Thermal Comfort Assessment of Two Semi-Detatched Houses

TECHNICAL BRIEF

Thermal comfort is defined by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) as the condition of mind which expresses satisfaction with the surrounding environment. It is assessed subjectively through ASHRAE Standard 55 (Thermal Conditions for Human Occupancy). Variables involved in maintaining optimal thermal comfort include temperature, humidity, air motion as well as a person's metabolic rate and clothing insulation value. Air quality and thermal comfort are important because they influence productivity and health.

Canadians spend close to 90% of their time indoors. Most complaints about indoor climate conditions relate to thermal comfort. Improving indoor comfort can enhance productivity, health and our sense of well-being. Alterations such as reduction of forced air heating and improved indoor/ outdoor air exchange can promote both thermal comfort and energy efficiency.

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The comfort of a home can be assessed through a thermal assessment of its indoor temperatures as experienced by its occupants. Controlling the temperature of a home allows occupants to experience thermal comfort. The level of thermal comfort that can be achieved for a given building depends, among other factors on the structure's thermal insulation and maintenance level. This study compares the winter and summer indoor comfort level in two semi-detached houses at the TRCA's Living City Campus. The two houses are similar in size but are heated, cooled and ventilated with different mechanical systems. The purpose of the research was to assess the thermal comfort performance of the two well insulated houses, to provide insights into how differences in heating, ventilation and air conditioning (HVAC) systems may affect the comfort of building occupants. The ASHRAE Standard 55 was used to assess thermal environmental and ventilation conditions. Psychological factors were determined through modeling based on measured parameters and predetermined relationships. A key objective of the study was to evaluate the effect of in-floor and forced air systems on interior comfort levels during the heating and cooling seasons.

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STUDY SITE

House Specifications

The study was conducted in two semi-detached houses, referred to as House A and House B within this report. Both houses are 3-storeys with similar floor areas, internal volumes, and levels of insulation (R-30 above grade, R-20 below). House B has roughly 20% more window coverage than House A, and has triple glazed windows with higher thermal resistance than the double glazed windows in House A. The design heating loads of House A and House B are 7.91 kW and 7.94 kW when outdoor and indoor temperatures are -22 °C and 22 °C, respectively. Table 1 summarizes the mechanical systems in the two houses. As shown in the table, the main differences between the houses relate to the heating, cooling and ventilation systems. House A was equipped with an air source heat pump and forced air distribution system. House B has a ground source heat pump with radiant floor heating, and forced air cooling. In House A, a heat recovery ventilator (HRV) is used to pre-heat or pre-cool incoming fresh air by allowing heat-exchange with the exhaust air. An energy recovery ventilator (ERV) installed in House B operates in a similar fashion but also allows for moisture exchange. Both House A and B include a 0.91 m (36") long grey water heat exchanger for grey water heat recovery.

Energy Audit

A blower door test was conducted to determine how much air was leaking into the houses, at an outside temperature of – 7.7°C and inside temperature of 20.0°C. Results of the blower test, showed that the exterior building envelopes were better sealed than most homes (exceeding the R-2000 Standard), particularly House B, which registered only 1.1 air changes per hour (ACH) during the blower test (more air changes mean leakier houses). House A registered 1.2 ACH. By comparison, the Energy Star label requires a maximum of 2.5 ACH, and the new 2012 Ontario building code allows 3.1 ACH.

APPROACH

ASHRAE Standard 55

Although the sense of thermal comfort varies among individuals due to unique preferences, laboratory and field testing has been conducted to standardize the requirements of thermal comfort by providing a range that is acceptable for a certain percentage of the building occupants, often 80%. The ASHRAE 55 Standard outlines six conditions that provide thermal comfort: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity. These factors are used to relate the predicted mean vote (PMV) and heat balance principles in order to estimate the associated predicted percentage of dissatisfied occupants (PDD) for various conditions (Figure 1). Software packages (LumaSense and SWEMA Multiport) were utilized to provide a value of PMV and a PPD.

Monitoring

Monitoring took place on May 5-10 in the heating season and on July 8-10 in the cooling season. Heating season measurements were taken when indoor and outdoor temperature difference was 18.5 °C, which was 2°C less than the ASHRAE requirement. Cooling period measurements were taken during temperature difference of more than 3.5 °C, meeting the requirements. Sensors to characterize the ambient conditions were placed in second floor north facing bedrooms, where less direct solar radiation was observed compared to the downstairs living areas. Sensor placement within each bedroom was chosen based on expected occupant positions with respect to existing furniture.

Measurements were taken for air temperature, radiant floor temperatures, humidity, and air velocity at 0.6 m above the floor for the cooling season (other heights not available due to computer

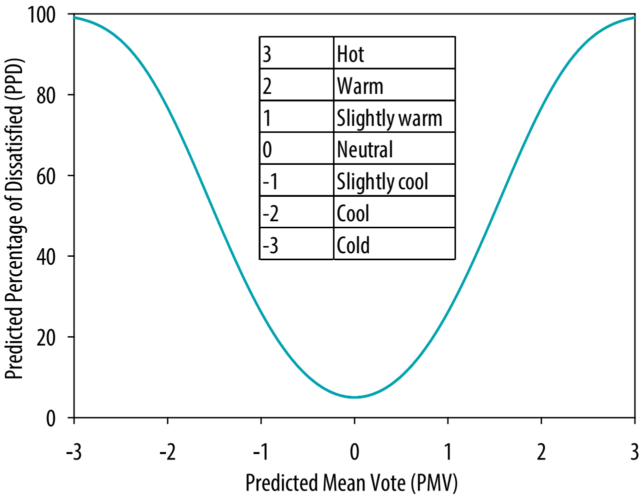

Figure 1. PMV and PPD relationship with qualitative descriptions of the PMV values. .

Table 1. Mechanical features of House A and B.

Features	House A	House B	Guest Suite
Heating and cooling appliance(s)	Variable capacity air-source heat pump (10.5 kW) with hydronic heating coil back-up (from wall-mounted mini gas boiler), both integrated into AHU	Horizontal loop ground-source heat pump system (13.3 kW) with desuperheater	Hydronic heating and cooling coil interconnected with House B distribution system; solar wall heater
	Wall mounted mini gas boiler	No back-up heating system	
Heating and cooling distribution systems	In-floor heating in basement (mini-boiler) and forced-air (air-source heat pump) on all other floors	GSHP charges buffer tank used for radiant in-floor heating and multi-zone forced-air cooling	Forced air distributon via AHU integrated ERV and hydronic heating/cooling coil
Ventilation system	Heat recovery ventilator (HRV)	Energy recovery ventilator (ERV)	HRV

malfunction) and for 0.1, 0.6 and 1.1 m for the heating season. The interplay of these factors was used to obtain values for subjective environmental factors such as metabolic rate (an indexed value of 1.1 for activities such as typing, sitting and relaxing,) and clothing level (1 for heating season – underwear, long sleeved shirt, trousers, long sleeved sweater, socks and shoes, and 0.5 for cooling season – underwear, short sleeve shirt, light trousers, socks and shoes).

Table 2. Summary results for House A and B thermal comfort performance.

		Heating		Cooling		
	Parameter / Output	**House A (May 10)**	**House B (May 5)**	**House A (July 8)**	**House B (July 8)**	**Standard**
Conditions	Average Air T (°C)	24.4	24.5	23.3	22.5	
	Mean Radiant T (°C)	24.3	24.3	23.4	22.7	
	Average Air Velocity (m/s)	0.06	0.01	0.08	0.01	0.15
	Relative Humidity (%)	28.9	28.8	51.1	54.5	85
	Max 15 min T variation (°C)	0.2	0.1	0.1	0.1	1.1
	Max 8 hr T variation (°C)	1.1	0.7	1.5	1.1	3.3*
Local Thermal Discomfort Conditions	Draft (max m/s)	<0.15	<0.15	<0.15	<0.15	0.15
	Vertical Air T Difference (°C)	<3	<3	2	0.4	<5 % (△ 3 °C)
	Warm or Cold Floors	6%	6%	7%	6%	<10 %
	Radiant Asymmetry	1%	1%	1%	1%	<5 %
Clothing Level = 1.0	PMV (-3 to +3)	0.4	0.4	0.3	0.1	-0.5-0.5
	PPD (%)	8.3	8.3	6.9	5.2	<10
	Operative T (°C)	24.4	24.4	23.4	22.6	21.5-25
Clothing Level = 0.5	PMV (-3 to +3)	-0.5	-0.4	-0.6	-0.9	-0.5-0.5
	PPD (%)	10.2	8.3	12.5	22	<10
	Operative T (°C)	24.4	24.4	23.4	22.6	25-28.2

FINDINGS

House B was found to have a higher level of thermal comfort than House A during the heating season when light clothing is worn. This can be explained by the difference in air velocity, with 0.06 m/s in House A, compared to 0.01 m/s in house B (Table 2). The higher velocity may be attributed to the forced air distribution system in House A. Since higher velocity creates higher discomfort for exposed skin, House A displayed a slightly higher discomfort level (i.e. higher PPD, 10.3 For House A and 8.3 for House B) under the lower clothing scenario of 0.5. With appropriate winter clothing, the discomfort levels were the same, and at both clothing levels, the ASHRAE Standard 55 for thermal comfort was met. These results would need to be based primarily on other factors, such as cost or environmental impact, rather than thermal comfort performance, which can be altered with different clothing levels.

During the cooling season, both Houses met ASHRAE 55 for a clothing level of 1.0 only. The cooling season indoor air temperatures were 23.3^{0}C and 22.5 ^{0}C, for House A and B, respectively, which registered a high level of thermal discomfort (i.e. high PPD and negative PMV) at a clothing level of 0.5 (Table 2). As was the case during the heating season, this was largely due to the poor matching of temperature and clothing level, rather than the HVAC system performance. Increasing the operative temperature would have improved the results while also conserving energy. At the higher clothing level, both houses met the standard, but House B slightly outperformed House A, likely due to the slightly lower air temperature in House B. Both houses would likely have met ASHRAE 55 at a clothing level of 0.5 had the temperature been set to an appropriate level, as indicated by the standard temperature range of 25-28.2 ^{0}C.

All Standard 55 requirements for Local Thermal Discomfort were met in both houses. Table 2 presents results for local thermal discomfort conditions. A draft causes unwanted cooling, which depends on air velocity, temperature and clothing level. To meet the Standard at operative temperatures below 22.5^{0}C, air speeds should not exceed 0.15 m/s as measured at any height surrounding the occupant. Maximum air velocities in both houses during the heating season were below the Standard maximum of 0.15 m/s.

Vertical air temperature differentials between the ankle and head can cause local warm or cold discomfort at the feet. There was a maximum 2°C differential in House A during the cooling season and 0.4 °C in House B, both of which were below the maximum allowable difference of 3°C. The presence of air vents closer to the equipment may explain why this differential was higher in House A than House B. This study design decision was dictated by expected typical location of occupants within the room as per furniture layout.

The floor temperature is important because the feet are sensitive to temperature variations and a feeling of cold at the feet is reflected in the rest of the body. The Standard requirement was met as both houses varied by less than 10 % (Table 2).

The Standard related to radiant temperature asymmetry refers to the temperature of the surrounding ceilings and walls. Discomfort is felt when these vary considerably in the horizontal or vertical planes. In both houses, temperature differentials between the air temperature and wall/ceiling surfaces were less than 2%, and well below the maximum allowed temperature difference in the Standard.

Requirements for indoor temperature variations over time were met in both houses, but House B was able to maintain

the desired temperature within a narrower range during both seasons. Changes in temperature that are not initiated by the occupant can cause discomfort and are therefore specified under ASHRAE 55. While 15 minute temperature variations were almost identical between houses, variations over longer periods were not. During the heating season, the radiant floor heating system in House B maintained a narrower temperature range, as expected. The difference in temperature variations between the two houses over an 8 hour period narrowed during the cooling season, when both Houses were distributing cool air via forced air distribution systems, but House B was still able to maintain marginally lower variations. Despite noted differences in 15 minute and 8 hour temperatures, the observed narrow range of temperature variations in both Houses would suggest that both HVAC systems function well and provide similar levels of comfort without the need to adjust clothing levels between system cycling.

The higher up-front cost of House B mechanical systems could not be justified based on improvements in thermal comfort alone. The houses differ only slightly in their comfort levels. These minor differences would not, by themselves, be sufficient to justify selecting the technology package in one of the houses over the other. Although, radiant floor systems are widely touted as providing improved thermal comfort during the winter, they come at a higher up-front cost. This study did not reveal significant advantages of House B based on comparisons with ASHRAE 55. It should be recognized, however, that the Standard lays out minimum requirements to avoid thermal discomfort, rather than to achieve optimal thermal comfort. If we were to rate satisfaction based on the higher level of comfort that the radiant floor system in House B provides, we may have found that House B occupants were indeed significantly more comfortable; many individuals would appreciate the enhanced thermal comfort of warmer floors. It should also be noted that measurements were not taken during the coldest winter temperatures, when the differences would have been more substantial and other patterns may have been revealed.

CONCLUSIONS

This study has shown that both houses meet the ASHRAE Standard 55, when clothing appropriate for the season is being worn. Both houses had higher PPD than ASHRAE 55 (except for House B during the heating season) when only light clothing is worn (0.5 to 0.7 levels), but otherwise performed well. These results highlight the importance of setting the temperature at a level appropriate for the type of clothing that is commonly worn during the summer or winter. Most occupants would find House B more comfortable based on PPD levels for the high clothing level, which is perhaps not surprising given that thermal comfort is one of the primary reasons that homeowners select radiant floor heating systems. House A was heated by a variable capacity air source heat pump that ran on part load most of the time resulting in infrequent cycling. This resulted in a more even temperature difference that likely contributed to high thermal comfort levels.

Further investigations are necessary to document differences between the houses during very cold weather, when indoor and outdoor temperature differentials are more extreme. Coordinated monitoring of thermal parameters with the cycling of HVAC systems on multiple floors would also allow thermal measurements to be related more specifically to the function and automated operation of HVAC systems.

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