

Ductless Mini-Split Heat Pump Comfort Evaluation

K. Roth, N. Sehgal, and C. Akers

Fraunhofer Center for Sustainable Energy Systems

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Golden, CO 80401

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Prepared by:

K. Roth, N. Sehgal, and C. Akers

Fraunhofer Center for Sustainable Energy Systems

25 First Street, Suite 102

Cambridge, MA 02141

NREL Technical Monitor: Chuck Booten

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Unless otherwise indicated, all tables were created by Fraunhofer.

Definitions

COP	Coefficient of performance
CAC	Central air conditioning system
DBT	Dry bulb temperature
DMSHP	Ductless mini-split heat pump

Executive Summary

Ductless mini-split heat pumps (DMSHPs) offer several advantages over conventional ducted heating, ventilation, and air conditioning systems. They save energy, eliminate the potential for in-duct mold growth, eliminate the space consumed for duct runs, and are easy to install in retrofits, as they do not need ducts.

The Fraunhofer team conducted field tests in two homes in Austin, Texas, from October 2011 to June 2012 to evaluate the comfort performance of DMSHPs. Specifically, we evaluated temperature and relative humidity (RH) measurements in four rooms in each home, both before and after retrofitting each home's central heating and cooling system (CAC) with a DMSHP.

Our analysis of the field measurements yielded several comfort-related observations. This small sample relies strongly on residents' preferences, so the findings should be used as a case study evaluation rather than as a general finding.

1. ASHRAE Standard 55 Evaluation.

- a. **Living room.** The percentage of time within the comfort zone, for either heating or cooling operation, was similar for the CAC and DMSHP, suggesting that the DMSHP indoor unit in the living room operates much like a CAC type system. Periods when the DMSHPs did not stay within the ASHRAE comfort zone were primarily when the RH was higher.
 - b. **Bedroom.** A large portion of the measurements do not lie within the comfort zone for 0.5 clo, but do fall within the comfort zone for 1.0 clo. Thus, we conclude that residents preferred lower temperatures during the cooling season than those indicated by ASHRAE standard 55 (assuming 0.5 clo).
 - c. **Bathroom.** The DMSHP had an appreciably higher portion of time when conditions lay outside the 0.5 and 1.0 clo comfort zones, primarily because of higher RH levels. This probably reflects the lack of DMSHP indoor units in the bathrooms; vent fan use was not, however, monitored.
 - d. In general, the RH levels were quite high for the DMSHP cases, which the occupants also noted. This suggests that the occupants did not run the DMSHP in its dehumidification mode, but instead tried to achieve lower RH by cooling the indoor spaces.
2. **Homogeneity of indoor temperatures, cooling season.** The maximum average hourly temperature difference among rooms on days where the outdoor temperature was 85°F or higher was around 3°F.

1 Introduction and Field Deployments

1.1 Introduction

Ductless mini-split heat pumps (DMSHPs) offer several advantages over conventional ducted heating, ventilation, and air conditioning (HVAC) systems. They may save energy, eliminate the potential for in-duct mold growth, eliminate the space consumed for duct runs, and are easy to install in retrofits, as they do not need ducts. Although DMSHPs are popular in Asia, they account for only 1% of residential HVAC systems installed in the United States (Baylon et al. 2010). Most U.S. consumers, architects, and HVAC installers are wary of DMSHPs, because they have limited or no familiarity with these systems and how they perform in the field.

Also, DMSHPs have the potential to achieve significant energy savings in at least three ways:

- They eliminate duct losses from leakage and conduction that lose an average of 20% of thermal energy delivered to the ducts by HVAC systems (Roth et al. 2006, based on Jump et al. 1996). In homes where ducts are primarily located in unconditioned spaces, such as attics in southern locations, the energy penalty will tend to be greater, ranging from 25% to 40% (NREL 2004).
- DMSHPs with multiple indoor units inherently provide zoned space conditioning. Occupants can use these to achieve further energy savings by allowing temperatures to float during unoccupied periods. This capability is enhanced in units integrated with an occupancy sensor, which are primarily available outside the United States (Moore 2011).
- They typically have variable-capacity compressors (inverter-driven for continuous capacity modulation) and variable-speed fans (Roth et al. 2006). Relative to conventional systems with fixed cooling and heating capacities and single-speed blowers, this results in annual energy savings of about 35% (ADL 1999). Moreover, these variable capacity and volume capabilities greatly enhance their ability to efficiently dehumidify at low sensible heat ratios, so occupants are less inclined to select lower cooling set points solely to run the air conditioning for dehumidification (for example, periods of moderate outdoor air temperatures and higher wet bulb temperatures, such as Florida in winter). Such conditions are also more common in low-energy homes, where sensible cooling loads through the building enclosure are greatly decreased, but indoor moisture loads do not change (Dieckmann 2008).

The space heating capacity and efficiency of conventional air source heat pumps diminish as outdoor air temperatures decrease. They thus require supplementary electric resistance space heating during colder periods (typically when outdoor temperatures approach freezing) that compromises their primary energy savings potential and operational cost. Over the last few years, “cold climate” air source heat pumps (units optimized to meet space heating loads instead of space cooling loads) have come to market (Roth et al. 2006). Very recently, DMSHP manufacturers have also begun to offer cold-climate units. For example, the Mitsubishi HyperHeat produces its full heating capacity at 5°F, with a coefficient of performance (COP) of 1.5–1.8 (Mitsubishi 2010). These units demonstrate superior performance at cold outdoor conditions, efficiently modulate capacity over a wide range of conditions, eliminate duct losses,

and are operated in zones. They may thus achieve significant primary energy savings relative to conventional space heating options in colder climates.

1.2 Research Questions

To address the issues noted in Section 1.1, we designed this research project to answer the following research question:

- What is the distribution of indoor temperature and relative humidity (RH) in different rooms during the cooling and heating seasons, and how do they compare to ASHRAE comfort criteria?

1.3 Experimental Design and Field Deployments

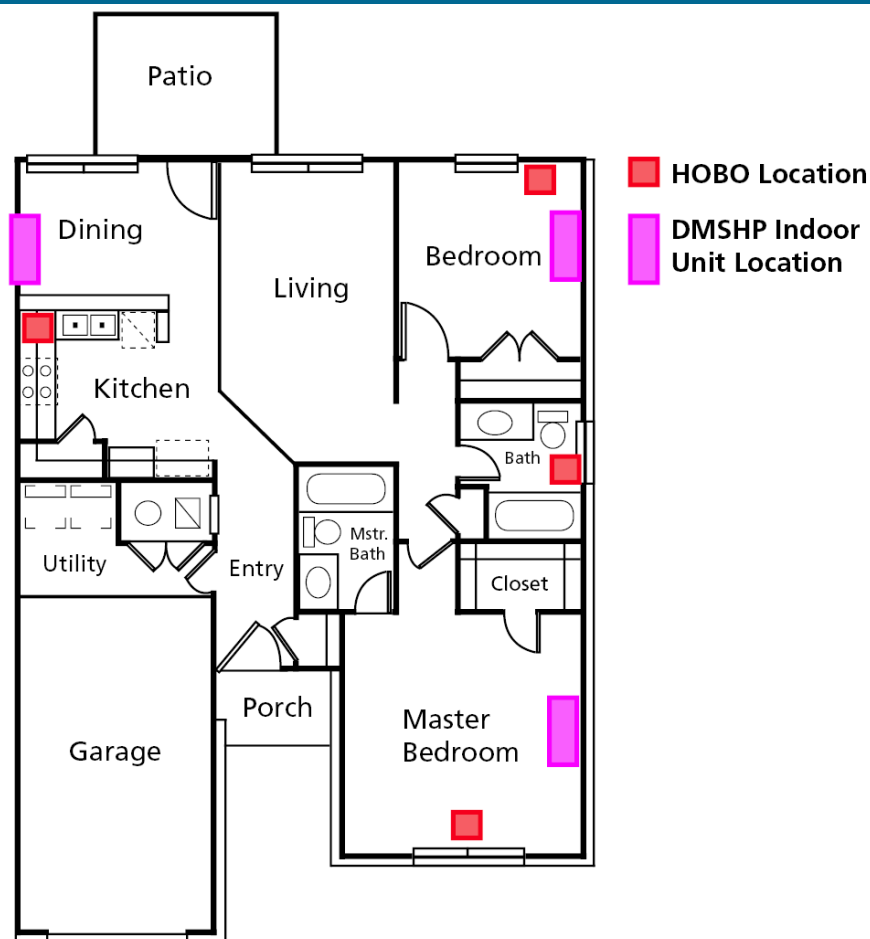
We made *in situ* measurements of temperature and RH in two households in Austin before and after the DMSHPs were installed. Our research partner, Mitsubishi Electric, also deployed on-board measurement systems to obtain field performance data for the real-world capacity and COP of the DMSHPs under the wide range of weather conditions experienced in these two households.

1.3.1 Field Deployment: Austin, Texas

We deployed the MSHPs in both units of a duplex, each with about 940 ft² of floor space. Figure 1 and Figure 2 show an image of the duplex and its floor plan, respectively, as well as the locations of the DMSHP indoor units and Onset HOBO (U12-011) temperature and RH monitoring units. We took measurements at 15-minute intervals.



Figure 1. Austin duplex DMSHP deployment site



**Figure 2. Floor plan of Austin duplex DMSHP deployment site
(second unit is mirror image, along garage-kitchen-dining room wall)**

Table 1 summarizes the three indoor and one outdoor units deployed in both units of the duplex.

Table 1. Austin DMSHPs Deployed

Location	Unit	Rated Cooling Capacity	Rated Heating Capacity	SEER	HSPF
Outdoor	MXZ-3B30NA	28,400	28,600	17.5	10.5
Common Areas	MSZ	17,200	21,600		
Bedroom	MSZ	6,000	6,600		
Bedroom	MSZ	6,000	6,600		

2 Thermal Comfort Analysis

An important point of comparison between CACs and DMSHPs is their ability to maintain thermal comfort in the conditioned space. CACs recirculate conditioned air to a common temperature, but often have only a single point for temperature control that does not necessarily reflect temperatures in spaces with significantly different internal loads, e.g., insulation levels or internal heat gains and loads. The multiple indoor units of distributed cooling and heating sources, such as DMSHPs, can respond to in-home variations of thermal loads using the in-room controls, but usually do not have indoor units in all rooms.

We used HOBO data collected from the two deployments at Austin to evaluate the thermal comfort in the conditioned space. Our evaluation includes data from the two housing units, both for the CACs (pre-retrofit) and for the DMSHPs (post-retrofit). In this report, the CAC system includes a ducted system with a CAC unit and furnace. We assessed thermal comfort based on ASHRAE Standard 55 (2004).

2.1 Procedures

We evaluated comfort based on hourly and daily mean outdoor temperatures, using indoor air DBT (dry bulb temperature) and RH that were measured every 15 minutes. We applied two procedures to analyze the real-time data (indoor temperature and RH) for thermal comfort performance.

2.1.1 Hourly Comfort Analysis

1. The data for indoor DBT and indoor RH for the living room, master bedroom, and bathroom were acquired through real-time monitoring at the site.
2. Assumption 1 (described in Section 2.2.1) was used to determine those readings when the system (either CAC or DMSHP) was considered “in operation.” A system is considered in operation when the building is expected to have either heating or cooling loads.
3. Assumption 2 was used to select those readings when the system was considered to be in heating or cooling mode.
4. For ASHRAE Standard 55:
 - a. Two areas were plotted in a temperature versus RH graph. These areas correspond to two levels of clothing: 1.0 clo and 0.5 clo. These areas together define the comfort zone for the ASHRAE Standard 55. (A “clo” is a unit used to quantify the thermal insulation provided by garments and clothing ensembles, where 1 clo = $0.155 \text{ m}^2 \text{ }^\circ\text{C/W}$.) Put in more intuitive terms (ASHRAE 2009):
 - i. Clo 1.01 corresponds to trousers, long-sleeved shirt, long-sleeved sweater, T-shirt.
 - ii. Clo 0.57 corresponds to trousers, short-sleeved shirt.
 - iii. Clo 0.36 corresponds to walking shorts, short-sleeved shirt.
 - b. We used the indoor temperature and RH measures to determine if the given condition lay within the comfort zone.

- c. The indoor conditions (temperature and RH at a given time) were plotted on this graph for a visual estimate of how many points lay within the comfort zone.
- d. We performed a similar analysis by plotting the points for cooling mode only (comfort zone corresponding to 0.5 clo) and heating mode only (comfort zone corresponding to 1.0 clo). We applied the above procedure for all the conditioned spaces.

2.2 Daily Mean Temperature Analysis

We applied this method while evaluating thermal comfort performance based on ASHRAE Standard 55 only. All the steps under hourly comfort analysis, for ASHRAE Standard 55, are followed in this procedure except for one difference. For this procedure, the analysis used the outdoor daily mean DBT instead of hourly outdoor temperatures (as used in Hourly Comfort Analysis). Assumptions 3 and 4 (see Section 2.2.1) hold true for this case.

The rationale for this approach is that the mean outdoor temperature over a 24-hour period takes into account how building thermal mass may impact indoor comfort conditions.

2.2.1 Assumptions

We did not measure occupancy patterns nor occupants' preferences, so we made the following assumptions for hourly comfort analysis and daily mean temperature analysis to predict the outdoor conditions when the systems would most likely operate in either heating or cooling mode.

For the hourly comfort analysis, the CAC and DMSHP most likely provided heating or cooling when the hourly outside DBT was either $\leq 60^{\circ}\text{F}$ or $\geq 77^{\circ}\text{F}$. Between these two temperatures, we assumed that both systems did not operate to meet the set points in the conditioned space.

The system was in heating mode when the outdoor DBT was $\leq 60^{\circ}\text{F}$ and in cooling mode when the outdoor DBT was $\geq 77^{\circ}\text{F}$.

For the daily mean temperature analysis, the systems (CAC and DMSHP) may have operated in either heating or cooling mode when the outside mean DBT was either $\leq 60^{\circ}\text{F}$ or $\geq 70^{\circ}\text{F}$. Between these two temperatures, both systems did not operate to meet the set points in the conditioned space.

The system was in heating mode when the outdoor DBT was $\leq 60^{\circ}\text{F}$ and in cooling mode when the outdoor DBT was $\geq 70^{\circ}\text{F}$.

Residents in the conditioned space were dressed per typical ASHRAE summer clothing assumption of 0.5 clo when the systems were in cooling mode and the winter clothing assumption of 1.0 clo when the systems were in heating mode.

The data for CACs are primarily for the month of October 2011.¹

The data acquisition period for DMSHPs was November 2011 to June 2012.

¹ The average high and low temperatures for Austin in October are 82°F and 61°F , respectively. Thus, significant space cooling typically occurs during this period (Weather Underground 2012).

2.3 Thermal Comfort Based on ASHRAE Standard 55 (2004)

The following sections describe the results from the thermal comfort analysis performed based on ASHRAE Standard 55.

Before installing the DMSHPs in Austin, we acquired a month of baseline indoor comfort data for the prior air-based CAC using HOBOs to record indoor temperature and RH. Similar data were collected when DMSHPs were installed. The outdoor weather data used are from Austin-Bergstrom International Airport (Weather Underground 2012). The results based on the procedures described in Section 2.1.1 follow.

2.3.1 Thermal Comfort Based on Either Cooling or Heating Operation

We first evaluated the data assuming either typical summer or winter clothing. Table 2 and Table 3 summarize the relative performance of the two systems for the hourly comfort analysis and daily mean temperature analysis, respectively, for both test households. Zones in test household 1 are identified by the number “1” and those of test household 2 with the number “2.” Performance here refers to the portion of time that the system maintained indoor conditions within the bounds specified by the comfort zone in either heating or cooling mode.

Table 2. Thermal Comfort Performance for CAC and DMSHP for Either Cooling or Heating—Hourly Comfort Analysis

CAC Thermal Comfort Performance				DMSHP Thermal Comfort Performance			
Living 1	Bed1a	Bed1b	Bath1	Living 1	Bed1a	Bed 1b	Bath1
87%	88%	88%	94%	87%	74%	93%	80%
Living 2	Bed2a	Bed2b	Bath2	Living 2	Bed2a	Bed2b	Bath2
100%	97%	100%	99%	94%	89%	92%	85%

Table 3. Thermal Comfort Performance CAC and DMSHP for Either Cooling or Heating—Daily Mean Temperature Analysis

CAC Thermal Comfort Performance				DMSHP Thermal Comfort Performance			
Living 1	Bed1a	Bed1b	Bath1	Living 1	Bed1a	Bed1b	Bath1
85%	87%	88%	93%	86%	73%	91%	79%
Living 2	Bed2a	Bed2b	Bath2	Living 2	Bed2a	Bed2b	Bath2
93%	94%	95%	87%	91%	87%	93%	83%

The plots for the living room (Living 1) that were prepared per the procedures described in Section 2.1.1 are shown in Figure 3 and Figure 4. We created similar plots for other conditioned spaces for both test households (see Appendix A for the plots for other conditioned spaces in household 1).

2.3.1.1 Observations and Findings

Based on the portion of time that indoor conditions lay within the ASHRAE comfort zone, the following points emerged.

Based on Table 2, the percentage of time when the conditions are within the comfort zone, for either heating or cooling operation, in the living room is almost the same for the CAC and DMSHP. This suggests that the DMSHP indoor unit in the living room operates much like a CAC, particularly because the CAC master thermostat is often in the living room. Periods when the CAC and DMSHP do not stay within the ASHRAE comfort zone are primarily when the indoor DBT (CAC) or indoor RH (DMSHP) are higher. It is not clear the extent to which this reflects the households' setting up the temperature (e.g., when out of the house).

The RH levels are quite high for the DMSHP case, something that the inhabitants also noted. This suggests that they did not run the DMSHP in its dehumidification mode, but instead tried to achieve lower RH by cooling the indoor spaces.

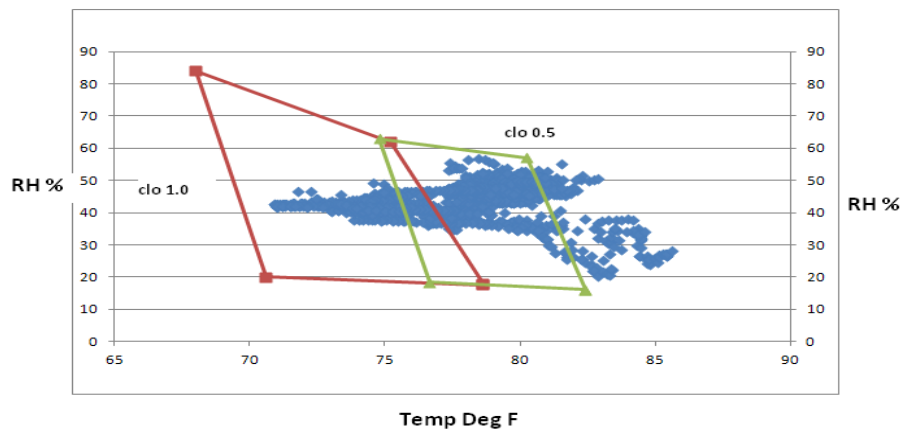


Figure 3. Thermal comfort performance of CAC for either cooling or heating operation for Living 1; hourly analysis

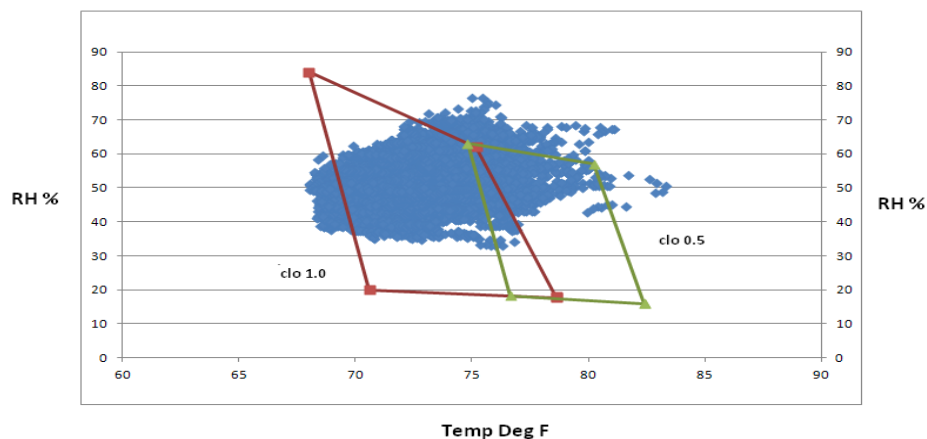


Figure 4. Thermal comfort performance of DMSHP for either cooling or heating operation for Living 1; hourly analysis

The results from daily mean temperature analysis also closely mirror the trends noted for the hourly data analysis. Thus, the effect of thermal mass may even out temperature over a period of 24 hours.

2.3.2 Thermal Comfort Performance in Cooling and Heating Modes

We also evaluated the performance of the two systems separately for heating and cooling modes.

2.3.2.1 Thermal Comfort Performance in Cooling Mode

Table 4 and Table 5 compare the thermal comfort performance in cooling mode of the two systems, assuming the typical ASHRAE clothing levels 0.5 clo. Later in this section, we also analyze the case where the systems are in cooling mode, but the thermal comfort is based on both 1.0 clo and 0.5 clo.

Table 4. Thermal Comfort Performance for DMSHP and CAC in Cooling Mode Hourly Comfort Analysis

CAC Thermal Comfort Performance (%) 0.5 clo/0.5 clo or 1.0 clo				DMSHP Thermal Comfort Performance (%) 0.5 clo/0.5 clo or 1.0 clo			
Living 1	Bed1a	Bed1b	Bath1	Living 1	Bed1a	Bed1b	Bath1
80/82	44/89	77/88	80/97	27/75	9/68	62/70	14/65
Living 2	Bed2a	Bed2b	Bath2	Living 2	Bed2a	Bed2b	Bath2
73/95	68/92	81/90	68/97	67/77	11/74	27/86	62/88

Table 5. Thermal Comfort Performance for DMSHP and CAC in Cooling Mode Daily Mean Temperature Analysis

CAC Thermal Comfort Performance (%) 0.5 clo/0.5 clo or 1.0 clo				DMSHP Thermal Comfort Performance (%) 0.5 clo/0.5 clo or 1.0 clo			
Living 1	Bed1a	Bed1b	Bath1	Living 1	Bed1a	Bed1a	Batha
79/82	44/88	74/88	78/97	29/71	7/63	64/91	11/63
Living 2	Bed2a	Bed2b	Bath2	Living 2	Bed2a	Bed2b	Bathb
68/71	25/66	33/79	41/66	33/80	16/68	31/80	28/70

The plots for conditioned spaces for household 1, prepared per the procedures described in Section 2.1.1, can be found in Appendix A.

2.3.2.2 Observations and Findings :

Table 4 and Table 5 show a difference in performance of the two systems in some areas. For instance, the comfort performance for Bed1a based on 0.5 clo only is 44% of CAC to 9% for DMSHP. Similarly, the ratios for Bed2b differ by as much as 81% to 27%.

Figure 5 and Figure 6 show plots of measured temperature and RH, for cooling mode only (0.5 clo and 1.0 clo), and for Bed1a for the two systems. A large portion of the measurements do not lie within the comfort zone for 0.5 clo, but do fall within the comfort zone for 1.0 clo. Thus, we conclude that the residents prefer lower set point temperatures. These values are also listed in Table 3 and Table 4. Indeed, we noted during site visits that the occupants of both units wore clothing consistent with 1.0 clo.

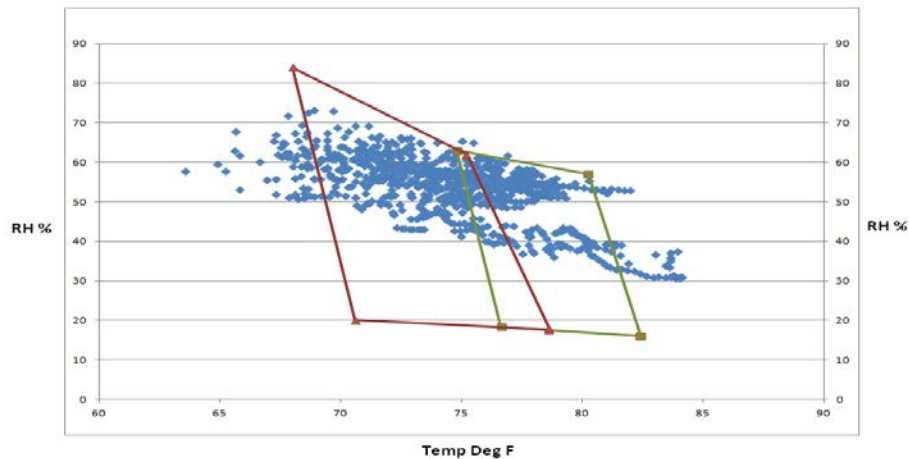


Figure 5. Thermal comfort performance of CAC for Bed1a in cooling mode for clo 0.5 or clo 1.0; hourly analysis

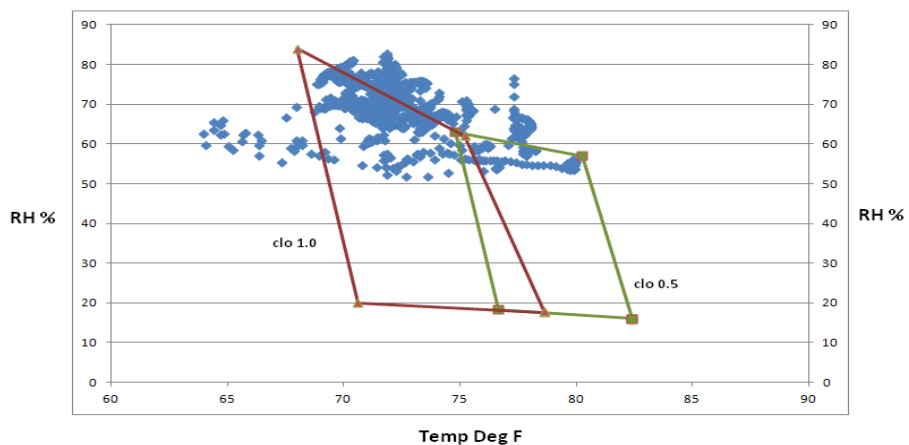


Figure 6. Thermal comfort performance of DMSHP for Bed1a in cooling mode for clo 0.5 or clo 1.0; hourly analysis

We investigated the significant difference in performance for the master bedrooms, Bed1a, and Bed2a, further hypothesizing that this could reflect distinct occupancy patterns for this space and the difference between central and distributed space conditioning systems. Specifically, CACs typically have only one thermostat that is usually located in the living room. Consequently, they cool other spaces even if those spaces are not occupied. In contrast, a DMSHP indoor unit might run only when that room is occupied, because DMSHPs have an individual control for each indoor unit. To explore this further, we analyzed bedroom comfort during times when we expected that the occupancy would be high (11:00 p.m. to 7:00 a.m.). We assumed that the DMSHP is always in operation (either in cooling or heating mode) for this time window. Figure 7 shows the performance of the DMSHP in Bed1a. In this case, the thermal comfort performance was 86% compared to 73% in the previous case. However, similar plots for the other bedrooms did not necessarily show different performance.

The RH levels are quite high for the DMSHP case, which the occupants also noted. This suggests that they did not run the DMSHP in its dehumidification mode, but instead tried to achieve lower RH by cooling the indoor spaces.

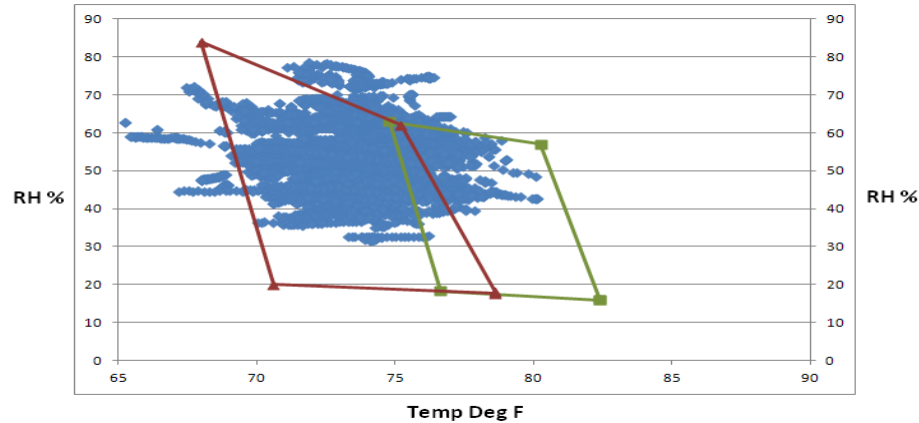


Figure 7. Thermal comfort performance of DMSHP for Bed1a for 11:00 p.m. to 7:00 a.m.; hourly analysis

1. The DMSHP also had an appreciably higher portion of time when conditions lay outside the ASHRAE comfort zones, primarily because of higher RH levels (see Figure 7). This probably reflects the lack of DMSHP indoor units in the bathrooms; vent fan use was not, however, monitored.

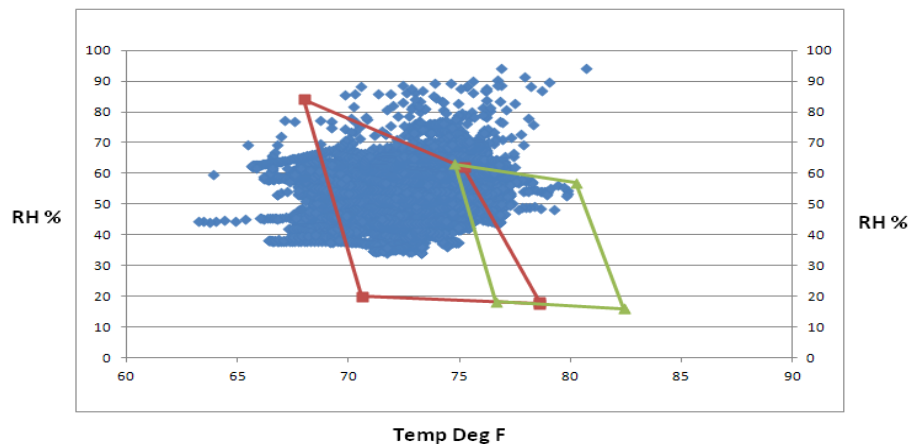


Figure 8. Thermal comfort performance of DMSHP for Bath 1 for either cooling or heating; hourly analysis

2. The results presented in Table 3 and Table 4 show that the daily mean and hourly temperature analyses yield similar conclusions, signifying that even when thermal mass of the building is taken into consideration the thermal comfort performance of DMSHP may be approximately the same as that calculated in hourly comfort analysis.

2.3.2.3 Thermal Comfort Performance for Heating Mode Only

We also considered the thermal comfort performance of the two systems in heating mode only. Table 6 and Table 7 summarize the results of this analysis. Although the performance during heating season appears to be broadly comparable for both systems, limited data were collected for the heating season with the CAC. Moreover, most of those data were taken during October, when outdoor temperatures were mild. Hence, it is difficult to draw meaningful conclusions about the relative performance of the two systems.

Table 6. Thermal Comfort Performance for DMSHP and CAC Heating Mode; Hourly Analysis

CAC Thermal Comfort Performance 1.0 clo(%)				DMSHP Thermal Comfort Performance 1.0 clo(%)			
Living 1	Bed1a	Bed1b	Bath1	Living 1	Bed1a	Bed1b	Bath1
82 %	89%	83%	97%	83%	75%	93%	87%
Living 2	Bed2a	Bed2b	Bath2	Living 2	Bed2a	Bed2b	Bath2
97%	78%	84%	91%	94%	78%	90%	84%

Table 7. Thermal Comfort Performance for DMSHP and CAC Heating Mode; Daily Mean Temperature Analysis

CAC Thermal Comfort Performance 1.0 clo [%]				DMSHP Thermal Comfort Performance 1.0 clo [%]			
Living 1	Bed1a	Bed1b	Bath1	Living 1	Bed1a	Bed1b	Bath1
88%	77%	78%	73%	83%	74%	89%	79%
Living 2	Bed2a	Bed2b	Bath2	Living 2	Bed2a	Bed2b	Bath2
92%	78%	73%	83%	85%	82%	90%	83%

Additional plots for household 1 that we prepared per the procedures described in Section 2.1.1 can be found in Appendix A.

2.4 Temperature Distributions Among Rooms During Cooling Season

As discussed earlier, the ability to individually control DMSHP indoor units raises the possibility that “uncomfortable” conditions may occur in spaces when the indoor units are switched off. This contrasts with a CAC, which provides cooling or heating to all conditioned spaces whenever the system runs in either cooling or heating mode. Therefore, it is worthwhile to note how the mean temperature distribution varies throughout the household. We performed the following analysis to determine the temperature variations in the test households during the cooling season.

1. Selected the days when the maximum outdoor air DBT $\geq 85^{\circ}\text{F}$; this limited the analysis to days expected to have significant cooling loads.
2. Calculated mean hourly temperatures for each day selected in step 1.
3. Calculated the average value of each mean hourly temperature, calculated in step 2, of all days where the maximum outdoor air DBT $\geq 85^{\circ}\text{F}$.

4. Plotted these averages to observe the variations over 24 hours (see Figure 9 and Figure 10).

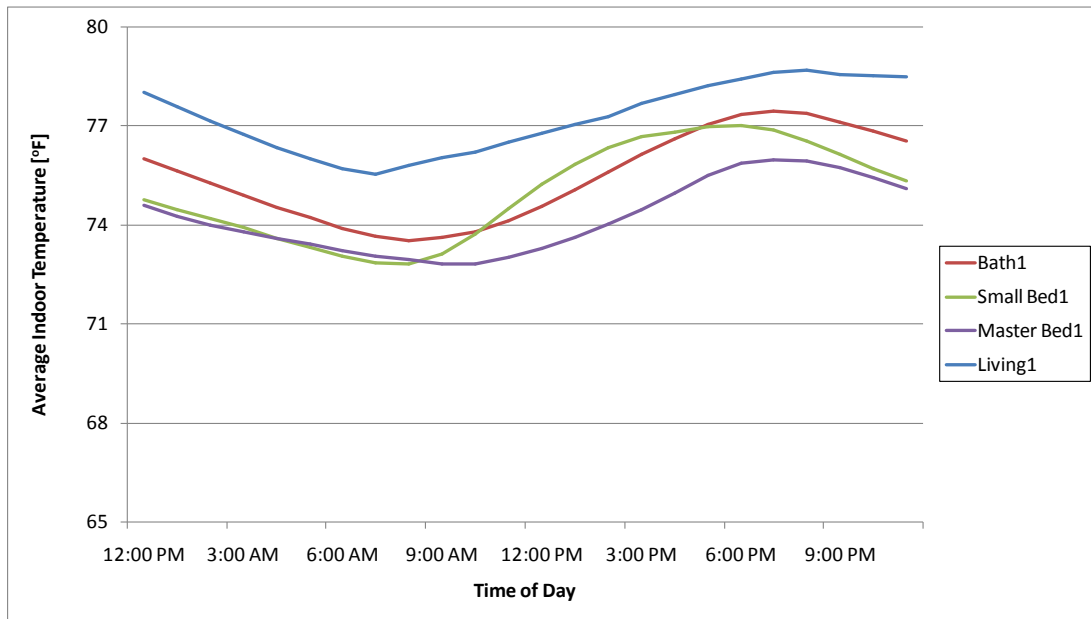


Figure 9. Temperature distribution with DMSHP in different rooms, household 1

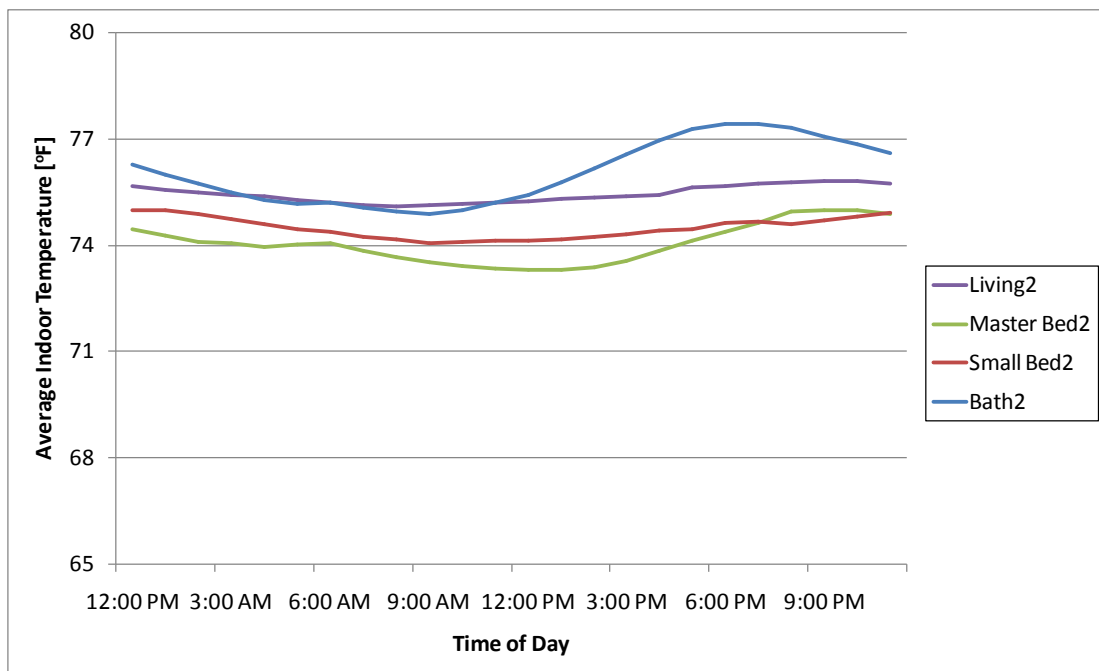


Figure 10. Temperature distribution with DMSHP in different rooms, household 2

2.4.1.1 Observations and Findings

The maximum average temperature difference among rooms is around 3°F.

3 System Costs

One objective of this study is to determine the impact of retrofitting a DMSHP unit to an existing home with CAC. Bergey and Ueno (2011) found that the DMSHP is a less costly option (by approximately \$3,000) than installing a CAC + condensing furnace in a very low-energy home, so we gathered data for the retrofit case in Austin.

We used the actual cost of the DMSHP retrofits for the deployment in Austin, based on capital costs from Mitsubishi Electric and installation costs from Foundation Communities. Table 8 and Table 9 summarize the economics of a retrofit.

Table 8. Summary of Economics of a DMSHP Retrofit

System Component	Cost	Specifications
One Outdoor Unit Plus Three Indoor Units	\$2,800	1 MXZ-3B30 outdoor unit, 1 MSZ-GE18 indoor unit, and 2 MSZ-GE06 indoor units
Installation Cost for One Household	\$4,163	Actual cost of installation at the Texas-Austin site
Total per Household	\$6,963	

Table 9 summarizes the cost for a complete retrofit of a CAC, using the same capacities as the DMSHP (28,400 Btu cooling and 28,600 Btu heating). We assume that the new CAC has seasonal energy efficiency ratio (SEER) of 15, and that the new furnace has an annual fuel utilization efficiency of 92.5%. The CAC retrofit cost comes from BEopt; the furnace costs come from BEopt and RSMeans (2011). Unfortunately, a full BEopt analysis could not be completed, because BEopt cannot yet model DMSHPs (Winkler 2012).

Table 9. Summary of Economics of a CAC Retrofit

System Component	Cost	Specifications
Cooling System	\$5,032	Retrofit: SEER=15; old: SEER=13
Furnace	\$1,276 ²	Retrofit: AFUE=92.5%;old: AFUE=72%
Total	\$6,308	

Assuming that the existing CAC and furnace both require replacement, the data show a \$655 incremental cost for the DMSHP.

²Based on: \$995 for furnace cost (BEopt), \$165 for installation labor (RSMeans), and 10% overhead and profit (RSMeans).

4 Conclusions and Recommendations

The Fraunhofer team conducted field tests in two homes in Austin, Texas, from October 2011 to June 2012 to evaluate the comfort performance of DMSHPs. Specifically, we measured temperature and RH in four rooms in each home, both before and after retrofitting each home's CAC with a DMSHP.

Our analysis of the field measurements yielded several comfort-related observations. This small sample relies strongly on residents' preferences, so the findings should be used as a case study evaluation rather than as a general finding.

3. ASHRAE Standard 55 Evaluation.

- a. **Living room.** The percentage of time within the comfort zone, for either heating or cooling operation, was similar for the CAC and DMSHP, suggesting that the DMSHP indoor unit in the living room operated much like a CAC. Periods when the DMSHPs did not stay within the ASHRAE comfort zone were primarily when the RH was higher.
 - b. **Bedroom.** A large portion of the measurements did not lie within the comfort zone for 0.5 clo, but did fall within the comfort zone for 1.0 clo. Thus, we conclude that residents preferred lower temperatures during the cooling season than those indicated by ASHRAE standard 55 (assuming 0.5 clo).
 - c. **Bathroom.** The DMSHP had an appreciably higher portion of time when conditions lay outside the 0.5 and 1.0 clo comfort zones, primarily because of higher RH levels. This probably reflects the lack of DMSHP indoor units in the bathrooms; vent fan use was not, however, monitored.
 - d. In general, the RH levels were quite high for the DMSHP cases, which the occupants also noted. This suggests that the occupants did not run the DMSHP in its dehumidification mode, but instead tried to achieve lower RH by cooling the indoor spaces.
4. **Homogeneity of indoor temperatures, cooling season.** The maximum average hourly temperature difference among rooms on days when the outdoor temperature was 85°F or higher was around 3°F.

A key recommendation from our study is to obtain detailed field performance data, i.e., unit power draw and heating and cooling capacity as functions of indoor and outdoor temperatures for the DMSHP units. These data are crucial for further validating and enhance EnergyPlus models for DMSHPs (see, for example, FSCE 2012). Similarly, it is crucial to obtain the same data for DMSHPs optimized for cold-climate performance to develop adequate models for these products as they become more prominent in the residential HVAC market. We continue to work with our field test partners to generate these data, that we hope to obtain and publish as part of a future study.

References

- ADL. 1999. “Opportunities for Energy Savings in the Residential and Commercial Sectors with High-Efficiency Electric Motors.” Final Report by Arthur D. Little (ADL) to the U.S. Department of Energy. October.
- ANSI/ASHRAE Standard 90.2. 2007. “Energy Efficient Design for Low Rise Residential Buildings.” ASHRAE: Atlanta, GA.
- ASHRAE. 2009. ASHRAE Handbook: 2009 Fundamentals. ASHRAE: Atlanta, GA.
- Baylon, D. 2010. “Performance of Ductless Heat Pumps in the Pacific Northwest”. *Proc. 2010 ACEEE Summer Study on Energy Efficiency in Buildings*, Pacific Grove, CA: August.
- Bergey, D. and K. Ueno. 2011. “New England Net Zero Production Houses”. *Proc. ASHARE Annual Conference*, Montreal, Canada. 25–29 June.
- Dieckmann, J. 2008. “Improving Humidity Control with Energy Recovery Ventilation” *ASHRAE Journal*, August.
- Jump, D.A., I.S. Walker, and M.P. Modera. 1996. “Field measurements of efficiency and duct retrofit effectiveness in residential forced air distribution systems.” *Proc. ACEEE Summer Study*, Pacific Grove, CA.
- Mitsubishi. 2008. Mitsubishi Electric Hyper-Heating INVERTER Product Manual. Form No. H2iBR0M-11-08-00MDigOn.
- Moore, A. 2011. Personal Communication. Mitsubishi Electric. January.
- NREL. 2004. “Better Duct Systems for Home Heating and Cooling”. Produced for the U.S. Department of Energy (DOE) by the National Renewable Energy Laboratory (NREL). November. Available at: <http://www.nrel.gov/docs/fy05osti/30506.pdf>.
- Roth, K., D. Westphalen, and J. Brodrick. 2006. “Ductless Split Systems”. *ASHRAE Journal*. July, pp. 115,117.
- Weather Underground. 2012. Data from Austin, TX Airport Weather Station (KATT). Accessed on from: www.wunderground.com/history/airport/KATT/2011/10/31/DailyHistory.html.
- Winkler, J. 2012. Personal Communication, National Renewable Energy Laboratory (NREL).

Appendix A: Thermal Comfort Performance Graphs for ASHRAE Standard 55, for Household1

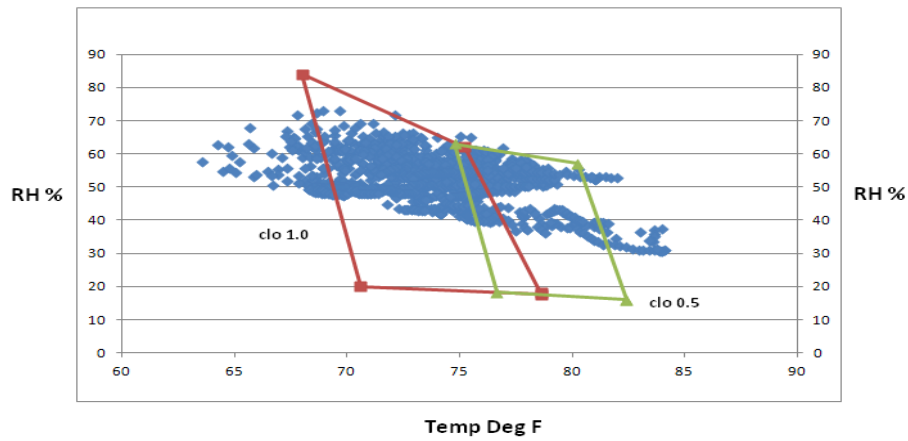


Figure 11. Thermal comfort performance of CAC for Bed1a for either cooling or heating; hourly

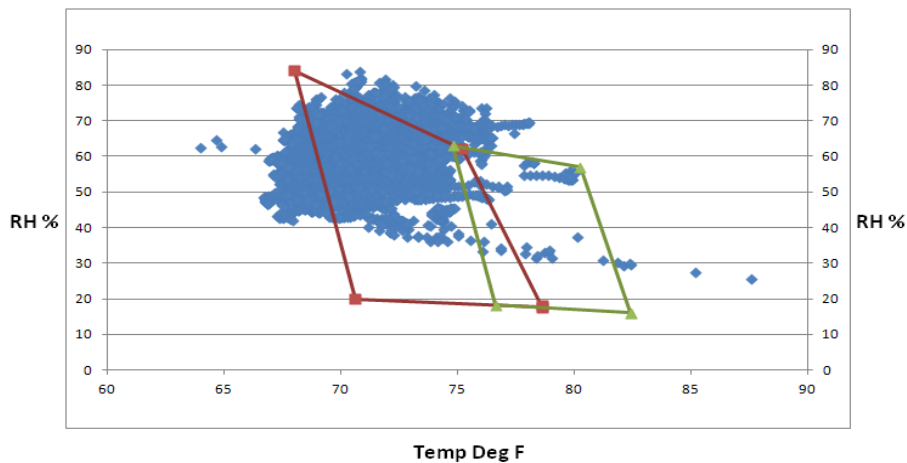


Figure 12. Thermal comfort performance of DMSHP for Bed1a for either cooling or heating; hourly

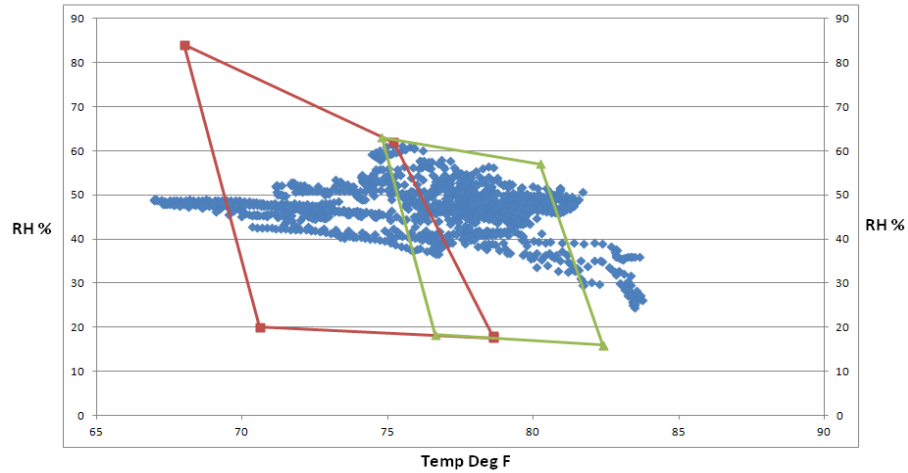


Figure 13. Thermal comfort performance of CAC for Bed 2a for either cooling or heating; hourly

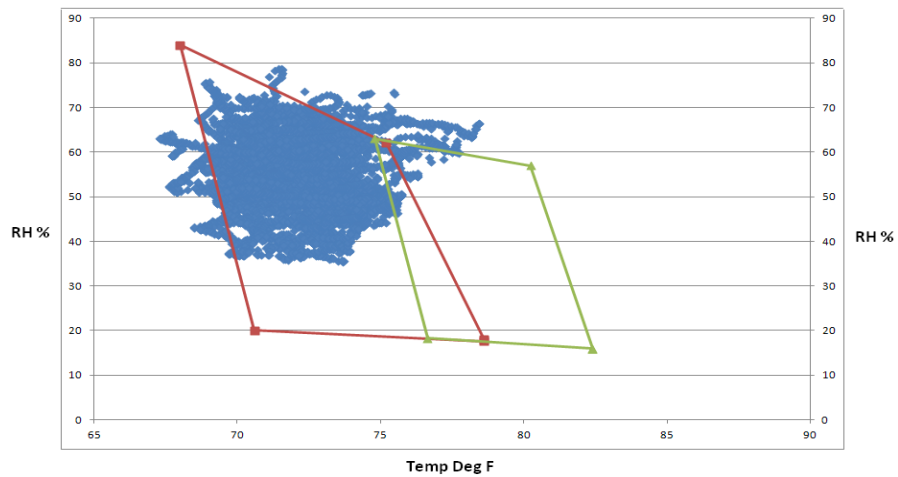


Figure 14. Thermal comfort performance of DMSHP for Bed 2a for either cooling or heating; hourly

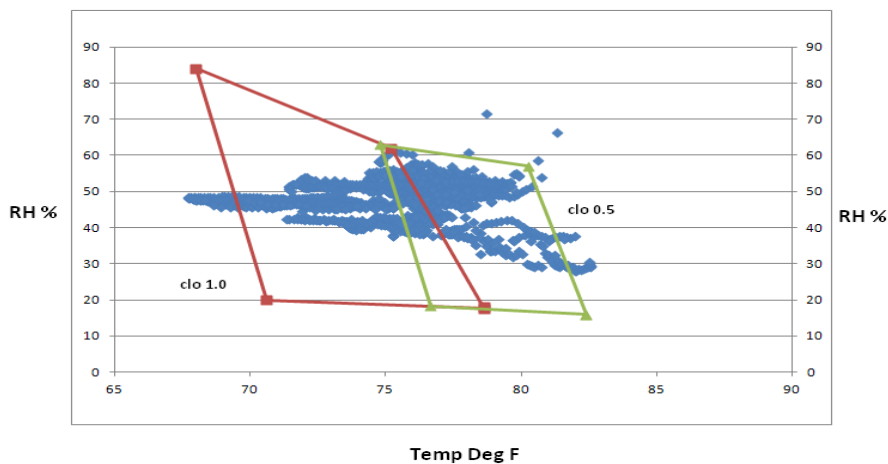


Figure 15. Thermal comfort performance of CAC for Bath 1 for either cooling or heating; hourly

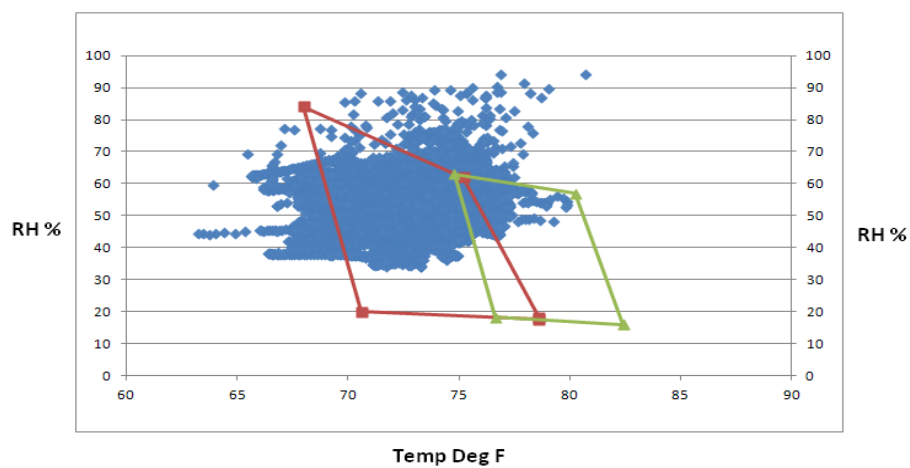


Figure 16. Thermal comfort performance of DMSHP for Bath 1 for either cooling or heating; hourly

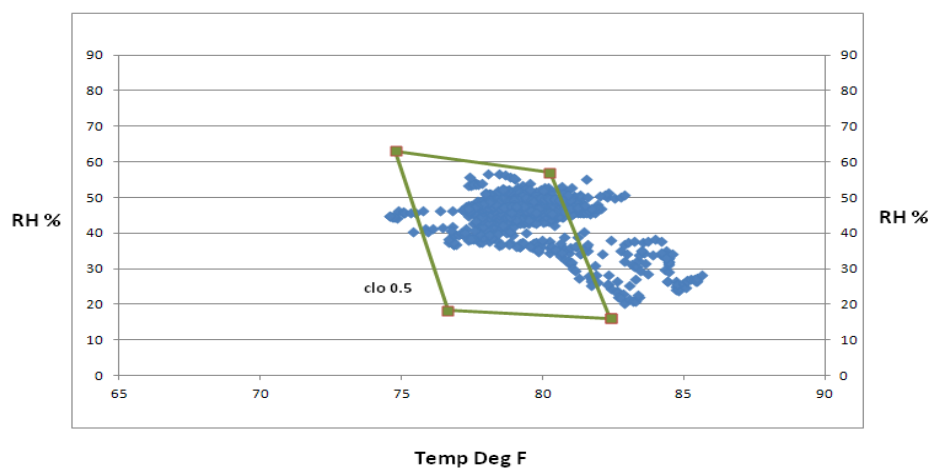


Figure 17. Thermal comfort performance of CAC for Living 1 for cooling; hourly

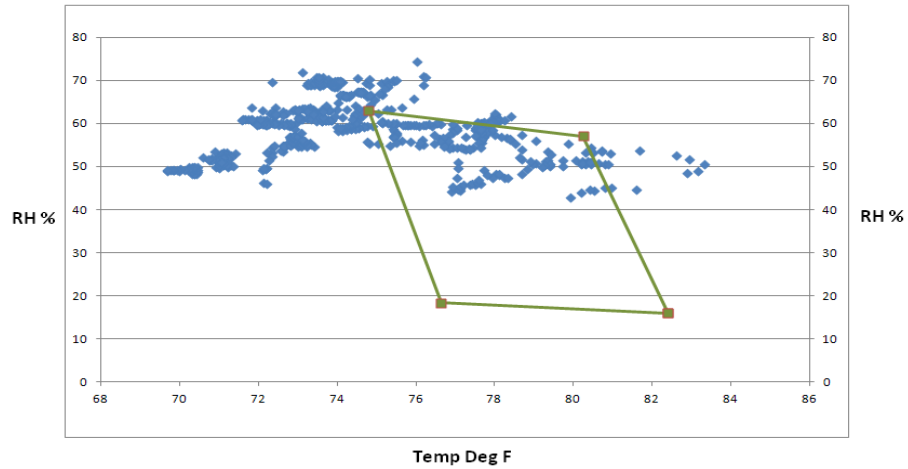


Figure 18. Thermal comfort performance of DMSHP for Living 1 for cooling; hourly

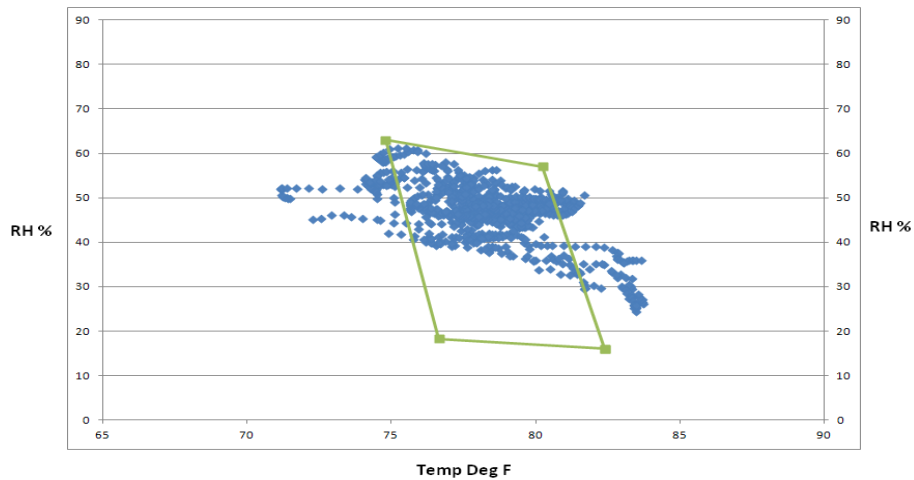


Figure 19. Thermal comfort performance of CAC for Bed2a for cooling; hourly

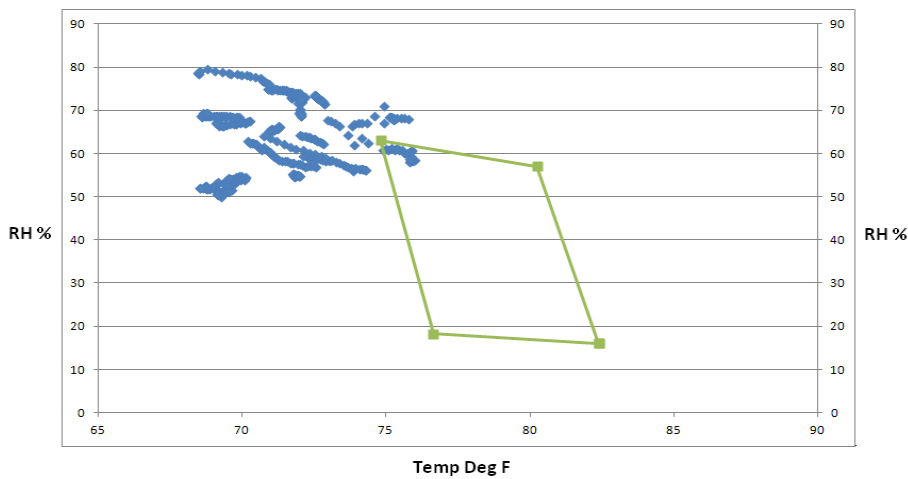


Figure 20. Thermal comfort performance of DMSHP for Bed2a for cooling; hourly

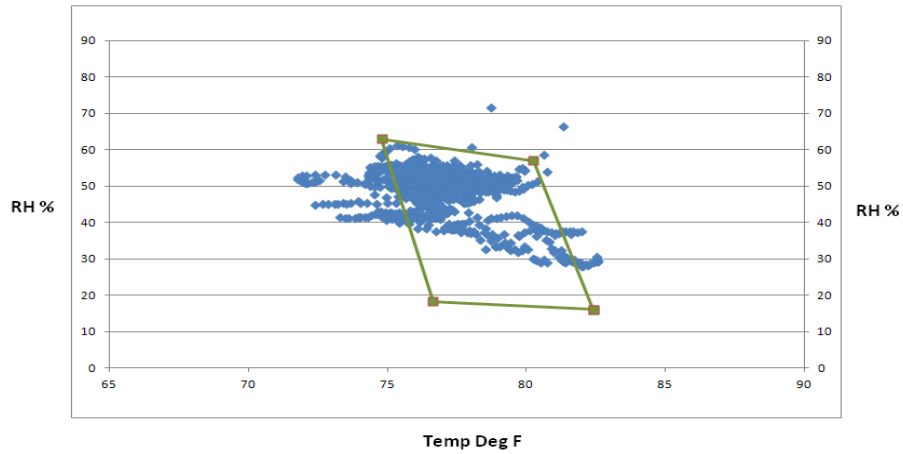


Figure 21. Thermal comfort performance of CAC for bath 1 for cooling; hourly

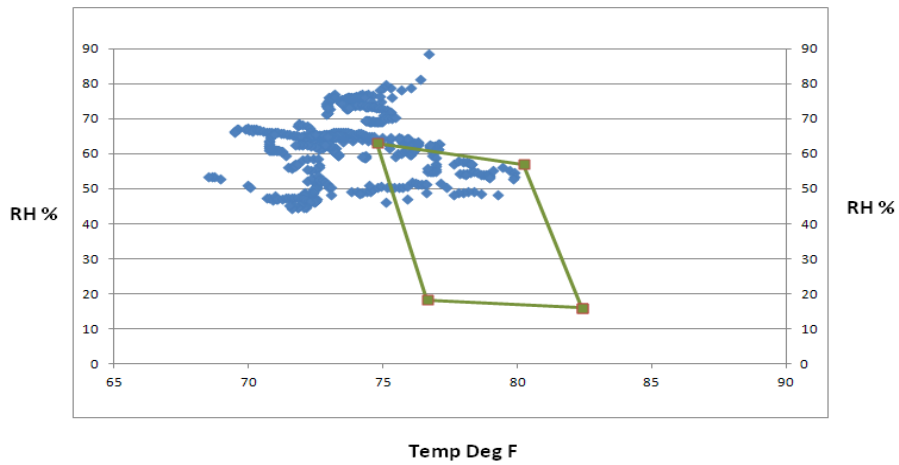


Figure 22. Thermal comfort performance of DMSHP for bath 1 for cooling; hourly

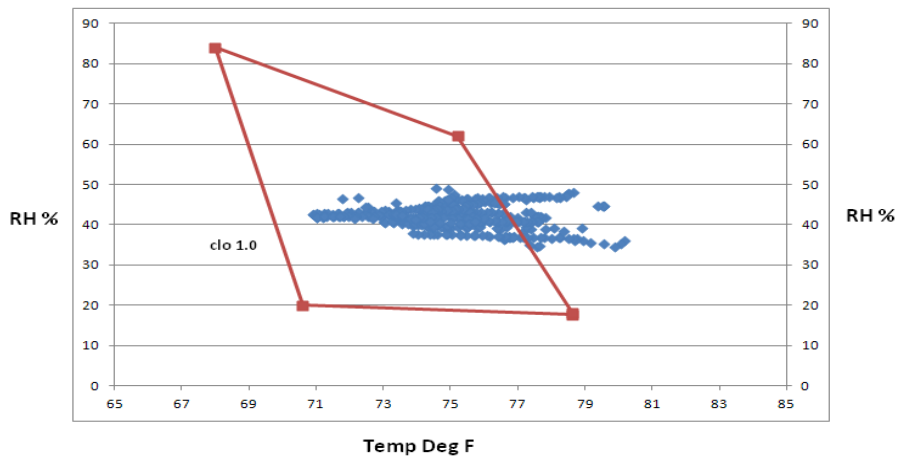


Figure 23. Thermal comfort performance of CAC for Living 1 for heating; hourly

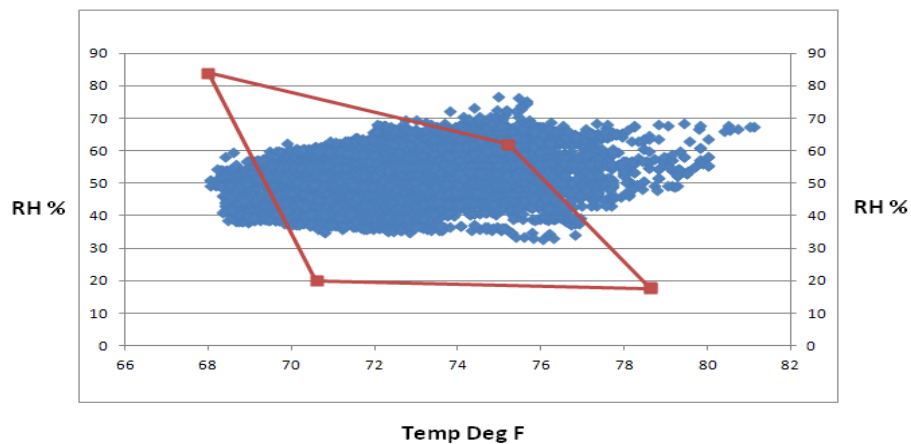


Figure 24. Thermal comfort performance of DMSHP for Living 1 for heating; hourly

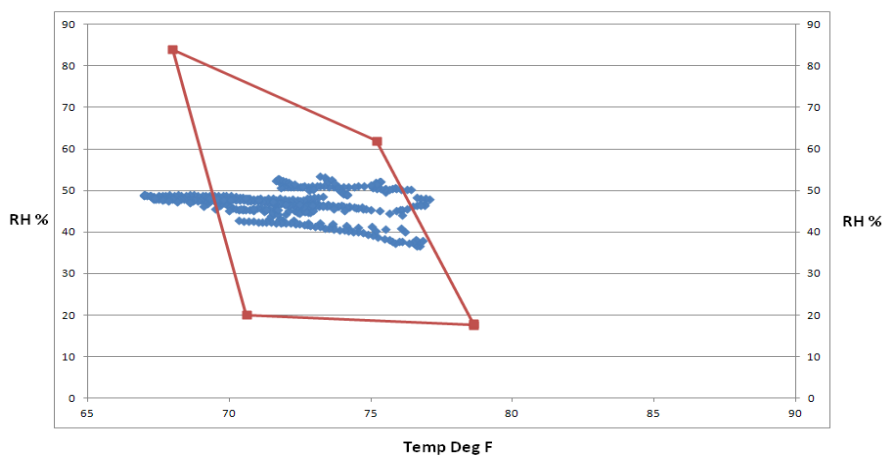


Figure 25. Thermal comfort performance of CAC for Living 1 for heating; hourly

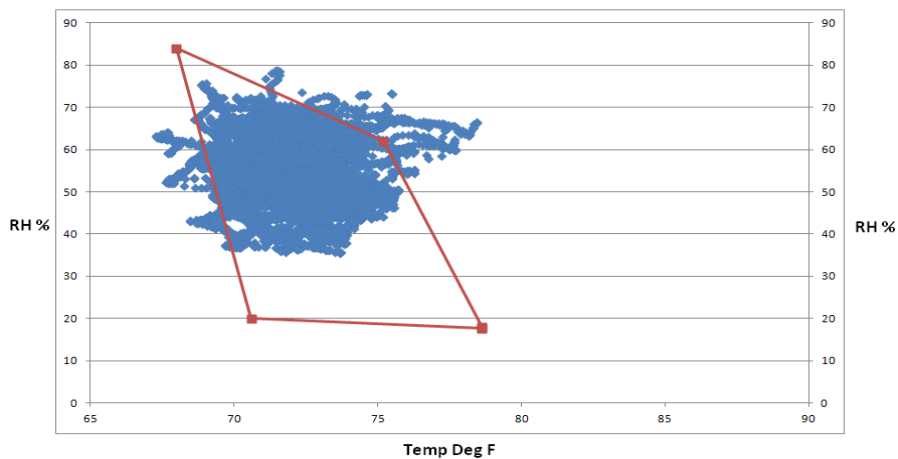


Figure 26. Thermal comfort performance of DMSHP for Bed2 for heating; hourly

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