of 15-50°C (corresponding to radiant temperature asymmetry for cool ceiling as 8°C, and for warm ceiling 15°C), also wider than in Standard 55 and ISO 7730 for warm ceiling (radiant asymmetry less than 14°C for a cool ceiling, and less than 5°C for a warm ceiling).

A 1°C increase in air temperature can be offset by a decrease in floor or ceiling temperature of approximately 5°C. A cooled ceiling is more effective at cooling occupants in warm environments, and a warm floor more effective at warming occupants in cool environments.

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