

Sol et Aquilo¹, Round 2: Hydronic vs. Hydronic, Comparing Performance of Air-to-Water Heat Pumps Coupled with Radiant Ceilings and Fan Coils

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ABSTRACT

Air-to-water heat pumps (AWHPs) using hydronic delivery have been tested since 2015 at one of the Central Valley Research Houses (CVRH) in Stockton, CA. These unoccupied laboratory houses are used to evaluate emerging technologies and potential code compliance options. CVRH has been sponsored by utilities, primarily Pacific Gas & Electric (PG&E) and Southern California Edison (SCE), and the California Energy Commission for almost a decade.

A 2018 ACEEE Summer Study paper based on CVRH work compared radiant ceiling systems to air-to-air ducted systems. While AWHPs with radiant ceilings performed well, the technology faces significant market barriers, such as high cost of materials and installation. However, AWHP-based hydronic systems could have a key role in the future of residential energy management, as they can provide both indoor heating and cooling and hot water production, potentially easing electrification retrofits, while also integrating with features like thermal storage, waste heat recovery, and zoning methods that do not compromise outdoor unit performance. Therefore, examination of alternative delivery methods with AWHPs that have fewer market barriers is warranted.

Hydronic fan coils are much more acceptable to the market, retain many of the benefits of hydronic systems, and are readily coupled to an AWHP. The energy use and comfort provided by a ducted hydronic fan coil system, tested at CVRH in 2020, was compared to a hydronic radiant ceiling system, both using the same AWHP. The radiant system was zoned upstairs and downstairs, while the fan coil ducts were not zoned.

While the fan coil system experienced comfort issues relative to the radiant system, these were due to being a single zone system compared to zoned system: excess heating upstairs in winter and excess cooling downstairs in summer. In heating, the fan coil system used approximately 20% less energy than the AWHP and radiant system, while also achieving a higher coefficient of performance (COP). However, in cooling the fan coil system used more energy than the radiant system, though the fan coil system achieved a higher energy efficiency ratio (EER). This is due to the fan coil provided both sensible and latent cooling while the radiant ceiling only met sensible load. When a ductless fan coil was added to the radiant system to address latent load concerns, cooling comfort, energy use, and efficiency were similar to that of the fan coil system.

Given the performance, the general need to address latent loads (especially in well-sealed dwellings), and the market barriers to radiant systems, ducted fan coils may be the better option to promote wider adoption of AWHPs and hydronic technology.

¹ “Sol et Aquilo” is the Latin title of Aesop’s fable “The Sun and the North Wind.”

Introduction

Air-to-water heat pumps (AWHPs) are air source heat pumps with refrigerant to water heat exchangers that chill and heat water. In a residential heating, ventilation, and air conditioning (HVAC) application, this conditioned water is pumped to either radiant panels or fan coils to deliver indoor space conditioning. While the heat exchange from outdoor air to refrigerant to water to indoor air seems like an unnecessary extra step (compared to conventional heat pump systems, which exchange heat from air to refrigerant to indoor air), there are many advantages.

The first is flexibility: unlike conventional air to air systems, AWHPs can easily use multiple delivery methods, including fan coils (ductless and ducted) and radiant (floors, ceilings, or walls). AWHP-based hydronic systems can also be integrated with waste heat recovery devices, desuperheaters, and solar thermal panels.

The second is that AWHP-based systems can do things which air-to-air systems cannot. For example, an AWHP-based system can decouple outdoor unit operation and indoor unit operation through a buffer tank, allowing for zoning methods that do not compromise outdoor unit efficiency. An AWHP can also provide domestic hot water heating, allowing the use of a single outdoor heat pump to serve all heating and cooling loads in a house. This has the potential to simplify electrification retrofits, as only a single 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 compromises on comfort (Haile, Springer and Hoeschele 2021).

Finally, another major advantage of the monobloc AWHP over air-to-air split systems is that only water (occasionally with non-toxic propylene glycol) 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 split systems must still have the refrigerant charge adjusted after install, unless the lineset is within a certain range of length. This reduces installation complexity and the amount of greenhouse gas released to the atmosphere for the entire lifetime of the system.

Clearly this is a technology with great potential that needs to be explored. An unoccupied laboratory test house in Stockton, CA has been used to evaluate hydronic systems using radiant ceiling panels and fan coils with AWHPs since 2015 as part of the Central Valley Research Houses (CVRH) project.

Hydronic radiant ceiling panels are large heated or cooled ceiling surfaces containing tubes to transport heated and chilled water, to directly serve thermal loads through radiative heat transfer from the ceiling surface to the conditioned space. Objects inside a room with radiant ceiling panels radiate heat to the ceiling panel surface, which is cooled by chilled water circulated through channels in the panel. Some heat is also transferred to the panel surface via natural convection where rising warm air meets the panel surface. Hydronic radiant ceiling panels can be operated in heating or in cooling when coupled to hydronic heat pumps. They also are better suited to retrofits than radiant floor systems and are more effective than floors in cooling.

Ducted hydronic fan coils distribute heating and cooling in a manner that is very similar to traditional air-to-air heat pump systems. Therefore, existing HVAC trades can design, install, and maintain hydronic fan coil systems without significant additional training. Hydronic fan

coils possess another advantage over radiant ceiling panels, as they can provide both sensible and latent cooling. Radiant panels ideally only provide sensible cooling as condensation on the panel surface could cause damage to the building and its contents, which limits the applicability of radiant panels.

Evaluations of AWHP and radiant ceiling systems at CVRH have included comfort performance, energy use, condensation risk, methods of dehumidification, and the effects of ceiling fans. Reports available on the Emerging Technology Coordinating Council (ETCC) website document these evaluations in detail. (Haile, Springer and Hoeschele 2016) (Haile, Springer and Hoeschele 2018). A paper based on CVRH work comparing the performance of a radiant ceiling system with two different AWHPs (one single speed and one variable capacity) to that of a conventional air-to-air heat pump was presented at the 2018 ACEEE Summer Study (Haile, Springer and Cunningham, et al. 2018). Hydronic work at CVRH since 2019 has focused on using hydronic fan coils 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.

This paper compares the summer and winter comfort performance and energy use of the AWHP and radiant system (with and without a ductless fan coil for dehumidification) and an AWHP and ducted fan coil with all ducts located within conditioned space.

Project Overview

Tests were conducted during multiple summer and winter seasons at one of the four laboratory research houses maintained by the Central Valley Research House (CVRH) project (Wilcox 2014). The CVRH project operates four laboratory houses of different vintages and envelope configurations in Stockton, California (CA Climate Zone 12, IECC 3B). Three have been used to evaluate the field performance of mini-split heat pumps (Wilcox 2016). The houses serve as a useful test bed for evaluating various building technologies and systems. The fourth house, pictured in Figure 1, is used for radiant and hydronic system evaluations. Built in 1996, the house is a 1,690 ft², two-story home with slab on grade construction and a mid-level entry.



Figure 1. CVRH Radiant House.

The house was equipped with resistance heaters and fans in each room and a humidifier in the kitchen to mimic internal heat and moisture gains due to occupants and appliances, according to schedules used by California energy compliance models (CEC 2012).

Radiant System

The radiant ceiling system consisted of two types of panels: site-built heat transfer plate and prefabricated modular panels. The prefabricated panels were installed only in the master bedroom, as they were added late in the initial installation phase of the project, while the site-built panels were installed in all other rooms. Panel characteristics are provided in Table 1.

The site-built panels consisted of a 26-gauge steel lath, 16" wide with grooves spaced 8" apart that receive 1/2" PEX tubing. The lath is screwed to the ceiling and lath and tubes are covered with a layer of drywall. The specified capacities are 15.0 Btu/ft²-hr at 55 °F mean water temperature (MWT) (heating) and 21.9 Btu/ft²-hr at 95 °F MWT (cooling) (Newberry 2012).

The prefabricated panels consisted of 8 mm PEX tubing bonded to an 18-gauge aluminum sheet, backed by 1½" thick EPS foam insulation, covered by specially formulated drywall glued to the aluminum sheet. The specified capacities are 23.8 Btu/ft²-hr at 55 °F MWT (heating) and 22.3 Btu/ft²-hr at 95 °F MWT (cooling) (Messana 2017).

Panels were selected based on availability and ease of installation in existing homes. Total house sensible load per square foot of panel is 20.5 Btu/h·ft² in cooling and 25.4 Btu/h·ft² in heating.

Table 1. Room and panel properties.

Name	Level	Installed Panel Type	Floor Area (ft ²)	Panel Area (ft ²)	Average Flow (gpm)	ACCA Manual J Load (Btu/h)	
						Cooling	Heating
Bonus	1 st	Site-Built	222	120	1.00	2,008	2,742
Bedroom 1	1 st	Site-Built	119	88	1.29	1,236	2,270
Bedroom 2	1 st	Site-Built	119	72	1.16	1,214	1,370
Bedroom 3	1 st	Site-Built	104	72	1.00	1,411	2,358
Bath	1 st	Site-Built	38	27	1.82	530	949
Living	2 nd	Site-Built	312	187	1.77	3,237	2,717
Dining	2 nd						
Kitchen	2 nd	Site-Built	131	108	0.79	2,307	1,424
Master Suite	2 nd	Prefab.	267	125	1.37	2,307	2,345

Two radiant system configurations were tested: a radiant ceiling system with no dehumidification and a radiant ceiling system with dehumidification provided by a ductless hydronic fan coil.

Figure 2 shows a simplified plumbing diagram of the radiant system configuration used without dehumidification and Figure 3 shows the same with the ductless fan coil for dehumidification.

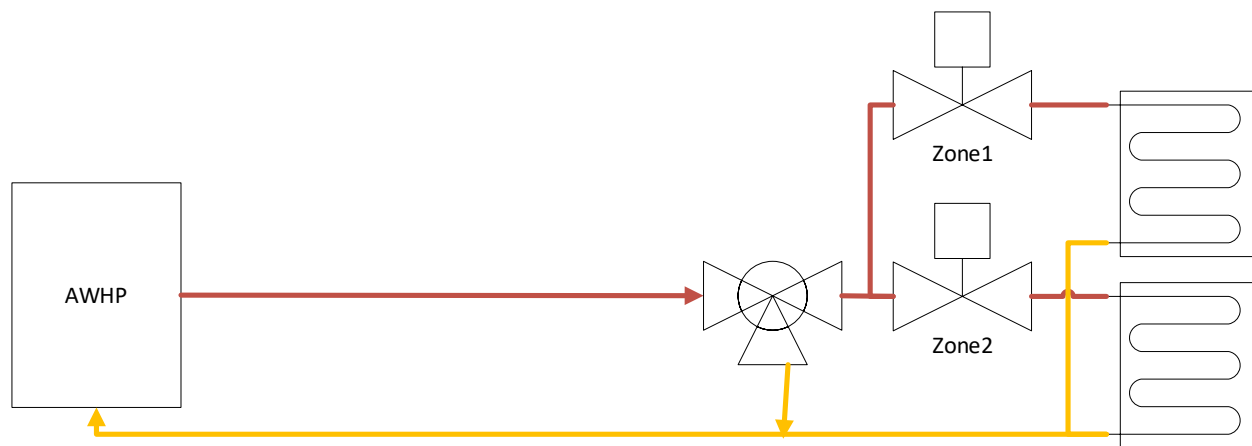


Figure 2. Radiant hydronic system schematic.

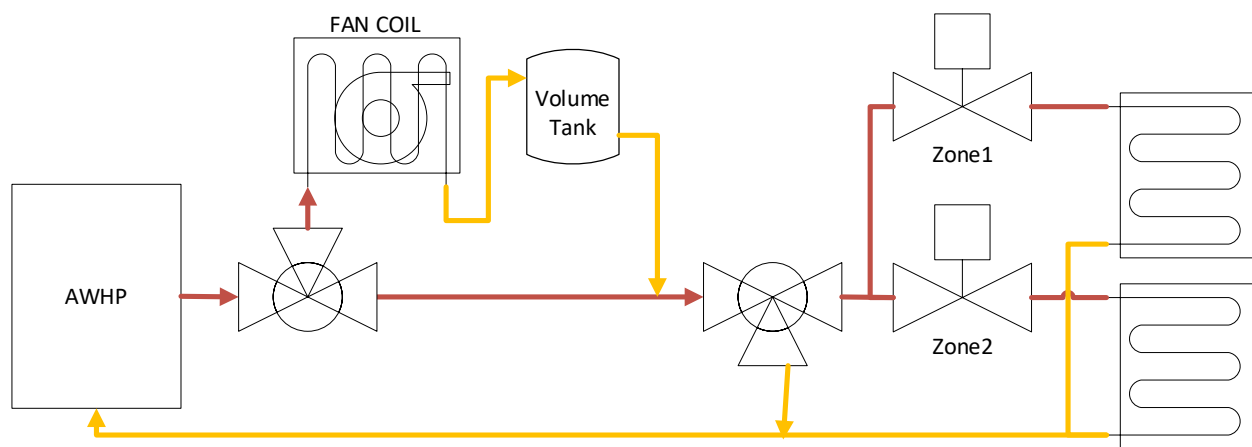


Figure 3. Radiant with ductless fan coil for dehumidification hydronic system schematic.

The radiant ceiling panels were zoned upstairs and downstairs, while the ductless fan coil was installed on the wall in the living room. A single zone version of the radiant system previously evaluated in 2015 is used in this paper as an additional comfort performance reference for the single zone ducted fan coil system.

Because the water volume of the ductless fan coil hydronic circuit was lower than the manufacturer's recommended minimum, a small tank was added to the return of the fan coil circuit to prevent short cycling. Additionally, the ductless fan coil was too restrictive for the AWHP's built-in pump so a second booster pump was added. Both pumps were variable speed electronically commutated motor-driven (ECM) pumps.

Thermostat setpoints were fixed at 76 °F in cooling and 68 °F in heating. AWHP water outlet temperature targets were 52 °F in cooling and 110 °F in heating. When the ductless fan coil was used for dehumidification, the AWHP would use two water outlet temperature targets: 52°F for radiant only and 45°F for operation with the fan coil. The fan coil was operated to maintain a dewpoint below 56 °F, which was selected based on the lowest recorded panel surface temperature in previous tests. Temperature rise through the fan coil was always sufficient to ensure panel supply temperatures were high enough to avoid condensation. Panel surface temperatures and room dewpoint temperatures were monitored during cooling tests. Panel

surface temperatures never dropped below dewpoint and no condensation on panel surfaces was observed.

Previous tests examined the possibility of using a portable dehumidifier for dehumidification, but found the energy use to be excessive (11.1 kWh relative to the 14 kWh energy use of the single speed AWHP used at the time with the radiant panels), and all energy used by the dehumidifier was introduced to the house as load (Haile, Springer and Hoeschele 2016).

Ducted Fan Coil

The ducted fan coil was a cased “A” coil with a nominal cooling capacity of 3-tons. A dimensioned drawing of the coil from the manufacturer is provided in Figure 4. This was paired with a variable speed ECM air handler and single zone ducts entirely within conditioned space (Figure 5). Cooling and heating setpoints were the same as those used for the radiant system.

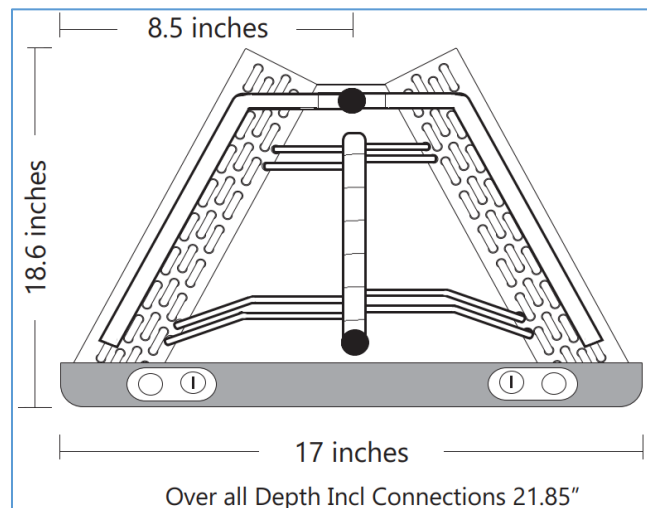


Figure 4. Drawing of the ducted fan coil and dimensions.
Image Credit: A.M.T.S LTD.



Figure 5. Duct system entirely within conditioned space.

Supply ducts and registers were carefully sized to produce a low static pressure of 0.13 in. w.c. in cooling and 0.24 in. w.c. in heating. The supplies to each room were manually balanced each season, to provide the appropriate airflow to meet load in each room. These airflows are shown below in Table 2, by room. Total airflows were 1098 cubic feet per minute (CFM) in cooling and 1082 CFM in heating, or 438 CFM/ton at the AWHP's nominal rating of 2.5 tons. Nominal fan efficacy was 0.22 W/CFM in cooling and 0.24 W/CFM in heating. For reference, California Building Energy Efficiency Standards (2019 Title 24, Part 6) minimum prescriptive requirements are 350 cfm/ton and 0.58 W/cfm (CEC 2018).

Table 2. Airflows and duct properties by room.

Name	Register Size	Duct Size	Airflow Heating (cfm)	Airflow Cooling (cfm)
Bonus	10" x 6"	9"	236	202
Bedroom 1	6" x 4"	6"	101	57
Bedroom 2	4" x 4"	5"	98	36
Bedroom 3	6" x 4"	6"	120	62
Living	10" x 8"	10"	126	167
Dining	10" x 8"	10"	147	240
Kitchen	8" x 6"	8"	115	127
Master Suite	10" x 8"	10"	139	206

The AWHP required a minimum system volume of 15 gallons to ensure operation without short cycling. To ensure this requirement was met, a 20-gallon tank was added to the return from the fan coil. A simplified plumbing diagram for the fan coil system is shown in Figure 6.



Figure 6. Ducted fan coil hydronic system schematic.

Air-to-Water Heat Pump

The AWHP used in these tests is a variable capacity heat pump with a nominal capacity of 2.5 tons in cooling (95 ambient and 54 leaving water temperature) and 33.8 kBtu in heating (43 ambient and 95 leaving water temperature). Nominal efficiencies are 12.7 EER and 3.9 COP. The same AWHP was used with both the radiant and fan coil delivery systems. The installed unit is shown in Figure 7.

Though the CEC requires manufacturers to certify AWHPs using ANSI/AHRI 550-590 test methods, there are no state or federal minimum efficiency requirements. The model used in these tests was selected because it is both AHRI certified and listed in the CEC appliances

database (CEC 2022). To date only 8 AWHPs are listed in the CEC appliances database for residential use, six of which are variable capacity units.



Figure 7. Installed variable capacity AWHP.

Test and Evaluation Methods

Daily total system energy use and daily efficiency of the radiant and fan coil systems were compared in aggregate for entire seasons. Efficiency in cooling is expressed as the energy efficiency ratio (EER) and efficiency in heating is expressed as the coefficient of performance (COP). Daily efficiencies are calculated as the daily total delivered energy (in kBtu for EER and in kWh for COP) divided by the daily total electrical energy consumption (in kWh).

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). Radiant panels only provide sensible comfort, therefore only dry bulb temperatures were considered. The bounds for these metrics are specified in Table 3 and referred to in this report as the “comfort criteria.”

The comfort criteria are 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.

Table 3. ACCA criteria for multi-zone systems.

	Room-to-Room		Floor-to-Floor		Room-to-Setpoint
	Average	Maximum	Average	Maximum	Maximum
Multi-Zone (Radiant)	2	4	2	4	2
Single Zone (Fan Coil)	3	6	3	6	3

Monitoring Results

Comfort Performance

Figure 8 and Figure 9 show the percentage of operating time for the season that house conditions did not meet each comfort criteria, by system, for the summer and winter seasons, respectively. The “Overall Noncompliance Rate” is the percentage of operating time for the season that house conditions did not meet at least one of the comfort criteria. For the winter results (Figure 9), the comfort criteria from a single zone radiant system (tested in 2015 with a different AWHP) are also provided for comparison to the single zone ducted fan coil.

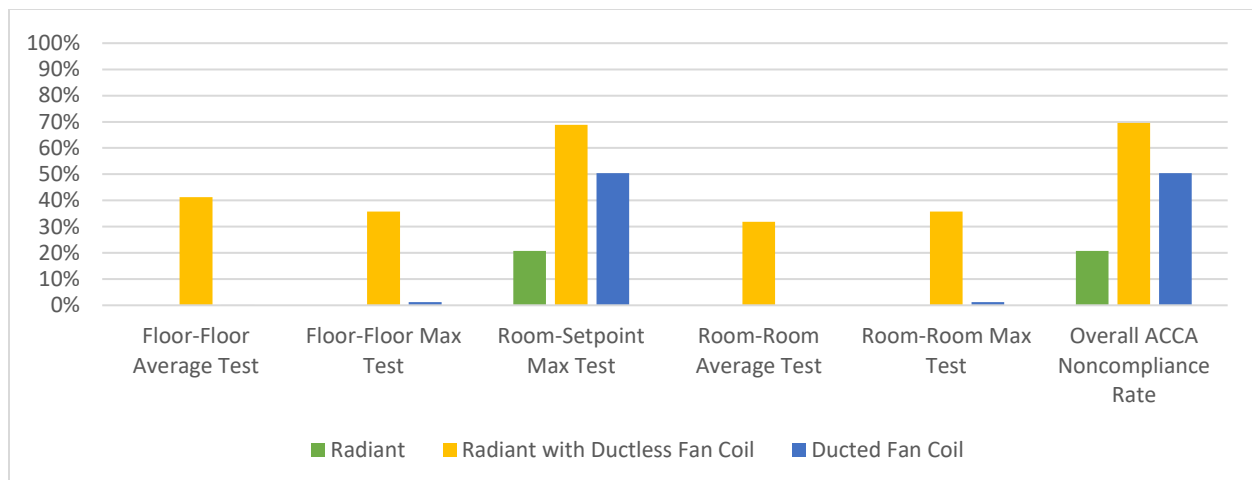


Figure 8. Summer season comfort noncompliance rates by system and comfort criteria.

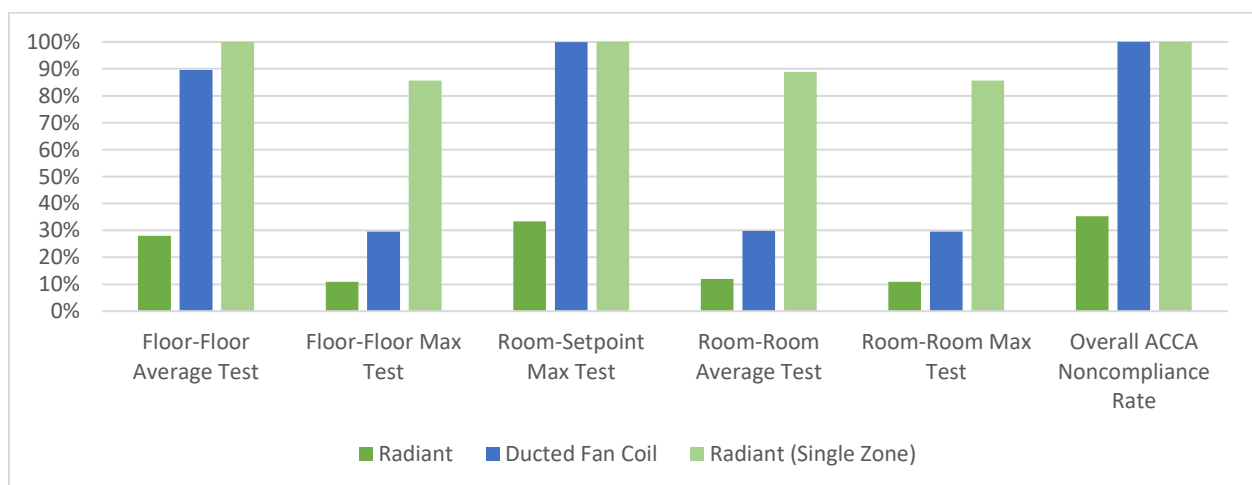


Figure 9. Winter season comfort noncompliance rates by system and comfort criteria.

Though Figure 8 and Figure 9 provide a sense of the level and distribution of comfort throughout the house, they do not convey whether the house was over or under conditioned. Examining the distribution of room-to-setpoint differences for each room provides deeper insight into these results.

Figure 10 shows the seasonal fraction of operating time that temperatures were within, above (under-cooling/over-heating), or below (over-cooling/under-heating) the room-to-setpoint comfort criteria by room, for each system and for the summer and winter seasons. The room name in the category axis includes the floor level.

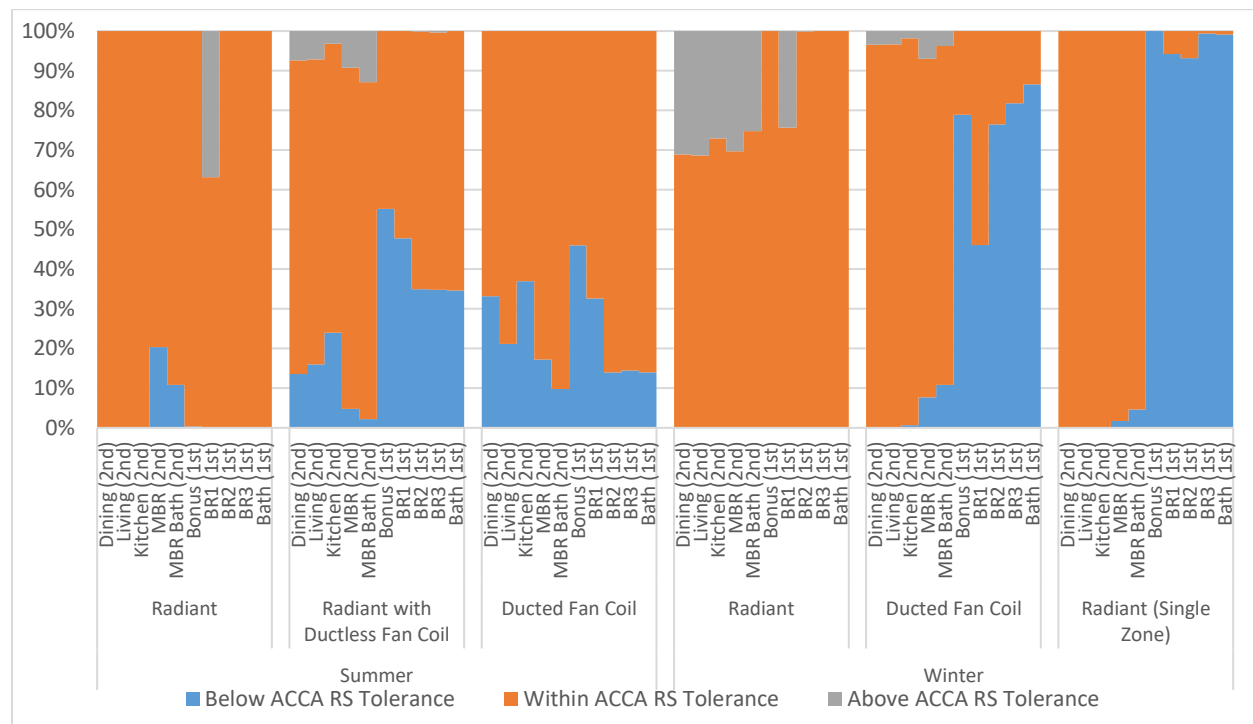


Figure 10. Room-to-setpoint noncompliance rates by room for summer (left) and winter (right).

These results are generally what one would expect comparing a zoned radiant system to an unzoned ducted system. The radiant system outperformed the ducted system for comfort in both heating and cooling. However, when the single zone ducted system is compared to the single zone radiant system, it becomes apparent that the comfort issue is caused by the lack of zoning due to the significant temperature difference between floors. Also, the ductless fan coil caused significant over cooling, as it contributed cooling while providing dehumidification.

This could be mitigated by using multiple ductless coils, though this would require a complex plumbing and control setup that would likely include a buffer tank and additional pump. Another option would be to use a single duct fan coil for dehumidification, though if not zoned, this would result in comfort results very similar to the ducted fan coil system. Additionally, based on the amount of cooling provided by the ductless fan coil during dehumidification (77 kBtu/day from the fan coil and 115 kBtu/day from the radiant ceiling on average), and the comfort performance of the ducted fan coil system, it would be difficult to justify installing both a ducted fan coil and radiant ceiling in the same house. A zoned ducted fan coil system would provide acceptable comfort on its own, without the cost of installing a secondary delivery system.

Energy Consumption

Figure 11 and Figure 12 show daily total energy (outdoor unit, fan/pump, and standby operation) plotted against daily average outdoor temperature by system for summer and winter seasons, respectively. Plotting energy use against outdoor temperature effectively normalizes for outdoor temperature effects on building load and heat pump performance.

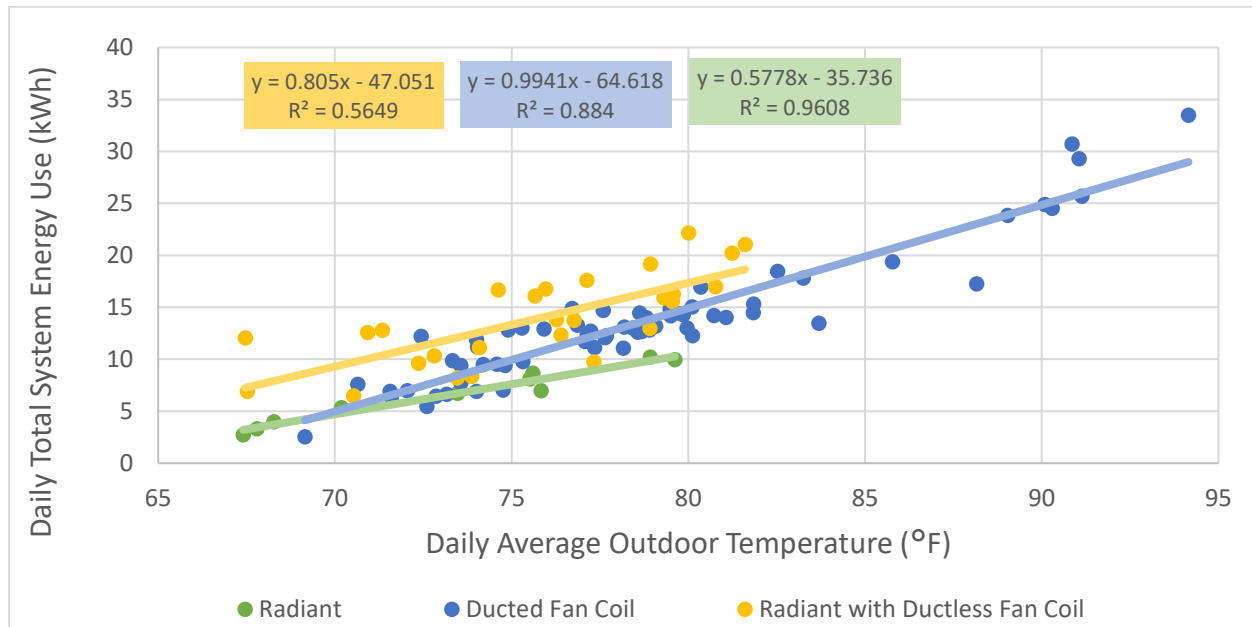


Figure 11. Summer season daily total energy use vs. average outdoor air temperature.

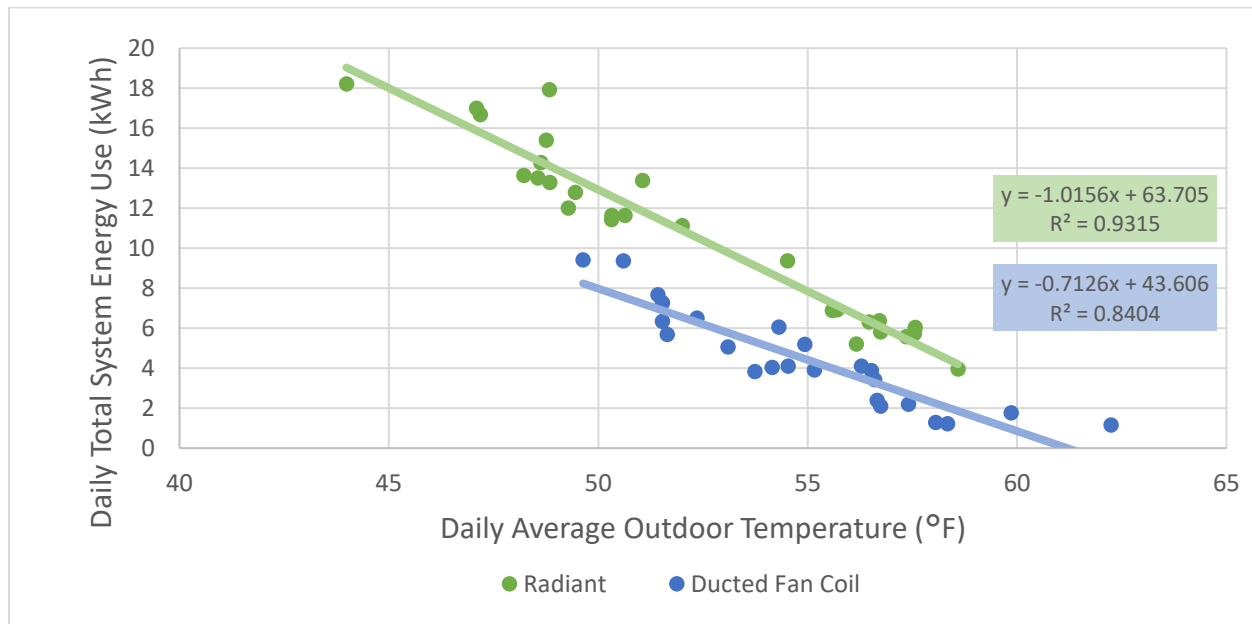


Figure 12. Winter season, daily electrical energy use vs. average daily outdoor air temperature.

While the energy use of both the radiant only system and the fan coil system are reasonably linear for outdoor temperatures. The radiant with ductless coil system has a lower R-squared on its regression because the system was also operated on a dehumidification call and therefore its energy use was not primarily driven by outdoor temperatures.

The radiant system marginally outperformed the ducted fan coil in cooling, but the ducted fan coil noticeably outperformed the radiant system in heating. This is because in cooling the radiant system is designed to only deal with sensible load, while the fan coil inherently provides both sensible and latent cooling. When the radiant system is forced to address latent load through the ductless fan coil, it actually uses more energy on average than the ducted fan coil. This is because, like the ducted fan coil, the ductless fan coil inherently provides both sensible and latent cooling, and so more sensible cooling is being provided than is necessary to meet the load.

Also, radiant ceiling systems have much lower heating capacity than cooling capacity due to thermal buoyancy. In cooling with a radiant ceiling system, buoyancy assists ceiling panel heat transfer by increasing convection at the panel surface. In heating, however, buoyancy works against ceiling panel heat transfer as hot air rises to the panel surface and stagnates, eliminating significant use of the convective heat transfer mode.

Though normalizing by outdoor temperature normalizes for the load, it does not normalize for delivered energy, which is an issue when comparing single zone to zoned systems, especially in a two-story house. It is also an issue when comparing a delivery method that is designed to only address sensible load (radiant) to a delivery method that inherently addresses both sensible and latent loads. In this instance it is important to additionally normalize by the delivered energy. This can be done by plotting the efficiency (daily total delivered energy over daily total consumed energy, expressed as daily EER for cooling and daily COP for heating) by daily average outdoor air temperature, as shown in Figure 13 for cooling and Figure 14 for heating.

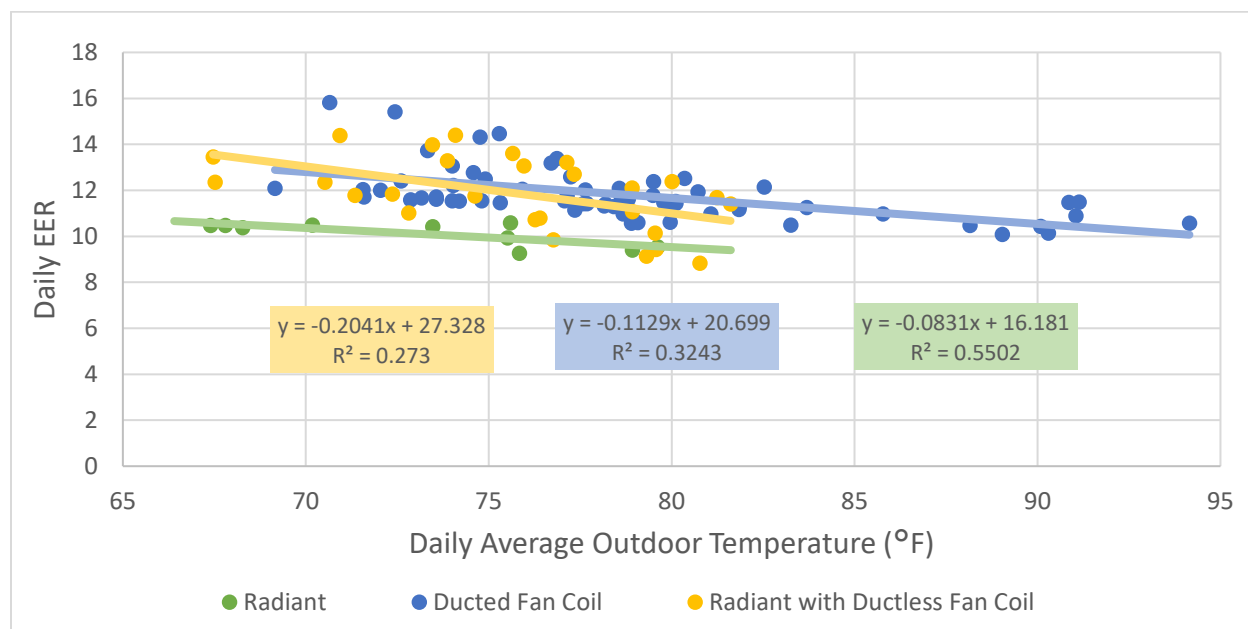


Figure 13. Daily cooling EER by daily average outdoor air temperature.

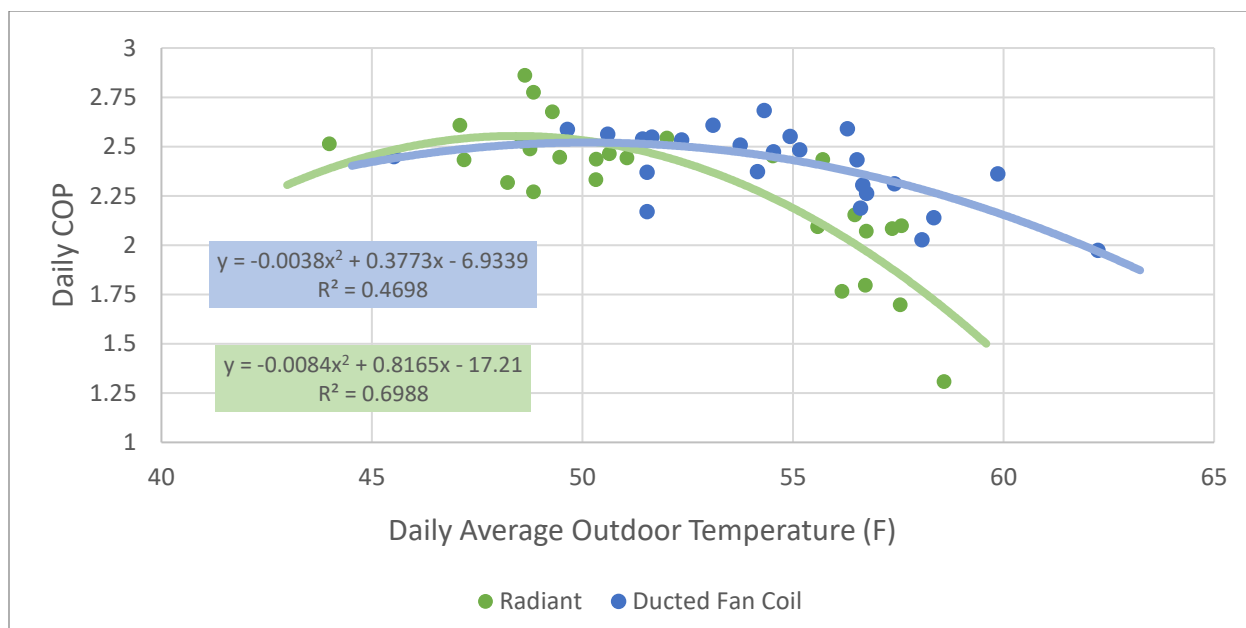


Figure 14. Daily heating COP by daily average outdoor air temperature.

By looking at the efficiencies, we can better understand the daily energy use trends. For example, in heating, the ducted fan coil used less electrical energy per day, but it also achieved a higher COP than the radiant system on average. This is again because the radiant ceiling system has reduced capacity in heating and therefore must run longer at a far less efficient duty point to meet the same load. Similarly, in cooling mode: even though the energy use of the radiant system is only marginally lower than the energy use of the ducted fan coil system, its EER is also lower. Because the capacity of the radiant system is so small, it forces the AWHP to operate for long periods of time at minimum speed. This is why efficiency improves with the addition of the ductless fan coil to the radiant system: now the AWHP can operate at an efficient speed during dehumidification calls and has room to ramp up and down to meet load. With the ducted fan coil, the variable capacity AWHP has that advantage in both seasons.

Using the linear regressions for energy in Figure 11 and Figure 12, the annual energy use (AEU) of each system for a typical meteorological year (TMY) was estimated and the results are shown in Table 4. The radiant ceiling with ductless fan coil for dehumidification and radiant ceiling without ductless fan coil used the same heating regression. The TMY weather data file for the local climate was used. When the energy use estimated by the regression was lower than the known standby energy use (approximately 0.25 kWh), the estimated energy use was substituted for the standby energy use.

Table 4. Estimated annual energy use of each system.

	AEU (kWh/year)		
	Total	Heating	Cooling
Radiant	3203	2272	931
Radiant with Ductless Fan Coil	4060	2272	1787
Fan Coil	2500	1387	1113

According to these estimates, the AEU of the hydronic radiant system is almost 24% higher than that of the ducted hydronic fan coil, and the AEU of the radiant system with the ductless fan coil for dehumidification is 55% higher, despite using the same AWHP.

For reference, the average AEU listed on the Energy Guide labels of AHRI-certified central air source heat pumps between 1.5 to 2 tons in size with efficiencies of 16 SEER and 9.5 HSPF or better, is approximately 5,400 kWh/year (AHRI 2018). It should be noted that all three hydronic delivery configurations with the AWHP are better than this baseline.

Results Summary

Though providing the best comfort in both seasons, the radiant system had the lowest efficiency in both seasons. The ducted fan coil system achieved better comfort than both the radiant with a ductless fan coil in cooling and the single zone radiant system in heating. The ducted fan coil also achieved energy use very close to that of the radiant system in cooling while addressing both sensible and latent loads, and much lower than the radiant system in heating, resulting in lower annual energy use than the radiant system.

Additionally, while there may be cases where radiant ceiling panels can be operated in cooling without supplementary dehumidification, in most cases at least some dehumidification is warranted. While this can be achieved through the addition of a ductless fan coil, this introduces comfort distribution, overcooling, and increased energy use.

Conclusions and Next Steps

Radiant ceiling panels coupled with AWHPs are a viable cooling and heating delivery method that can match or exceed comfort and energy use expectations of conventional heat pump systems. However, ducted fan coils coupled with AWHPs can as well, and with far fewer market barriers and built-in latent removal. While the hydronic systems and AWHPs work at CVRH began with radiant ceilings, ducted fan coils have revealed themselves to be the better avenue for wider adoption of AWHP technology.

Ducted fan coil and AWHP systems offer all the advantages of hydronic systems, including three-function operation (space heating and cooling and domestic water heating), which can ease electrification retrofits, and using thermal energy storage to reduce on-peak heating and cooling energy use.

The work at the Stockton research home also continues with an experiment that will examine using a hydronic fan coil system with thermal energy storage to shift cooling and heating load off peak, as well as domestic hot water load through a DHW storage tank, using the same AWHP. California utilities are moving to time-of-use electric rates for all customers. As this change occurs, there will be financial benefits for ratepayers to reduce on-peak energy use. HVAC is one of the largest peak loads in California, which is challenging to address using conventional forced air systems.

At the same time, residential natural gas prices are starting to go up, while rooftop solar continues to get cheaper and has been required on new construction for three years, incentivizing electrification. AWHP-based hydronic systems with three-function capability may provide a cheaper and simpler route for electrification retrofits that can also provide heating and cooling load shifting without significant reductions in equipment efficiency or comfort.

Acknowledgements

The authors would like to thank the following for their continuing contributions to, and support of, the research that forms the foundation of this paper:

- Marc Hoeschele (Frontier Energy Inc.)
- David Springer (Frontier Energy Inc.)
- Andy Doeschot (Pacific Gas & Electric)
- Mike MacFarland (Energy Docs)
- Abram Conant (Proctor Engineering Group)

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