The Benefits of Zoning with Ducted Hydronic Fan Coils and Air-to-Water Heat Pumps

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ABSTRACT

Zoning provides improved comfort for the occupant, diverting heating and cooling airflow to where it is needed. However, zoning and efficiency typically don't mix well with traditional air-to-air systems. Most zoning methods restrict or bypass airflow, resulting in diminished performance. Because of this, California energy code has long required a minimum of 350 CFM/ton in each zonal configuration. This requirement makes effective zoned ducted systems difficult, as it often requires single zone airflows much greater than needed. Hydronic radiant systems, however, have long enjoyed the benefits of efficient and easily installed zoning through buffer tanks and zone valves. When a zone calls for space conditioning, its valve opens and pre-conditioned water flows from the buffer tank through the zone. The air-to-water heat pump (AWHP) only operates once sufficient load has built up in the tank, preventing inefficient low load conditions.

An experiment at one of the Central Valley Research Homes (CVRH), four unoccupied laboratory houses in Stockton, CA, was conducted to evaluate the performance of an AWHP coupled to ducted hydronic fan coils in two configurations: a central ducted air handler with supply ducts zoned upstairs and downstairs, and two separate air handlers (one upstairs and one downstairs). Each configuration was also operated with two different airflows: one sized according to the Air Conditioning Contractors of America (ACCA) Manual J and the other meeting the CA Title 24 minimum requirements. Seasonal comfort and performance were measured. The buffer tank successfully prevented short cycling of the AWHP, resulting in the same seasonal efficiency profile, regardless of zonal configuration.

Introduction

Air to water heat pumps (AWHPs) are air source heat pumps with refrigerant to water heat exchangers that chill and heat water. In residential heating, ventilation, and air conditioning (HVAC) applications, this conditioned water is pumped to an indoor space conditioning delivery system, typically radiant panels. (Caleffi 2020) While the heat exchange from outdoor air to refrigerant to water to indoor air seems like an unnecessary extra step compared to conventional direct expansion (DX) heat pump systems (where the heat exchange pathway is outdoor air to refrigerant to indoor air), there are many advantages.

Unlike conventional DX systems, AWHP-based hydronic systems can be more easily integrated with waste heat recovery devices, desuperheaters, and solar thermal systems. An AWHP can also provide domestic hot water heating, allowing the use of a single heat pump unit to serve all household thermal loads. This has the potential to simplify electrification retrofits, as only a single electrical panel double breaker is needed to electrify indoor heating and water heating, and that breaker can be the one from the existing air conditioner. AWHPs can also be integrated with thermal energy storage, allowing little or no on-peak energy use for heating or cooling, without comfort compromises (Haile, Springer and Hoeschele 2021).

Another critical advantage, specifically of monobloc AWHPs over all split systems, is that water is plumbed into the house instead of refrigerant. Monobloc AWHPs ship from the factory as pre-charged package units, so the refrigerant-containing components are never even touched by the installer. Even pre-charged air-to-air split systems must still have the refrigerant charge adjusted after installation, unless the lineset is within a certain range of length. Regardless, installation of split system linesets is challenging and fraught with issues, especially leaks. Monobloc AWHPs reduce installation complexity and provide better refrigerant leak mitigation for the entire lifetime of the system.

Additionally, because monobloc AWHPs keep all of the refrigerant containing components outside, they provide a safe avenue to implement near-zero global warming potential (GWP) refrigerants. While most DX equipment manufacturers are moving to R-454B (GWP 466) and R-32 (GWP 771[1]), other options for consumer-sized equipment[2] exist, such as R-290 (propane, GWP 0.02) and R-717 (ammonia, GWP 0), which have near-zero GWPs, are naturally occurring, and offer improved efficiency over synthetic refrigerants. However, these low-GWP refrigerants are ASHRAE class A2 and up (flammable, such as R-32, R-454B, and R-290) or B2 and up (toxic, such as R-717). Monobloc AWHPs enable the safe use of these refrigerants, which are also naturally occurring, reducing the environmental impacts of manufacturing, and better performing, with some R-290 AWHP manufacturers claiming being able to provide 125F water at outdoor temperatures of -25F.

Finally, AWHPs ease many typical acceptance issues associated with heat pumps, such "cold blow," which happens when the heat pump enters a defrost cycle. In DX heat pumps, the heat for defrost must come from the conditioned air, resulting in temporarily blowing cold air on occupants. With AWHPs, there is sufficient heat storage in the water loop for most defrost cycles in California climates, eliminating any such comfort concern. (Higa, et al. 2024)

Based on these advantages, this technology clearly has great potential that needs to be explored.

Residential AWHPs can be easily coupled to multiple delivery methods, including fan coils (ductless and/or ducted) and radiant, either floors (tubing embedded in floor slab or lightweight concrete topping) or radiant panels (either ceiling or wall mount). These different comfort delivery methods have different advantages and disadvantages, affecting system performance and comfort. Radiant is a common delivery system coupled to an AWHP, which typically consists of long hydronic circuits of tubing imbedded in the ceilings, walls, and/or floors. Because there are no ducts involved, adding zoning to radiant systems is generally relatively simple: add a zone valve activated by a thermostat in the zone. If a zone is small in load or volume, a buffer tank can be used to decouple AWHP and zone operation, enabling the AWHP to continue operating efficiently. (Siegenthaler 2024)

However, radiant systems can be difficult and expensive to implement in a retrofit and are unfamiliar to most installers and homeowners. (Pallin, Haile and Chally 2022) Using a ducted hydronic fan coil unit (FCU) as the delivery system would enable the AWHP system to present as something much more familiar to the market: traditional ducted split systems. The AWHP becomes analogous to a heat pump outdoor unit, the ducted hydronic FCU becomes analogous to a heat pump indoor coil and air handler, and the plumbing between them becomes

[1] In 2007, the GWP of R-32 was estimated to be 675. In 2021, this was revised to 771.

[2] R-744 (CO_2) has a GWP of 1, but no residential technology exists which can achieve cooling using R-744.

analogous to the refrigerant lineset. Many of the previously mentioned benefits of AWHPs still apply (easier integration with secondary systems, devices, and thermal resources, safer implementation of low-GWP refrigerants, etc.).

But does the simplified zoning still apply? Energy efficient implementation of zoning with ducted DX heat pump systems is challenging and resulted in significant restrictions in California energy code. To ensure that zoning does not impact heat pump efficiency, Title 24, Part 6 required minimum airflows of 350 cfm per ton of nominal cooling capacity for each potential zonal configuration. This makes zoning impractical and results in potentially providing any single zone with far more airflow than required by ACCA Manual J load calculations. As currently written, the same airflow requirements would apply to AWHP systems with ducted fan coils, even though, as with radiant systems, a simplified duct zoning method (dampers that open and close) should be implementable in an AWHP-based system using a ducted hydronic FCU without impacting AWHP efficiency by decoupling AWHP and FCU operation through a buffer tank.

The project discussed in this paper specifically examined the necessity of the 350 cfm/ton in each zonal configuration requirement when zoning ducted hydronic systems with AWHPs. This project documents the energy and comfort performance of an AWHP with two duct configurations (a central duct system zoned upstairs and downstairs using dampers vs. two separate ducted FCUs, one upstairs and one downstairs) in a two-story home with two different airflows (ACCA Manual J design and minimum Title 24, Part 6 required airflow).

Project Overview

This project was conducted during the winter/spring heating season of 2023 and spring/summer cooling season of 2023, and funded by PG&E's Code Readiness program, with oversight by Thomas Mertens of PG&E, as well as Edie Taylor and Decker Ringo of West Monroe Partners.

Test Location

These evaluations were performed in one of the four unoccupied laboratory houses in the Central Valley Research Homes (CVRH) project. Located in Stockton, CA, the Fedelia house has been used to evaluate hydronic systems using AWHPs since 2015. Prior CVRH evaluations have included comfort performance, energy use, condensation risk, methods of dehumidification, and the effects of ceiling fans on panel cooling performance. These evaluations are documented in detail in reports available on the Energy Transition Coordinating Council (ETCC) website and prior ACEEE Summer Study and ASHRAE papers. (Haile and Springer 2018) (Haile and Chally 2022) (Chally and Haile 2022) Hydronic work at CVRH since 2019 has focused on using hydronic FCUs as the indoor comfort delivery method, due to the reduced market barriers and wider applicability, while still retaining all the benefits of the AWHP technology.

The Fedelia house pictured in Figure 1, is an 1,894 ft2, two story home with slab on grade construction and mid-story entry built in 1996. Table 1 summarizes key characteristics of the house prior to testing. While this study focuses on a single home and climate (CA Climate Zone 12, DOE 3B), the Fedelia site was intentionally selected as a representative vintage slab-on-grade residence with severe attic thermal exposure, providing a stress test for distribution system performance under hot-dry conditions.

Figure 1. Front of Fedelia House.

Table 1. Fidelia House Characteristics

Blower Door Air Leakage Rate	1,168 CFM50 (5.2 ACH50)
Attic Insulation	R-49 (846 ft2 ceiling area)
Attic Ventilation Area	10.5 ft2 (1 ft2 vent/ 85 ft2 ceiling area)
Wall Insulation	R-13
IAQ Ventilation Rate	ASHRAE 62.2-2010 compliant bath exhaust fan, 57 CFM

Air-to-Water Heat Pump

Figure 2 shows a picture of the installed AWHP, which is a variable capacity heat pump with a nominal cooling capacity of 2.5 tons (95°F ambient and 54°F leaving water temperature) and 33.8 kBtu in heating (43°F ambient and 95°F leaving water temperature). Nominal efficiencies are 12.7 EER and 3.9 COP.

Figure 2. Installed AWHP.

Figure 3 shows a diagram of the whole hydronic system. The AWHP has an internal pump which circulates water between the AWHP's refrigerant to water heat exchanger and a 40-gallon buffer tank. The AWHP is controlled by an aquastat on the buffer tank which signals the AWHP to operate. In heating mode, the AWHP maintains the buffer tank at 105 F, while in cooling mode the buffer tank is maintained at 50 F. Leaving water temperature targets were 105 F and 45 F. To avoid unnecessary cycles on low load days, the signal from the aquastat is locked out unless there is a cooling or heating call from one of the zone thermostats.

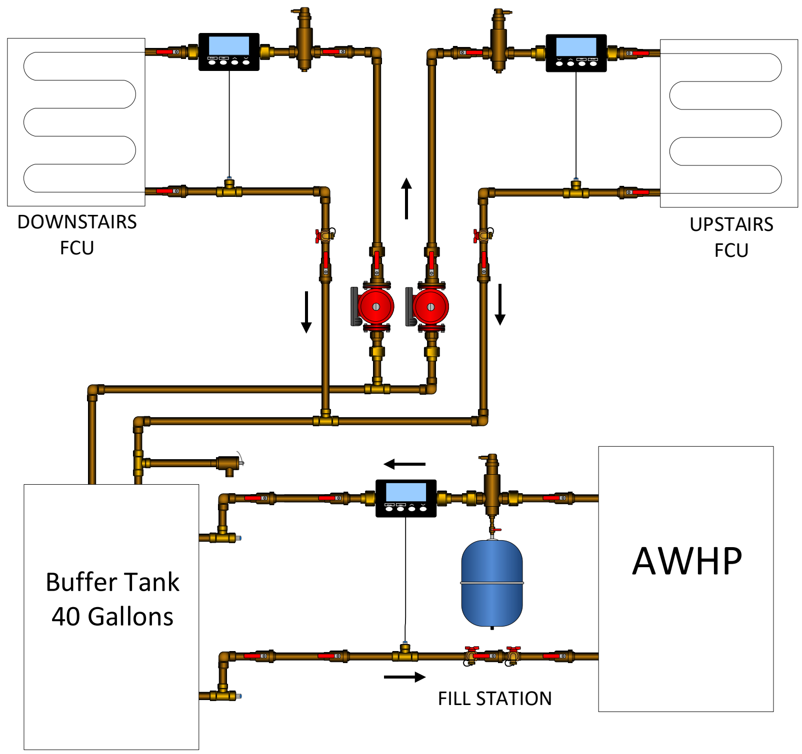

Figure 3. Diagram of hydronic system, excluding the AWHP.

Ducted Hydronic FCUs

Two different FCU and duct arrangements were used:

1. Two separate ducted FCUs, one with supply and return located upstairs and one with supply and return located downstairs. ("Two FCU System")
2. A central FCU system with upstairs return and dampers to zone upstairs from downstairs. ("Central System")

Figure 4 shows a 3D rendering of the duct systems. To limit differences between each evaluated case that could impact the results, the same supply ducts were used for both Two FCU System and Central System duct configurations. This was achieved using a mechanical damper and two ultra-light gravity dampers just off the downstairs supply plenum which prevented one air handler's supply airflow from discharging out the return of the other FCU.

For example, in Central System mode, with the downstairs zone calling, the upstairs air handler would open its mechanical damper to downstairs, releasing airflow to the downstairs supply plenum. (The downstairs air handler would be off, per evaluated case configuration.) That airflow would open the ultra-light gravity damper (negligible impact on static pressure) between the duct coming down from upstairs and the downstairs supply plenum. This same airflow would keep the other gravity damper closed and all supply airflow downstairs would flow through the downstairs supply ducts and out the supply registers.

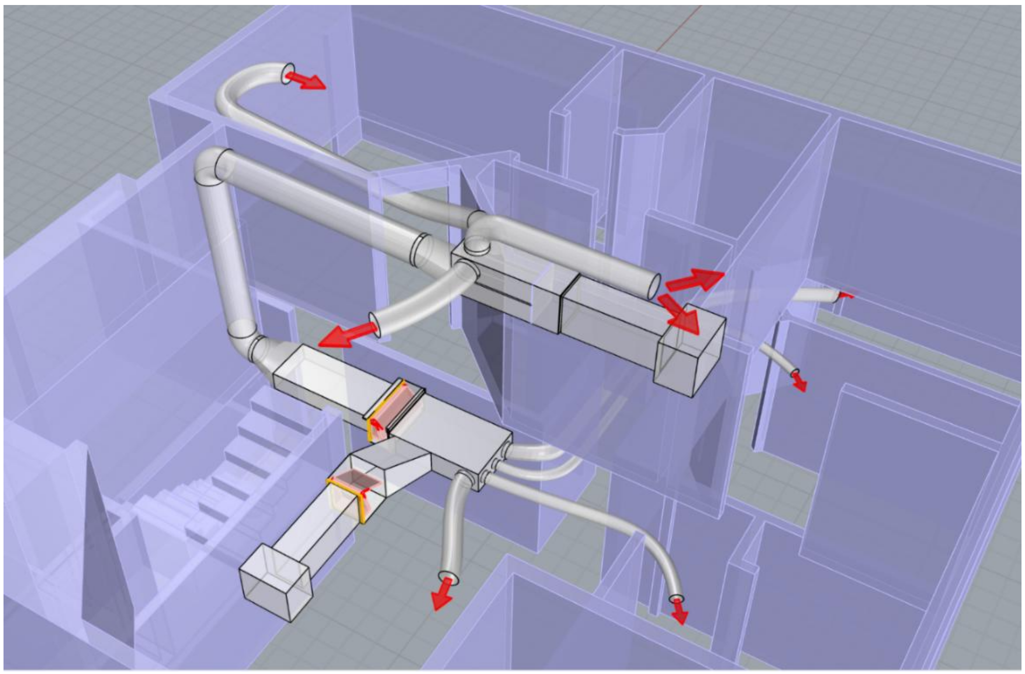

Figure 4. 3D rendering of the ventilation ducts for the Two FCUs, one upstairs and one downstairs. *Source:* Energy Docs High Performance Contractors Inc.

As previously mentioned, each duct configuration was tested with two different total airflows:

1. ACCA Manual J airflow: The design airflow resulting from ACCA Manual J calculations.
2. Title 24 airflow: The airflow required by California Title 24 energy code. (350 cfm/nominal ton of cooling)

This results in four total combinations of duct configuration and total airflows, which comprise the four evaluated test cases in this project, summarized in Table 2.

Table 2. AWHP Zone and Airflow Configurations

Test Case	Zone Configuration	Airflow Configuration
1	Central Upstairs FCU	Title 24
2	Central Upstairs FCU	Design
3	Two FCUs	Title 24
4	Two FCUs	Design

Supply register airflows for each configuration were measured. Table 3 shows the individual supply register airflows for when both zones are calling. Each supply has a manual balance damper and the condition of both zones calling was the configuration used for that balancing. Note that Title 24 airflows are much higher than Design airflows.

Table 3. Supply airflows by configuration when both zones are calling.

Room	Central – T24	Central - Design	Two FCUs – T24	Two FCUs - Design
Primary Bed	197	147	222	190
Living Room	176	143	250	184
Kitchen/Dining	166	131	208	183
Bonus Room	173	109	272	185
Bedroom 1	85	48	118	79
Bedroom 2	79	51	121	81
Bedroom 3	129	83	196	129

Test and Evaluation Methods

Daily total system energy use and daily efficiency of the FCU systems were compared both for individual peak days and in aggregate for entire seasons. Efficiency in cooling and heating is expressed as the coefficient of performance (COP). Daily efficiencies are calculated as the daily total delivered thermal energy in kWh divided by the daily total electrical energy consumption in kWh. These are calculated with standby energy use.

Comfort performance was compared in aggregate for entire seasons, using the criteria provided in ACCA Manual RS for air temperature distribution and deviation from setpoint (ACCA 1997). The bounds for these metrics are specified in Table 4 and referred to in this report as the “comfort criteria.”

Table 4. ACCA criteria for multi-zone systems.

	Room-to-Room		Floor-to-Floor		Room-to-Setpoint
Zone Type	Average	Maximum	Average	Maximum	Maximum
Multi-Zone (Two FCU)	2	4	2	4	2
Single Zone (Central FCU)	3	6	3	6	3

The comfort criteria is based on temperature differences between each room and setpoint, each room and each other room, and floor-to-floor. Indoor temperatures in real houses may or may not meet these criteria, but they are a useful tool for evaluating comfort and serve as an indicator of how effectively a system maintains and distributes comfort throughout a space.

For example, significant noncompliance with the floor-to-floor criteria implies a zoning controls issue. Significant noncompliance with room-to-room criteria indicates poor distribution. Significant noncompliance with the room-to-setpoint test implies a sizing issue. Low noncompliance with distribution criteria, but high noncompliance with room-to-setpoint criteria, implies that distribution is effective, but the system is not appropriately sized.

A modified version of ASHRAE Standard 55 was also used to evaluate relative comfort, using measured air temperatures in two rooms (upstairs living room and downstairs bonus room).

Results

Comfort Performance

Figure 5 details the heating season floor to floor temperature differences. Heating season floor to floor temperature differences indicate that Design airflow fails the ACCA difference criteria, but the Title 24 (T24) airflow does not. The Two FCU Design airflow fails the floor-to-floor temperature difference by about ten percent more than the centrally zoned AWHP configuration.

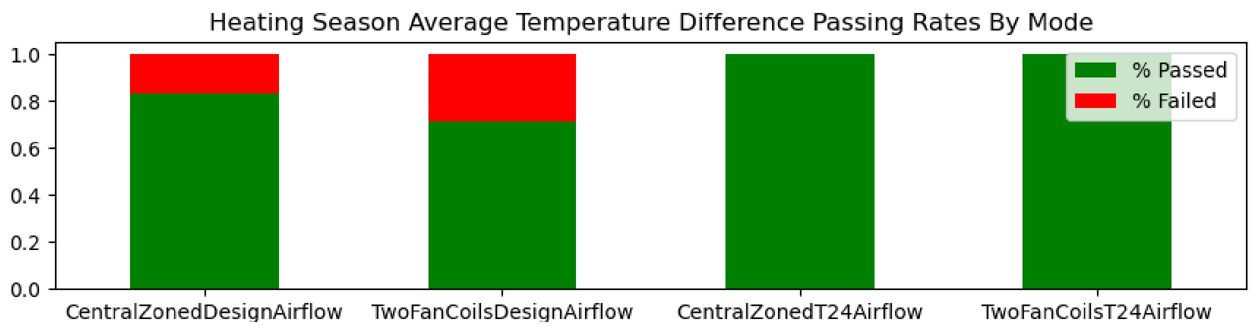

Figure 5. Winter compliance rates for floor-to-floor temperature difference comfort criteria by mode.

Figure 6 shows the percentage operation time in summer that house conditions were within and outside of the ACCA floor to floor comfort levels, for each system configuration. Cooling season floor-to-floor and floor-to-setpoint temperature differences stayed within the ACCA comfort criteria for all duct configurations.

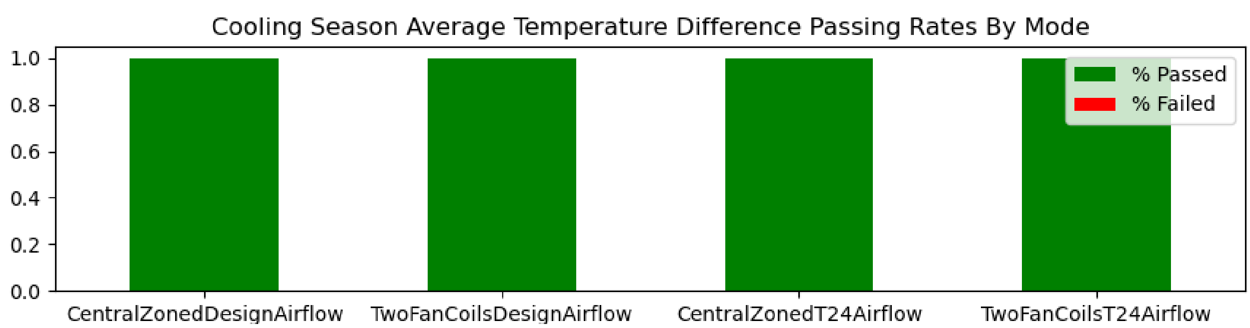

Figure 6. Summer compliance rates for floor-to-floor temperature difference comfort criteria by mode.

Figure 7 and Figure 8 show the percentage operation time that house conditions were above, within and below ACCA floor to setpoint comfort levels, for each system configuration in heating season and cooling season, respectively.

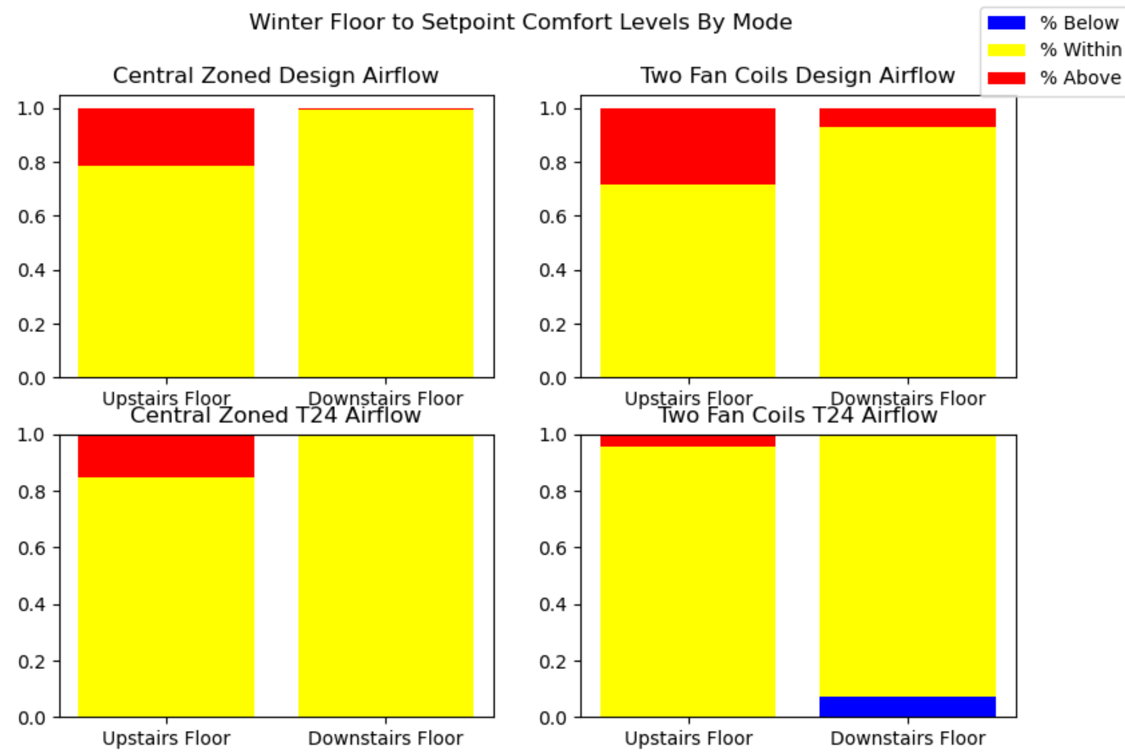

Figure 7. Winter compliance rate for room-to-setpoint temperature difference comfort criteria.

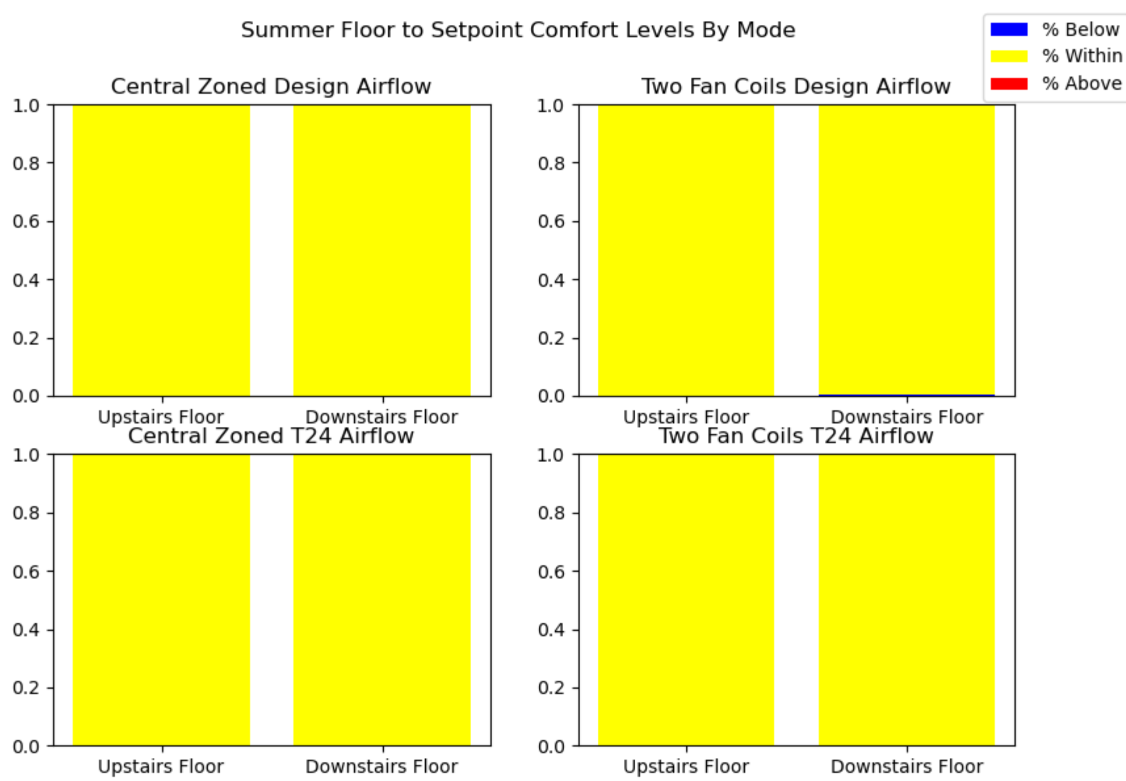

Figure 8. Summer compliance rate for room-to-setpoint temperature difference comfort criteria.

The average floor-to-setpoint temperature differences for all heating season days shown in Figure 7 indicate that the Title 24 airflow minimizes overall comfort concerns. Though all four configurations result in excess heating upstairs, with the Title 24 airflow this is only 16 percent of the time for the Central configuration and less than 5 percent of the time for the Two FCUs configuration. However, the Two FCUs configuration with Title 24 airflow is the only configuration that results in underheating, specifically in the downstairs zone. Figure 8 indicates that all four evaluated cases were practically flawless from a comfort perspective in cooling, regardless of configuration and airflow.

Figure 9 shows comfort plotted on a psychrometric chart, similar to ASHRAE 55 guidelines for cooling and heating. Human thermal comfort areas are based on two different clothing configurations 0.5 clo for summer clothing and 1 clo for heaver winter clothing where 1 clo is 0.155 m^2-°C/W. Each test configuration is depicted including: the Two FCU T24 (TFCUT24) airflow, Central Zoned Title 24 (CZT24) airflow, Central Zoned Design Airflow (CZDA) and Two FCU Design Airflow (TFCUDA).

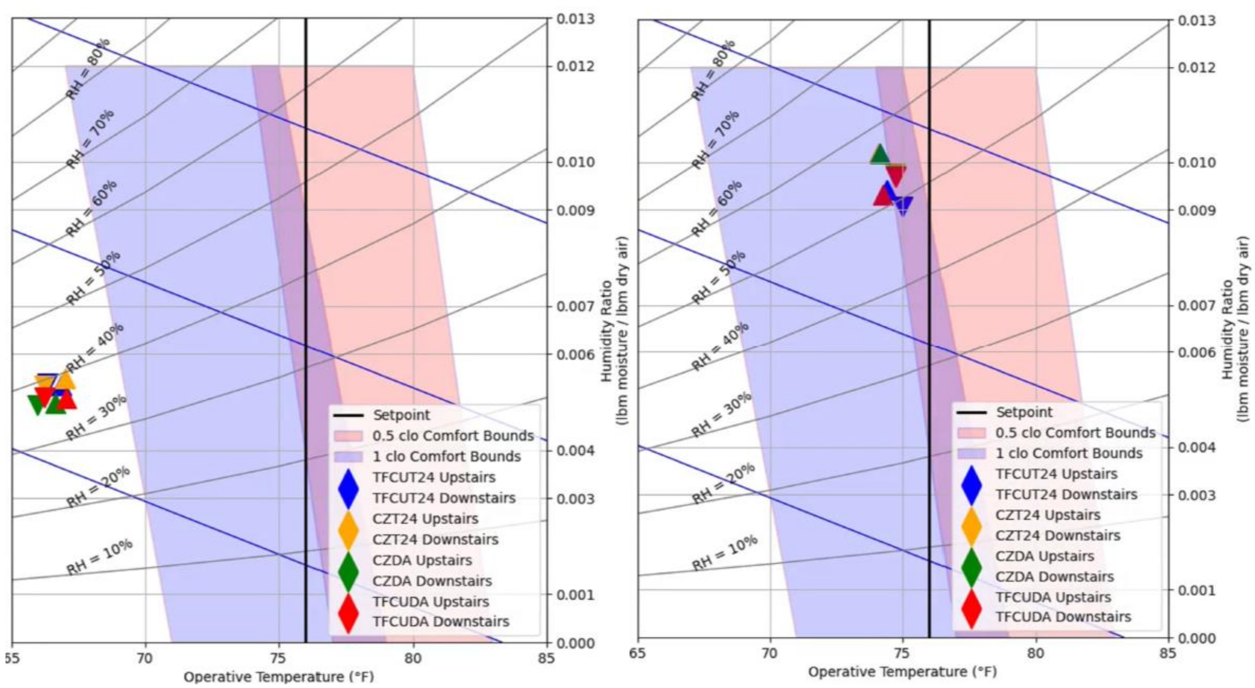

Figure 9. Average of All Daily AWHP Heating Season (Left) and Cooling Season (Right) Based on Average Indoor Temperature and Humidity in Upstairs and Downstairs Zones on the ASHRAE 55 Guideline Plot with 0.5 clo and 1 clo Temperature Comfort Zones.

Overall, the four configurations provided similar comfort based on daily average zonal temperature and humidity in heating season and cooling season. Heating season results indicate that on average all four configurations lead to indoor comfort levels outside of the 1.0 clo comfort bounds for ASHRAE 55, but this is because of the winter setpoint of 67°F which is outside the comfort region. As expected, the upstairs zone is a couple degrees warmer due to stack effect in the two-story home. In cooling, the upstairs is just within the 0.5 clo comfort bounds, though close to the edge of the 1.0 clo bounds. Meanwhile the downstairs is not far off, but just within the 1.0 clo bounds.

Overall System Performance

Overall system performance is provided as an average for heating and cooling season and average daily performance relative to the outdoor air temperature. Performance was analyzed in two ways, a single peak day performance for each configuration where the outdoor ambient conditions were similar and aggregated for all heating and cooling days.

More applicable than the COP, the average daily energy use of each zone configuration was plotted vs. average outdoor air temperature. Figure 8 compares the whole house daily average total system energy associated with the AWHP system during the cooling season, while Figure 9 shows the heating season.

There is a strong linear relationship between the average outdoor temperature and the total system energy used by the AWHP to cool the home. The two central duct configurations have the steepest slope fit lines among these data sets. This means that as the days get hotter, the central zoned duct configuration uses more energy than other duct configurations per degree of outdoor air temperature. The Two FCUs configuration with Title 24 airflow uses the most energy among the four tested configurations. The two central zoned configurations have a similar energy consumption per degree of outside air and this is slightly more than the Two FCUs configuration with the Design airflow on average.

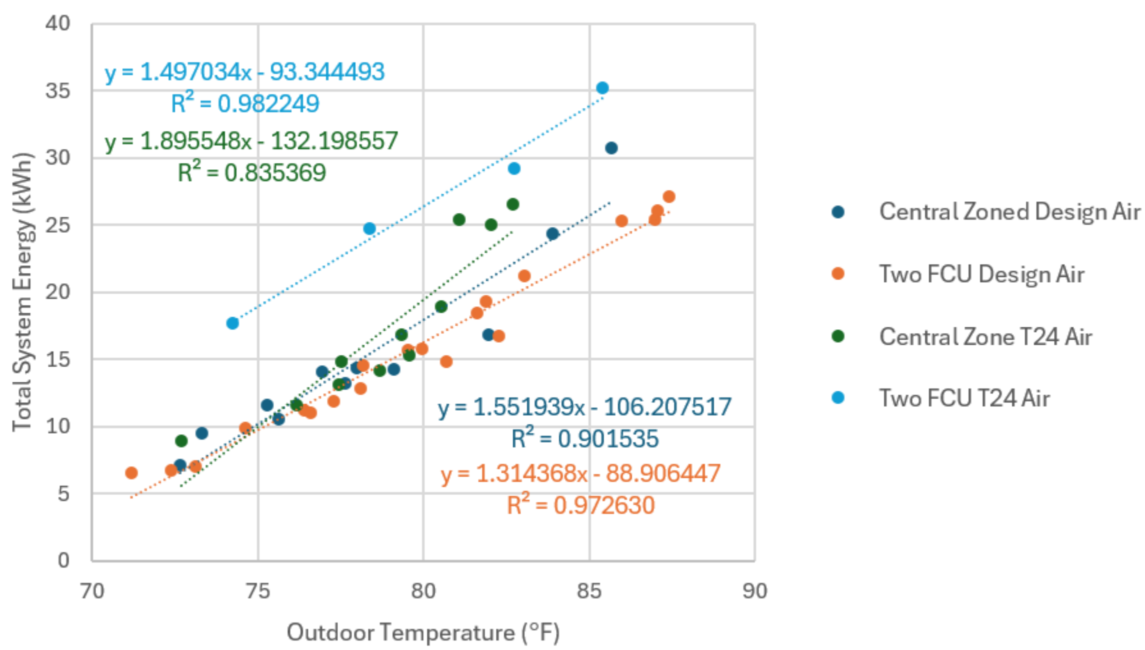

Figure 10. Cooling Season Daily Energy Use vs. Average Daily Outdoor Air Temperature for Different Modes.

Similar to the cooling season results, there is a strong linear relationship between the average outdoor temperature and the total system energy used by the AWHP to heat the home. Different from the cooling data, the Two FCUs configuration with the Design airflow has the steepest slope. The two test cases that use the most energy are the Central Zoned duct configuration with Design airflow and Two FCUs duct configuration with Design airflow.

Table 5 lists average performance of similar high average outdoor temperature cooling days for each system configuration including temperatures, total energy delivery, total non-standby energy use, full load coefficient of performance (COP), total daily energy use including standby, and daily average COP. Daily average COP is the total energy delivery divided by the total energy use including standby energy which can be compared to the AWHP rated COP.

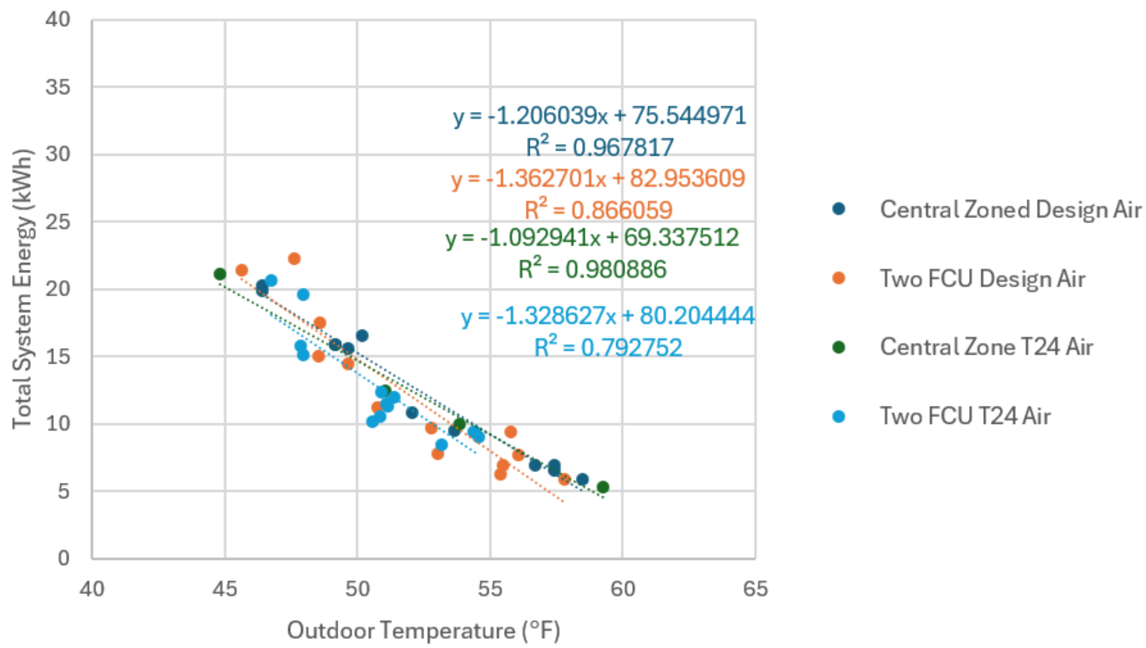

Figure 11. Heating Season Daily Energy Use vs. Average Daily Outdoor Air Temperature for Different Modes.

Table 5. Peak Cooling Day and Heating Day System Performance

Duct Case	Central	Two FCUs	Central	Two FCUs	Central	Two FCUs	Central	Two FCUs
Airflow Case	Design	Design	Title 24	Title 24	Design	Design	Title 24	Title 24
Mode	Cool	Cool	Cool	Cool	Heat	Heat	Heat	Heat
Outdoor Temp.	83.9	83.0	82.7	82.7	46.4	45.7	44.8	46.8
Indoor Temp.	76.2	76.0	76.1	76.1	68.0	68.0	68.0	67.2
Daily Delivery (kBtu)	204.1	202.6	194.1	198.0	308.9	259.4	273.7	229.6
Daily Energy Use, Excluding Standby (kWh)	24.2	20.9	26.4	29.0	20.0	21.1	20.8	20.4
Daily Full Load COP	2.47	2.85	2.15	2.00	4.54	3.60	3.86	3.30
Daily Energy Use, Including Standby (kWh)	24.3	21.2	26.6	29.2	20.3	21.4	21.1	20.7
Daily COP	2.46	2.80	2.14	1.99	4.46	3.55	3.80	3.25

A comparison of similar high average outdoor temperature cooling days indicates that the Design airflow provided the highest system performance regardless of the duct configurations for daily COP and full load COP. Both Design airflow tests resulted in higher system performance than the Title 24 airflow tests with daily COPs ranging from 0.30 to 0.81 higher (14 percent to 41 percent higher) than the Title 24 airflow system cooling efficiency during equivalent days. The Central Zone FCU duct configuration provided higher system performance than the Two FCU configuration for the Title 24 airflow (0.15 higher COP or 8% higher efficiency), but the Two FCU duct configuration provided higher system performance than the Central Zone FCU for the Design airflow (with a daily COP 0.34 lower or 14% lower). Similar to the peak cooling day analysis, the peak heating day analysis shows that the Design airflow configurations provided higher system performance than the Title 24 airflow rates for both daily COP and full load COP. During heating, the Central Zone FCU duct configuration provided the highest system performance regardless of the airflow rates for both daily COP and full load COP. The Central Zone FCU duct configuration with Design airflow resulted in higher system performance than the Two FCU duct configuration with a daily COP improvement of 0.91 (or 26%) using Design airflow rates during equivalent days. When comparing the configurations for the Title 24 airflow, the central zone configuration resulted in a daily COP improvement of 0.55 (or 17%). Table 6 lists average performance of all valid cooling days and heating days for each system configuration.

Comparing all valid cooling days provides similar results to the peak cooling day analysis. The Design airflow results in the highest daily COP in all cases, but here the Two FCU duct configuration results in higher system performance than the Central Zone FCU configuration. Similar to the all valid cooling day analysis and peak heating day analysis, the all valid heating days analysis indicates that the Central Zone FCU configuration provided higher system performance regardless of the airflow rates. The Central Zone FCU configuration with Design airflow resulted in higher system performance than the Two FCU configuration with a daily COP improvement of 0.57 (or 25%) using Design airflow during equivalent days, while the Central Zone FCU with Title 24 airflow resulted in a daily COP improvement of 0.16 (or 5%) over the Two FCU configuration.

Table 6. Average of All Valid Day System Performance for Cooling and Heating System Performance

Duct Case	Central	Two FCUs	Central	Two FCUs	Central	Two FCUs	Central	Two FCUs
Airflow Case	Design	Design	Title 24	Title 24	Design	Design	Title 24	Title 24
Mode	Cool	Cool	Cool	Cool	Heat	Heat	Heat	Heat
Outdoor Temp.	78.2	79.7	78.9	80.2	52.2	52.1	52.1	50.9
Indoor Temp.	76.1	76.0	76.1	76.0	68.5	68.5	68.3	67.6
Daily Delivery (kBtu)	139.1	147.8	144.2	187.4	184.1	145.1	149.9	146.6
Daily Energy Use, Including Standby (kWh)	15.1	15.9	17.3	26.7	11.6	12.0	12.2	12.5
Daily COP	2.69	2.73	2.44	2.06	4.42	3.55	3.59	3.43

Conclusions

This project was focused on assessing the energy and comfort performance associated with AWHPs heating and cooling a home with two different duct zoning configurations and two different airflow rates. These four configurations indicate the range in system performance that can be seen by different implementations of the same AWHP which can exceed the rated COP of 3.9 during heating season.

All four configurations provided a high likelihood of comfort satisfaction during the cooling season, but there was some overwarming during the heating season due to the stack effect (heat rising) in a two story home. Title 24 airflow configurations minimized overwarming of the second floor because the high flow rate causes the first-floor temperature setpoint to be met sooner than with the low airflow rate of Design airflow configurations. The upstairs zone was outside of the ACCA temperature setpoint to floor temperature requirement less than 5 percent of the time for the two Title 24 airflow configurations, while the Design airflow configurations resulted in at least 20 percent over-warming of the space for both duct cases.

System efficiency results indicate that Design airflow configurations provide a higher COP than the Title 24 airflow configurations during peak heating and cooling days. One exception to this is the Central Zone FCU with Title 24 airflow, which had a higher COP than the Two FCU configuration with Design airflow during heating season.

Energy consumption results indicate that three configurations (centrally zoned Title 24 airflow, centrally zoned Design airflow and Two FCU Design airflow) in cooling season use nearly identical amount of energy to cool the home. All three of these configurations use less energy than the Two FCU configuration with Title 24 airflow for daily energy use savings of at least 9% or more on average for a day with an average outdoor temperature of 75°F. The Two FCU configuration with Design airflow had the lowest energy consumption and is best suited for hot climates. Because system performance results during heating season do not follow the same trends as cooling season, the best configuration selected for a home may depend on the climate. Residences with AWHPs in climates with 45°F or warmer heating days would benefit most from the Two FCU configuration with Title 24 airflow or the Two FCU configuration with Design airflow.

This project illustrates that while the AWHP system has a COP rating of 3.9, actual system performance during cooling season were in a COP range of 2.06 to 2.73 on average and heating season COPs were typically in the range of 3.43 to 4.42 on average.

In addition, this project indicates that zoning can be beneficial for occupant comfort under certain airflows. In this case, the Two FCU Title 24 airflow test mode provided the highest overall comfort by heating each floor of a two-story single-family home with separate FCUs.

References

ACCA. 1997. *ACCA Manual RS: Comfort, Air Quality, and Efficiency by Design.* Washington, D.C.: ACCA.

ASHRAE. 1985. *ASHRAE Handbook: Fundamentals.* Atlanta: ASHRAE.

Caleffi. 2020. "Design details for air-to-water heat pumps." *idronics* 58-72. https://www.caleffi.com/sites/default/files/media/external-file/Idronics_27_NA_Air-to-water%20heat%20pump%20systems.pdf.

CEC. 2022. *MAEDBS Advanced Search.* March. Accessed March 2022. https://cacertappliances.energy.ca.gov/Pages/Search/AdvancedSearch.aspx.

Chally, Stephen, and James Haile. 2022. "Evaluation of Condensation Risk Mitigation Methods for Residential Radiant Ceiling Cooling Systems." *ACEEE Summer Study.* Asilomar. https://www.researchgate.net/publication/373682874.

Haile, James, and David Springer. 2018. "Sol et Aquilo: Improving Sensible Comfort and Energy Efficiency with Hydronic Radiant Ceiling Panels." *ACEEE Summer Study.* Asilomar. https://www.researchgate.net/publication/373682921.

Haile, James, and Stephen Chally. 2022. "Sol et Aquilo, Round 2: Hydronic vs. Hydronic, Comparing Performance of Air-to-Water Heat Pumps Coupled with Radiant Ceilings and Fan Coils." *ACEEE Summer Study.* Asilomar. https://www.researchgate.net/publication/373683298.

Haile, James, David Springer, and Marc Hoeschele. 2021. *Assessment of Residential Air-to-Water Heat Pumps with Thermal Energy Storage.* January 4. Accessed March 2022. https://www.etcc-ca.com/reports/assessment-residential-air-water-heat-pumps-coupled-thermal-energy-storage.

Higa, Randall, Matt Horwitz, Jose Buendia, Jon McHugh, James Haile, and Kristin Heinemeier. 2024. "Yeah, But It's a Dry Cold: Applicability of Cold Climate Heat Pumps in California." *ACEEE Summer Study.* Asilomar. https://www.aceee.org/sites/default/files/proceedings/ssb24/pdfs/Applicability%20of%20Cold%20Climate%20Heat%20Pumps%20in%20California.pdf.

Hoeschele, Marc, and James Haile. 2020. *Enhanced Air-to-Water Heat Pump Compliance Options.* California Statewide Codes and Standards Enhancement Program. https://title24stakeholders.com/wp-content/uploads/2020/09/Res_2022_T24_CASE-Report_Final_SF_AWHP.pdf.

Pallin, Simon, James Haile, and Stephen Chally. 2022. "Radiant ceilings as a residential retrofit: Examining the myths a realities." *ACEEE Summer Study.* Asilomar. https://www.researchgate.net/publication/373682952.

Siegenthaler, John. 2024. *Air-to-Water Heat Pump Fundamentals.* June. https://www.heatspring.com/courses/air-to-water-heat-pump-fundamentals.