Thermal Comfort: Radiant Systems—A Review of Experimental-based Thermal Comfort Research in Radiation Systems

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1. INTRODUCTION

Buildings use 40% of the global energy consumption and emit 30% of the CO_2 emissions [1]. Of the total building energy, 30-40% are for building heating and cooling systems, which regulate the indoor thermal environment and provide thermal comfort to occupants. In the United States, most buildings use forced air technology to deliver heating / cooling to the targeted thermal zones as shown in figure 1. This system may cause complaints for thermal comfort from inhabitants due to excessive draft movement, inhomogeneous conditioning, and difficulty in accurately controlling the temperature for a system serving multiple rooms [2].

To address these issues, researchers have suggested the use of radiant heating and cooling system as a better alternative to all-air systems, as depicted in figure 2 and 3. Radiant systems supply heating or cooling directly to the building space using radiation released by the heated or cooled building enclosure via the embedded heating or cooling tubes. In the cooling season, the radiant system often works with a separated dehumidifier together to meet space latent and sensible cooling load (called separate sensible and latent cooling system SSLC). The SSLC has shown higher efficiency than forced air systems [3]. However, it is unsure whether the radiant heating and cooling system can provide better thermal comfort to occupants. Moreover, the evaluation method for thermal comfort in the current standard is only suitable for forced air systems. A new method shall be developed to evaluate the radiation system’s thermal comfort.

In this paper, we review the experiment-based studies on the thermal comfort of radiant systems. According to the experimental studies regarding thermal comfort and radiant systems, the key findings are concluded to help guide the evaluation of thermal comfort for radiant systems.

2. NEW PARAMETERS FOR THERMAL COMFORT EVALUATION

Traditionally, thermal comfort studies for building heating and cooling systems consider both physical conditions and human factors. The physical parameters measured include mean radiant temperature (MRT), relative humidity, air velocity, and indoor air temperature. These are coupled with human parameters such as clothing level and metabolic rate.

Radiant heating and cooling system utilize radiation rather than convection to transfer heat to the occupants in the building space. It is not enough to study the air condition and mean radiant temperature since the radiation is related to the surface temperatures and the geometry relation between an occupant and the radiant surface. In the various studies of radiant heating and cooling systems we reviewed, the physical parameters measured include MRT (mean radiant temperature), relative humidity, air velocity, and indoor air temperature. Table 1 summarizes the sensors used for both commonly used evaluation parameters and new parameters being proposed in the studies. The information of the sensors used in the studies include sensor categories, descriptions, producers, accuracy specifications, and general pros & cons [4-36].

The sensors are placed 0.9 m above the floor which is considered the standard height for a sedentary person, and close to the test subject for more accurate results. Air temperature was also measured in selected studies at four different heights including 0.1m, 1.1m, 1.7m, and 2.8m to evaluate local discomfort that could potentially be brought about by vertical temperature difference [11].

Additionally, the new proposed parameters for assessing thermal comfort in other states are individual surface temperature and skin temperatures. Kashif, et al. [4] assessed

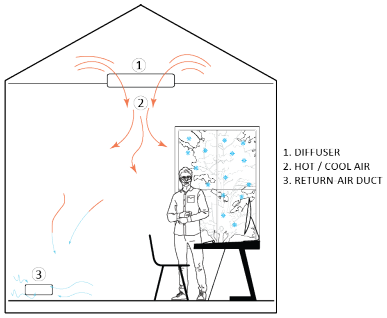

Figure 1. Forced-air Heating & Cooling.

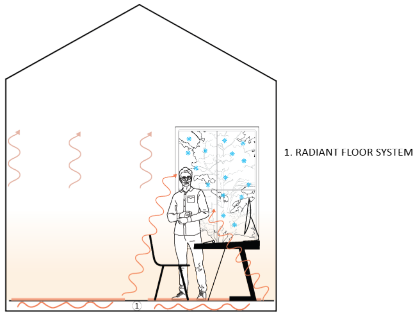

Figure 2. Radiant Heating.

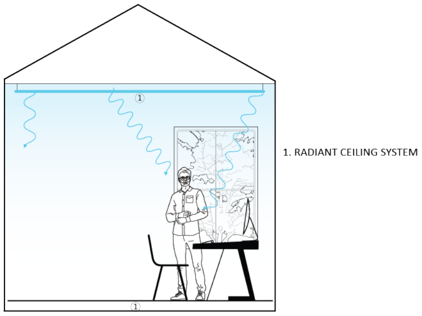

Figure 3. Radiant Cooling

sleeping parameters for sleeping comfort and quality of sleep under thermoelectric air-cooling systems. Parameters including sleep onset latency, efficiency of sleep, and wake abouts are involved in the thermal comfort assessments to reach a more accurate result. Skin temperature parameters were measured at various parts of the body including head, chest, back, arms, thighs, calves, and core using thermocouples with adhesive or infrared thermometers to calculate local thermal sensation for individual body parts, then developed overall thermal sensation results. In consideration for radiant asymmetry that might cause local discomfort, thermal sensation vote and thermal comfort vote that are calculated from skin temperature information are utilized to assess discomfort and surface temperature limit [4,7,10,13,19,23].

Radiant systems can be classified as per the location of the architectural construction with respect to the radiant system. Figure 4, illustrates the most commonly used configurations

3. ASSESSMENT METHODOLOGY FOR RADIANT SYSTEM

Since radiant heating and cooling focuses more on the transfer of heat that is not achieved through convection, temperatures of the radiant surfaces and local temperatures of test subjects are used along with indoor parameters to evaluate subjective thermal comfort.

Teitelbaum, developed a new thermal comfort evaluation framework for forced air systems and radiant systems by defining comfort as when the heat flux of convective, radiative, and evaporative modes equal to the individual's metabolic rate [24]. Researchers can thus adjust specific parameters without changing the air temperature to provide better comfort based on the chart [24].

4. THERMAL COMFORT EVALUATION

Skin temperature measurements on local body parts help thermal comfort evaluation for radiant systems because they account for vertical and horizontal radiant temperature asymmetries induced by the high-temperature difference between the body and radiant panels. Local skin temperatures measured were at the forehead, back, chest, forearm, upper arm, backhand, thigh, calf, and foot. They are then used to calculate mean skin temperature [21]. Since core temperature is an internal temperature, the variation of core temperature is only 0.1°C, which is not significant in thermal comfort evaluation [22]. Zhang, [22] developed a relationship between local skin temperature and local thermal sensation/comfort using physiological measurement data and subjective responses.

5. SUBJECTIVE THERMAL COMFORT EVALUATION

Different types of surveys and questionnaires are included in every research with slight differences in the approach. The questionnaires are conducted in small intervals during the test based on mostly ASHRAE 55-2004 or ASHRAE RP-921 protocol [8,10,11,13]. The number of responders varies by the study, but they are in the low one hundred in terms of magnitude. Geographically these were conducted across the globe in Asia and Europe. The following techniques were used to evaluate thermal comfort for radiant systems subjectively.

5.1 PMV & AMV

PMV: PREDICTED MEAN VOTE AMV: ACTUAL MEAN VOTE

Using the ASHRAE 7-point thermal sensation scale, the questionnaires addressed occupant thermal sensations, acceptability of thermal environment, thermal preference, satisfaction with general comfort, clothing level, etc., which varies with different research. The ASHRAE 7-point thermal sensation scale is a scale that ranges from -3 to +3 with 3 being feeling hot, -3 being feeling cold, and 0 being feeling neutral. PMV and AMV (thermal sensation reported by occupants) are then calculated based on the parameters addressed above and compared in selected research. Positive PMV-AMV difference indicates that test subjects perceived cooler with a radiant system under the same operative temperature than with a conventional air system

5.2 TSV: THERMAL SENSATION VOTE

Thermal sensation vote (TSV) is a subjective vote from the occupants on a scale from -4 to 4, with 4 being very hot and -4

ID	Parameters	Type	Products	Accuracy Level	Pros	Cons	Reference
1	Temperature	**Thermocouple (K- or T-types)**	Testo[4], Swema 03[10],Aosong GSP 958[11]	±2.2°C ±1%	Low Cost, Economical, Good Availability, Self-Powered	Low accuracy, Low-High Power Consumption	[4],[6], [8],[9],[10],[11],[17]
		Integrated Chip		Good	Low Cost, Small Size, Accurate, Low Power Consumption	Small Range of Detected Temperature	[5]
		IoT Temp sensors	Arduino+data storage device	Good	Wireless + Cloud Computing, Remote Control, Real Time Data Collection	High Price	[7]
		Thermistor	TandD Coorporation TR-72UI[12],NTC thermistor[13],Precon,ST-S3EW-XPA[14], Thermistor probe and tape on thermistor[23]	Depends on Calibration	Good Sensitivity	Suffers from Self-Heating	[12],[13],[14],[23]
		Resistance Temeprature Detector (RTD)	EE21 transmitter[16]	Best	Very High Accuracy	Very High Price Point, Less Sensitivity, High Power Consumption	[16]
	Relative Humidity	**Capacitive sensor**	Aosong GSP 958[11],Honeywell HIH-4000[13]	±2% RH	Able to Function at High Temperature and Low Temperature, Full Recovery from Condensation	Direct Field Interchangebility	[4],[11],[13]
2		**Resistive sensor**	Rotronic HC-S[10],Vaisala, HWM90[14]	±2% RH 0.1% accuracy	Low Cost, Small Size, Readily Interchangeble, Remote Control, High Repeatability	None, Resistant to Condensation	[10],[11],[14]
3		**Thermal sensor**	Testo Hygrometer[8]	±5% RH at 40°C and ±0.5% RH at 100°C	Able to Function at High Temperature, Durable at High Temperature (300 °C), Provides High Resolution		[8],[9]
4	Wind Speed	**Cup anenometer**			Omnidirectional, Reliable and Resistant	Low accuracy on low measurements, Ice could Disturb Proper Reading	
5		**Hotwire anenometer**	Testo IAQ probe, Swema 03[10][14], VELOCICALC-8347[12], Dentec[13]	±0.2m	Higher Durability than Cup Anenometer, High Precision, Quick Response, Small Size	Large Particles could Damage Anenometer, not Suitable in Places with High Temperature Fluctuation	[4],[8],[10],[12],[13],[14]
6		**Hotbulb anenometer**					[9]
7	MRT	**Globe thermometer with thermocouple**	TESTO 480 Globe Probe[4], Combined sensor device(Arduino)[7], Swema05[10], TR-102Black globe[12], Kimo TM110[14], TJHY HQZY[20]	±2°C ±1%			[4],[7],[8],[10],[12],[14],[19],[20]
12	Skin Temperature	**Infrared thermometers**	Swema Multipoint[10]			Less Accurate But Statistically Insignificant	[10]
13		**Wired sensor(resistive)**	PT1000[4], Wired Skin Temperature Sensors of YSI400 standard[7], Wireless iButtons (Thermochron iButton, DS1291H)[13], T-type thermocouple[19]	±0.1%	More accurate measurement		[4],[7],[13],[19]
14	Human/Physiological Parameters(heart rate, metabolic rate, movement, state of being)		Fitbit Alta HR Watch[4], ORMON HEM-7112[19]				[4],[19]
15	Surface Temperature		FLIR c3 handheld infrared imaging thermometer[10],NTC Thermistor, U-type EU-UU-10-PTFE[13]				[10],[13]

Table 1. Common Sensors used for Thermal comfort research in Radiant Systems.

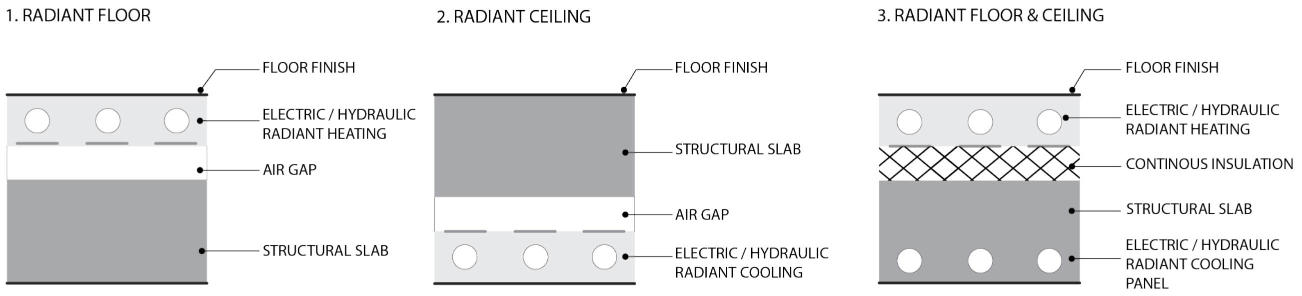

Figure 4. Configuration of Radiant Systems.

being very cold. Since TSV is a subjective vote, its relationship with skin temperature has been analyzed from experiment results. Skin temperatures were measured at 28 locations on the body, and sensation and comfort questions were asked for 19 local body parts and for the whole body [22]. In asymmetrical environments, thermal sensation and thermal comfort can be estimated mainly by the local skin temperatures and core temperatures [22].

5.3 TCV: THERMAL COMFORT VOTE

Thermal comfort vote (TCV) is the local thermal comfort of a body part voted on a scale from -4 to 4, with -4 being very uncomfortable and 4 being very comfortable. When subjects are thermally neutral, thermal comfort vote and thermal sensation vote shows a linear relationship. As local TSV shifts to a higher value (warm), local TCV starts to decrease from 2 to -4, which indicates a warm local discomfort.

6. THERMAL DISCOMFORT EVALUATION FOR THE RADIANT SYSTEM

In evaluating thermal discomfort for radiant systems, draught, vertical temperature difference (VTD), and radiant asymmetry have been analyzed with parameters including surface temperature, skin temperature, and air velocity.

6.1 DRAUGHT

Since the radiant system involves low air velocity (< 0.2m/s) and vertical temperature difference (<0.4°C), it eliminates potential discomfort caused by excessive air movement compared to all air systems [14]. Azad, Abdus Salam, [14] found that the percentage dissatisfied due to draught for the radiant system is 10 while 20 for the conventional all-air system [14].

6.2 VERTICAL TEMPERATURE DIFFERENCE (VTD)

Air temperatures were measured at different height levels, including 0.1m, 1.1m, 1.7m, and 2.8m [8]. As radiant temperatures asymmetry and surface temperatures could affect test subjects' thermal sensation, the walls, ceiling, and floor's temperature were measured using a FLIR handheld infrared imaging thermometer in research regarding radiant cooling [10].

6.3 RADIANT TEMPERATURE ASYMMETRY

The ASHRAE guideline for radiant asymmetry presents all the comfort limits for overhead radiation and horizontal radiant asymmetries, including warm ceiling, cold ceiling, warm wall, and cold wall. The findings done by the researchers include maximum vertical temperature difference from ankle to head, comfort limit of floor heating, the effect of the cold window on radiant asymmetry, air stratification for floor heating, the effect of exposure duration for radiant asymmetry, and comfort limit for cold floors.

7. CONCLUSION

The review studies have the following findings that are important for future research and design of thermal comfort in radiant systems. (1) Except for the mean radiant temperature, new parameters that are more suited for thermal comfort evaluation of radiant systems include skin temperature and surface temperature. (2) The thermal comfort evaluation parameters in the studied literatures include predicted mean vote, actual mean vote, thermal sensation vote, thermal comfort vote. (3)Using PMV (Predicted Mean Vote) alone as subjective evaluation of thermal comfort does not account for thermal discomfort brought by vertical temperature difference (VTD), and local discomfort caused by radiant asymmetry and increased air velocity. (4)Thermal discomfort including draught, vertical temperature difference (VTD), and radiant asymmetry could be adequately evaluated using the new parameters introduced above.

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