Operative temperature control of radiant surface heating and cooling systems


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SUMMARY

The present study investigates the type of temperature sensor that best represents the operative temperature, i.e., the type of sensor that will integrate the influence of air and mean radiant temperature in the same way as a person. Size, shape and colour of the sensor will have an impact on the relative influence of air and mean radiant temperature in a space.
In an experimental chamber different combinations of air temperature and radiant heated or cooled surfaces were tested. Several types of sensor (flat, sphere, ellipsoid, half-sphere, grey, black, white) were used to measure the operative temperature. Besides comparing the type of sensor, the influence of the sensor position in the room was experimentally investigated. The results show that a grey sensor of 3-5 cm diameter is the best size. The best shape, however, depends on the position of the sensor in the space.

1. INTRODUCTION

Several indoor environmental parameters influence the thermal comfort condition for the occupants. In all existing standards for the indoor environment the requirements for the thermal environment and the room temperature are given by using the operative temperature as reference. (ISO EN 7730 [1], EN 15251 [2]).
The present paper analyses how the measured room temperature varies as a function of position and type of temperature sensor. The influence of sensor type and position in the room was studied in a test chamber with different combinations of heated and cooled surfaces.

The room temperature sensor (or thermostat) represents the first element of a heating/cooling system control loop and is therefore significant for the quality of the control. The operative temperature is defined as the uniform temperature of an enclosure where a person would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment [1]. Thus the sensor should represent the same ratio of heat exchange as the person. The operative temperature can be expressed as:

$$t_o = \frac{\left(h_c \cdot t_a + h_r \cdot t_r\right)}{\left(h_c + h_r\right)} \quad , \qquad (1)$$

where t_o is the operative temperature, t_a is the air temperature, t_r is the mean radiant temperature (°C), h_c is the convective heat exchange coefficient, and h_r is the radiant heat exchange coefficient for a person (W/m^{2}K).
In practice, in most cases where air velocity is small (<0.2 m/s), or where the difference between mean radiant temperature and air temperature is small (<4 °C), the operative temperature can be

calculated with sufficient approximation as the mean value of air and mean radiant temperature [3]:

$$t_o = \frac{(t_a + t_r)}{2}, \qquad (2)$$

This means that air temperature and mean radiant temperature are equally important for the level of thermal comfort in a space and therefore they have the same influence in providing acceptable thermal conditions.
In particular the mean radiant temperature, and consequently the operative temperature, are not evenly distributed and vary according to the location in the room. With radiant surface heating and cooling systems, the mean radiant temperature depends strongly on the surface temperatures of the heated/cooled surfaces, but also on the angle factors between the human body (position of occupant) and the room surfaces, as well as on the emissivity of the surfaces [4].
Therefore if the operative temperature is measured by a sensor, the result will be influenced not only by the position, but also by the shape, size and colour of the sensors.
Among commercially available sensors a grey coloured, ellipsoid-shaped (light grey, 160 mm long, 54 mm in diameter) has angle factors and projected area factors equivalent to the human body [4]. An approximation could be the use of spherical, half spherical and flat plane sensors.
By means of theoretical calculations and experimental testing, this project investigates how representative the temperature measured by the different shaped sensors and in different positions, is of the person's operative temperature in the centre of the room. The paper gives recommendations on positioning the sensor in a room and the type of sensor that is appropriate for radiant surface heating and cooling systems.

2. METHODS AND RESULTS

A theoretical calculation method was used to investigate the influence of sensor size, while an experimental set-up was used to test the influence of a sensor's colour, shape and position.

2.1 Influence of the sensor size

To measure the operative temperature directly, it is necessary to use a sensor with a diameter that will be influenced by the air temperature and mean radiant temperature equally as a person. By transformation of Equation (1) we obtain the following expression of the operative temperature, including the influence of the ratio of radiative/convective heat loss:

$$t_o = \frac{1}{1 + \left(\frac{h_r}{h_c}\right)} \cdot t_a + \frac{1}{1 + \left(\frac{h_c}{h_r}\right)} \cdot t_r, \qquad (3)$$

$$\left(\frac{h_r}{h_c}\right)_{sensor} = \left(\frac{h_r}{h_c}\right)_{person}, \qquad (4)$$

where h_c for a person was calculated based on ISO EN 7730 [1], Vogt et. al [7] and Mitchell (1974) [8], for a sphere according to ISO EN 7726 [4, 9] and for a plate according to [10]. The relative influence of the air temperature (a – weighting factor [1, 4, 6, 7, 8, 9]) can be calculated as a function of the temperature difference (Δt) by natural convection (see Figure 1) or air velocity (v_a) by forced convection (see Figure 2) and compared for sensors of different dimensions.

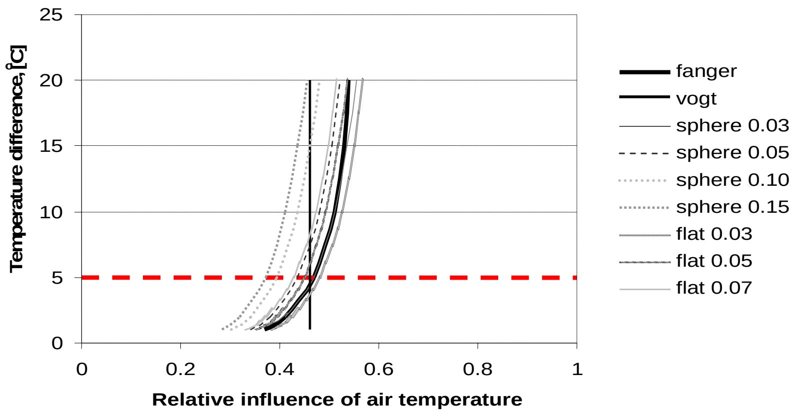

Figure 1. Comparison for natural convection.

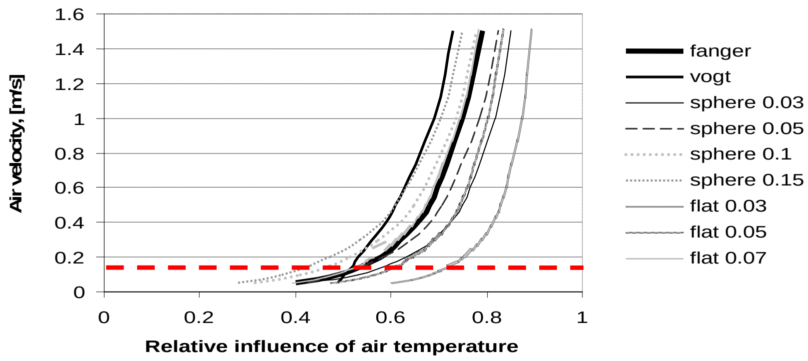

Figure 2. Comparison for forced convection.

The optimal size of the sensor depends on air velocity and Δt, and there is no general optimal size that represents a person's operative temperature. There is also disagreement concerning the convective heat loss for a person [5, 7]. In moderate indoor thermal environments the air velocity is normally lower than 0.15 m/s and the temperature difference between air- and mean radiant temperature is lower than 5 K. For such boundary conditions a diameter between 0.03 and 0.05 m for the sphere, and a length between 0.04 and 0.07 m for the flat shape may suffice (the one used in the present experiment had 3 cm). The lower the air velocity the smaller the required sensor.

2.2 Influence of colour

Three coloured sensors (black, grey, white) and one polished aluminium flat sensor were used in the experiment. The sensors were first exposed to a radiant ceiling (about 42 ^{o}C). The results in Figure 3 show that the colour of a sensor is not important when exposed to long-wave infrared radiation. A polished sensor, however, will reflect more of the radiation and show less influence. In the present test the polished sensor showed a 1 to 2 K lower temperature, depending on the position to the heated ceiling. Room sensors or thermostats may often be exposed to short-wave radiation from direct or diffuse sunlight. This was tested in another experiment. The sensors were exposed to short-wave radiation produced by a high temperature sun-spot lamp. The sensors' direction to the lamp was changed from a perpendicular (position 1 a), 45^{o} angle (position 1b) and a 90^{o} angle (position 1c). The results in 4 shows that the colour and finishing of the sensors had a significant influence on the temperature reading. The lowest effect was on a white and a polished sensor; the highest was on the black sensor. The highest differences (approximately 6 K between black and white) appeared when all sensors were placed 3.5 m from the lamp and faced front perpendicularly to the lamp. By turning around the horizontal axis from the perpendicularly facing position (0°) to parallel with the radiation from the lamp (90°), sensors receive less short-wave radiation and the influence decreases. In a real room the angle of the short-wave sun radiation varies during the day. Generally, a grey sensor gives intermediate results between black and white (see Figures 3 and 4), but closer to the black, and the polished sensor gives results very close to the white, especially when the sensors face the light source directly.

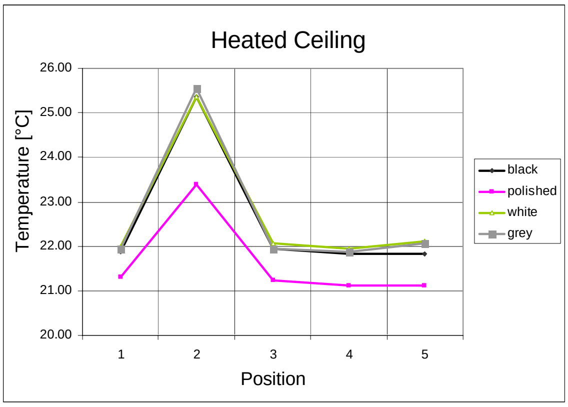

Figure 3. Sample of measured temperatures for flat sensors exposed to heated ceiling

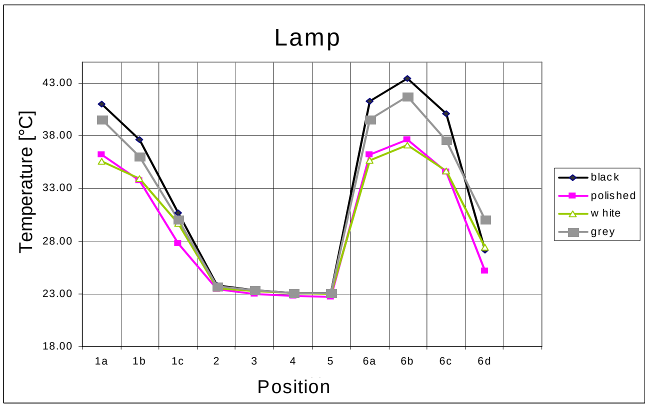

Figure 4. Influence of sensor colour when exposed to sun-lamp at different angles.

2.3 Experimental test of sensor shape and position

The experimental part was completed in a test room (see Figure 5). The tests included experiments with cooled and heated surfaces at different surface temperatures and sensors positioned at different room locations and directions (Figure 6). The experimental room was equipped with a heated/cooled window, heated/cooled ceiling, heated/cooled wall, heated floor, and combinations.

The operative temperatures were measured at 1.1 m height, to simulate the centre of the standing human body. This parameter was estimated by an ellipsoid-shaped sensor (assumed as reference, see Figure 7), a spherical sensor of 4 cm diameter (optimum diameter for use indoors [11] see Figure 8), a half spherical sensor of 4 cm diameter (see Figure 9) and four flat circular sensors of 3 cm diameter. They were made of aluminium plate and painted with black, grey and white colour and one was in polished material. The wall surface temperature was measured with surface temperature sensors.

All sensors were calibrated in a special chamber (with uniform and equal air t_a and wall temperature, placed inside an insulated polystyrene box of 3 cm in five steps (20, 25, 30, 34, 38 °C) and consequently the correction regression lines were developed.

Water-cooled panels (down to 10 °C, sizes of 0.8 m*2 m and 0.8 m*2 m) and electrical heating foils (up to 43 °C sizes of 0.6 m*1.25m and 0.6m*1.75 m) were installed in the test room in order to create significant differences between air- and mean radiant temperature and a high radiant asymmetry. The surface temperatures exceeded the standard values in order to be sure that the results will always be applicable for cases in the comfort range.

The air temperature in the test room was controlled by piston flow through a perforated floor in the range (19-21 °C).

2.4 Test results

The measurement was taken with the different sensors at different room locations at the same height (1.1 m). The results of the measurements with the different sensors are shown in Tables 1 and 2.

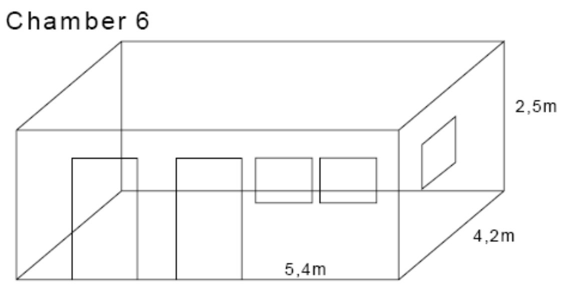

Figure 5. Test room, climate chamber 6 [12]

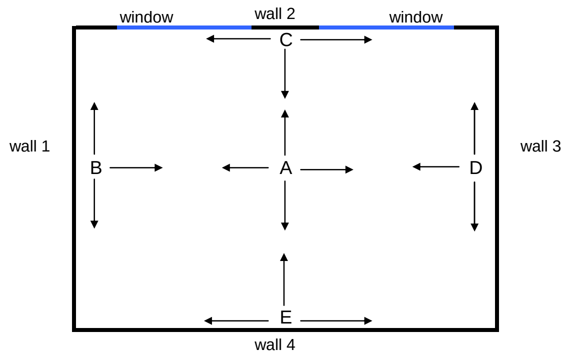

Figure 6. Position and direction of sensors in room test.

Figure 7. Ellipsoid-shaped sensor

Figure 8. Spherical sensor

Figure 9. Half-spherical sensor

Figure 10. Air temperature sensor

The radiant temperature asymmetry is used to describe the non-uniformity of the radiant environment by floor and ceiling heating. The difference between air and mean radiant temperature is also used to describe the non-uniformity. Table 1 shows the results for all sensors in the centre. This comparison is thus influenced only by the type of sensor and not the position. For typical conditions, the floor and the ceiling temperatures were respectively 29.2 °C and 42.4 °C, generating a maximum horizontal radiant temperature asymmetry of 18.8 °C for a heated ceiling. The maximum vertical asymmetry of 8.1 °C was found in the test with a heated wall combined with a cooled wall.

Even if in some cases the radiant temperature asymmetry was quite big the difference between operative and mean radiant temperature were in only two cases higher than 1K (heated ceiling, cooled wall/heated wall).

Table 2 shows the difference between the reference operative temperatures in the centre compared to the measured sensor temperatures in different locations. This is influenced by both the difference in sensor type and position. Table 2 also includes the measured air temperature at the different sensor locations.

Discussion

In terms of thermal comfort, it is preferable to control the room temperature as a function of the operative temperature in the area occupied by people. The positioning of the room temperature sensor in the occupied area may also save energy of 3 to 5% [16] as opposed to positioning the sensor on the wall, and the variations in the room temperature due to the control are smaller.

Other authors have shown the advantage of operative temperature control for maintenance of human comfort compared to air temperature control [13, 14].
In general, a high radiant asymmetry results also in a large difference between air and mean radiant temperature. The results show that using a sensor that is influenced by the radiation gives much better results than just using the air temperature.
Looking at Table 1 for the measurements in the centre, it can be seen that in all cases the sphere will give the best approximation. This difference is in all cases less than 0.5 K except for cases 8 (cooled wall/heated wall) and 2 (cooled windows), where it is respectively 1.7 K and 0.9 K. This is not surprising as the projected area factor for the sphere is closest to the ellipsoid. In the present tests the ellipsoid was in an upright position (standing person), which means a higher influence from the vertical radiation (walls) than from the horizontal radiation (floor-ceiling). This also explains why the greatest difference for the sphere is found for cases 2 and 9.
There is no clear difference between using a half-sphere and a flat sensor. In most cases the difference between the sensors and operative temperature (ellipsoid) were less than the difference between air- and operative temperature.
The results in Table 2 show also in most cases relatively small differences between the different sensors and the reference operative temperature in the centre. However, the sphere in general is not better than the flat and the half-sphere. In most cases the difference between local air temperature and operative temperature in the centre is bigger than the difference between the other sensors and the operative temperature. If positioned close to a heated or cooled wall, the sphere will over-evaluate the influence of the wall. The same is true if the half-sphere or flat sensor faces the heated-cooled surface.

Table 1. Comparison of measured data of all sensors to reference data of ellipsoid in the centre.

	$\Delta(t_{op}\text{-}t_{air})$	$\Delta t_{p,max}$			ΔT_{op} (ellipsoid-sensors)			
Set-up	Centre	horizontal	vertical	sensors	A1	A2	A3	A4
Case 1 Cooled Wall-3 Heated Ceiling	1.0	15.3	5.4	sphere	0.1	0.1	0.1	0.1
				flat	-0.2	-0.6	0.9	-0.6
				half sphere	-0.3	-0.3	0.8	-0.3
Case 2 Cooled Window	-1.0	0.7	1.3	sphere	-0.9	-0.9	-0.9	-0.9
				flat	-0.6	-0.1		
				half sphere	-0.7	-0.4		
Case 3 Cooled Window Heated Wall-1	0.7	1.5	5.3	sphere	0.5	0.5	0.5	0.5
				flat	-0.9	1.5	-0.9	-0.7
				half sphere	0.7	1.1	-0.7	0.1
Case 4 Cooled Wall-3	-0.2	0.5	1.9	sphere	-0.2	-0.2	-0.2	-0.2
				flat	-0.3		0.5	-0.3
				half sphere	-0.4		0.4	-0.2
Case 5 Cooled Window Heated Ceiling	0.8	15.6	1.6	sphere	0.1	0.1	0.1	0.1
				flat		0.9	-0.1	-0.5
				half sphere	0.0	0.6	-0.4	-0.3
Case 6 Heated Wall-1	0.9	3.1	5.4	sphere	0.3	0.3	0.3	0.3
				flat	-1.0	0.1		
				half sphere	-0.7	0.4		
Case 7 Heated Ceiling	1.6	**18.8**	0.2	sphere	0.2	0.2	0.2	0.2
				flat		-0.2		
				half sphere		-0.2		
Case 8 Cooled Wall-1 Heated Wall-3	**2.7**	1.0	**8.1**	sphere	1.7	1.7	1.7	1.7
				flat	0.4	2.8	1.6	
				half sphere	0.8	2.1	3.1	
Case 9 Heated floor	0.1	6.1	0.2	sphere	-0.1	-0.1	-0.1	-0.1
				flat	-0.2	-0.2	-0.2	
				half sphere	-0.2	-0.2	-0.2	

The room sensor should be placed either on an interior wall (half-sphere, flat) or preferably in the occupied zone (all wireless, sphere) of the room. Since the effects of the weather (solar radiation) often affect the area nearby windows, and often people are even positioned close to windows in rooms, it is recommended to position the room sensor approximately 1-2 m from a window at a height of 0.6 to 1.1 m since this height represents a sitting/standing person
Since solar radiation often causes an increase in the temperature in a room, it is beneficial if the room sensor (preferably grey coloured) is affected by solar radiation as soon as possible. A further advantage comes with wireless room sensors that can be installed (placed) in accordance with the room furnishings (furniture, shelves, pictures, etc.).

Table 2. Comparison of measured sensor temperature and air temperature in different locations with the reference operative temperature in the centre (ellipsoid).

	$\Delta(t_{op}-t_{air})$	$\Delta t_{p,max}$			ΔT_{op} (ellipsoid in the centre-sensors)					
Set-up	Centre	horizontal	vertical	sensors	B	C	D1	D2	D4	E
Case 1 Cooled Wall-3 Heated Ceiling	1.0	15.3	5.4	air	1.0		1.1	1.1	1.1	1.3
				sphere	0.4		1.1	1.1		0.3
				flat	-0.3		-0.6	0.3		-0.4
				half sphere	-0.1		-0.4	0.9		-0.1
Case 2 Cooled window	-1.0	0.7	1.3	air	-1.0	-0.7				-1.0
				sphere	-0.6	-1.1				-1.2
				flat	-0.8	-0.4				-0.9
				half sphere	-0.1	-0.5				-0.8
Case 3 Cooled Window Heated Wall-1	0.7	1.5	5.3	air	0.7		0.9	0.9	0.9	0.7
				sphere	-0.4		0.7			0.5
				flat	-2.9		0.0			0.5
				half sphere	0.4		0.4			0.2
Case 4 Cooled Wall-3	-0.2	0.5	1.9	air	-0.6		-0.1	-0.1	-0.1	-0.3
				sphere	-0.5		0.2		0.2	0.1
				flat	-0.4		-0.3		0.4	-0.2
				half sphere	-0.5		-0.2		0.2	0.0
Case 5 Cooled Window Heated Ceiling	0.8	15.6	1.6	air	0.9	1.4				1.0
				sphere	0.1	0.7				0.1
				flat	-0.8					-0.2
				half sphere	-0.4	0.6				-0.1
Case 6 Heated Wall-1	0.9	3.1	5.4	air	0.4		1.2	1.2	1.2	0.9
				sphere	-0.7		0.7			-0.4
				flat	0.0		0.3			-0.5
				half sphere	-0.9		0.2			-0.2
Case 7 Heated Ceiling	1.6	18.8	0.2	air	1.9					1.4
				sphere	0.4					0.1
				flat	-0.4					-0.2
				half sphere	-0.2					-0.2
Case 8 Cooled Wall-1 Heated Wall-3	2.7	1.0	8.1	air	1.7		3.1	3.1	3.1	2.5
				sphere	0.2		3.3			1.6
				flat	2.2		2.1			2.2
				half sphere	1.9		2.5			2.3
Case 9 Heated floor	0.1	6.1	0.2	air			0.1	0.1	0.1	0.4
				sphere			0.0			0.1
				flat			-0.2			0.1
				half sphere			-0.2			-0.1

CONCLUSION

The investigations show the advantage of taking into account the thermal radiation in a room, when controlling heating and/or cooling systems according to the operative temperature.

A sensor size (flat, sphere, half-sphere) about 3 to 5 cm will be influenced by radiant and convective heat exchange in a similar way as a person.
For long-wave radiation the colour of the sensor is not important.
For short-wave radiation such as sunshine, a black sensor will overestimate and a white or reflective sensor will underestimate the influence of the radiation. A flat grey or similar colour is recommended.
The influence of the sensor shape depends on the position of the sensor. If the sensor can be positioned in the centre of the room the best shape seems to be a sphere.
As a room thermostat is most often positioned on a wall, the sphere will overestimate the influence of the wall close to the sensor. In this case, a half-sphere is a better shape.
The half-sphere and the flat sensor give in many cases similar results; however, the half-sphere gives values closer to the operative temperature in the centre.
The influence of the sensor shape and position may be up to 2 K in environments where the difference between air and mean radiant temperature is less than 3 K.

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