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A Case Study on Air-to-Water Heat Pump Systems in Minnesota

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ABSTRACT

Air-to-water heat pumps (AWHPs) are a flexible type of air source heat pump (ASHP) system with several advantages over forced-air ASHP systems. For example, distribution is more efficient when moving water instead of air and the very low distribution temperatures of modern hydronic systems, particularly radiant floors, may further improve the heat pump cycle's efficiency. The applications of AWHPs are also diverse. Water distribution systems can incorporate a variety of heating and cooling equipment simultaneously, including radiant emitters, central hydronic air handlers, mini-split-style individual room cassettes, domestic hot water systems, and thermal storage systems. However, with this flexibility comes complexity, which may be compounded in cold climate applications that already require more advanced compressors and controls to achieve efficient operation. In this case study, three AWHP systems of varied complexity were installed in single-family homes with radiant floor heating located in the state of Minnesota (U.S.), climate zone 6. AWHP systems are new to this market and the lack of published field performance data remains a technical gap for the technology's acceptance. Through continuous power, flow, and temperature monitoring, we assessed each system's operational behavior and calculated system performance efficiencies. Our examination of the select systems' operations highlighted the challenge in optimizing the control of AWHP systems. While coefficient of performances (COPs) above 3 were observed, unaligned control logic between the outdoor compressor unit, indoor distribution unit, and thermostat can quickly reduce the COP by 50% or more, even during mild temperatures. Suppressed seasonal efficiency does not necessarily correlate to less occupant comfort, but suboptimal control settings, equipment failures, or imperfect installations are sources of comfort complaints. Delivering reliable comfort and efficiency gains will be vital to leverage the remarkable flexibility AWHP systems may offer.

INTRODUCTION

Air source heat pumps (ASHPs) powered with low-carbon electricity are broadly considered a key, cost-effective strategy to decarbonize and improve the efficiency of residential space heating (Kaurfman 2019). Additionally, as variable speed systems have improved, so has the cold climate performance achievable through ASHPs. This has led to increasing use of these technologies in cold climates, including the state of Minnesota in the United States, the location where the test systems exaimined in this paper were installed. Alongside improved cold weather performance, manufacturers of ASHPs have also been developing more advanced subcategories of ASHPs, including air-to-water heat pumps (AWHPs).

Like any ASHP, AWHPs use ambient outdoor air as the heat sink or source in a bi-directional refrigeration loop. The distinct feature of AWHPs is that they contain a heat exchanger that transfers energy from the working refrigerant to a

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water-based distribution fluid instead of directly to indoor air (ENERGY STAR 2019). While this addition introduces new complexity and a potential efficiency penalty, hydronic distribution systems provide several advantages. First, water is a more efficient heat distribution medium than air. A given volume of water can absorb almost 3,500 times as much heat as air given the same temperature differential and provides a distribution efficiency on the order of four times that of a forced air system (Siegenthaler 2021). Second, modern hydronic systems, particularly radiant floors, use very low distribution temperatures as low as 85°F. Lower delivery temperatures are more efficiently achieved in a heat pump cycle. Third, water distribution systems can incorporate a variety of heating and cooling equipment simultaneously, including radiant emitters, central hydronic air handlers, mini-split style individual room cassettes, and domestic hot water systems, as well as thermal storage systems for both heating and cooling (Siegenthaler 2017). Additionally, AWHPs offer a distinct advantage over ASHPs because of their simplicity of integration with inexpensive electric resistance systems for backup, something that has been difficult with forced-air ASHP systems. This flexibility is a major benefit that allows these systems to meet a variety of the end-use cases for the residential HVAC market.

However, installations of AWHPs with cold climate capabilities are limited and third-party demonstrations are scarce in North America. The lack of information and case studies supporting the application of AWHPs in cold climates remains a market barrier to adoption of AWHPs in North America while other barriers may yet remain unidentified. The motivation for this work is to reduce the information gaps faced by early adopters of AWHP technologies and evaluate the performance of AWHPs in the field compared to manufacturer's expectations in a cold climate application. To this end, three test systems were installed with continuous power, temperature, and flow rate monitoring in the state of Minnesota, located in climate zone 6. The ASHP market within Minnesota is still in early development and AWHP installations are extremely scarce. This contrasts with the fact that approximately 10% of residential 1-4 unit buildings in the state rely on electric heating (EIA 2020) and could unlock energy and cost savings through efficient ASHP technologies, if only the market matured to full adoption.

AIR-TO-WATER HEAT PUMP SYSTEM TYPES

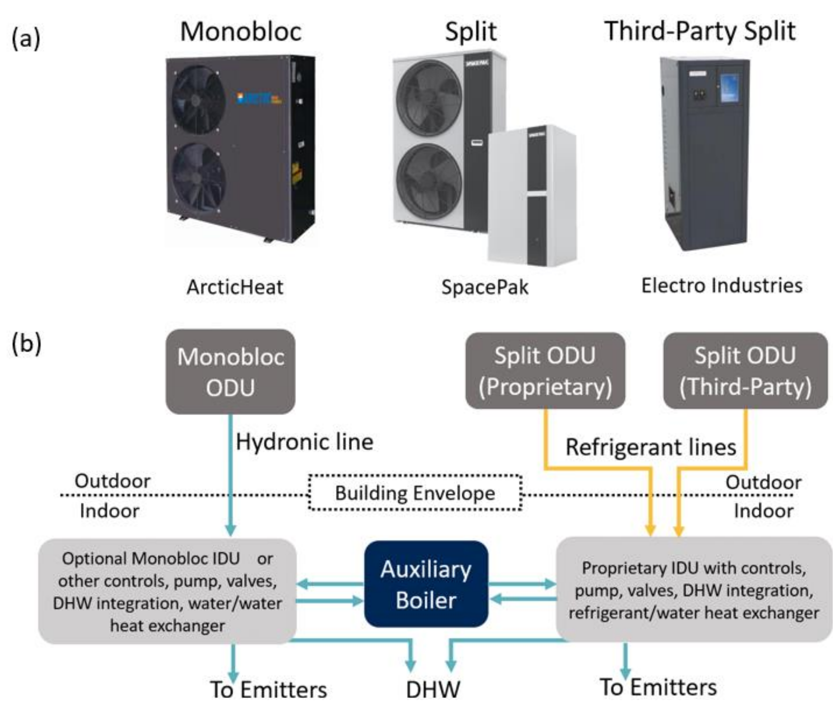

Figure 1 (a) Examples of monobloc, split, and third-party split air-to-water heat pump systems as they appear delivered from the manufacturer. (b) A schematic diagram of monobloc and splity system air-to-water heat pumps.

Three subtypes of AWHPs were identified through a review of available product literature in April 2021. These subtypes include: traditional split systems, third-party split systems, and monobloc systems. Example equipment for each type are shown in **Error! Reference source not found.**a and illustrated schematically in Figure 1b. All AWHP systems include an outdoor unit (ODU) which contains the ASHP compressor. For monobloc systems, the ODU also contains the refrigerant-to-hydronic heat exchanger. As a result, only the water-based working fluid needs to penetrate the building envelope. In cold climates, monobloc systems will require a freeze-protected primary water loop, typically provided by a 30% to 60% water-glycol mixture. In practice, installers may add similar amounts of glycol to conventionally heated indoor radiant floor loops that do not cross the building envelope as additional antifreeze protection.

Monobloc ODUs may or may not be paired with an indoor unit (IDU). The IDU may contain additional controllers, valving, pumps, etc. or it may be a simple package only designed to consolidate connections between the ODU and the indoor hydronic distribution system. In contrast, split system AWHPs always have both an ODU and IDU with the refrigerant-to-hydronic heat exchanger located within the IDU. In split system AWHPs, the working refrigerant crosses the building envelope, not the hydronic fluid. The ODU and IDU often pair in a proprietary (communicating) bundle as a traditional split system but at least one manufacturer offers a third-party split system as an IDU designed for non-communicating, third-party ODUs.

AWHP IDUs of split systems of monoblocs may contain or interface with auxiliary heating such as an electric boiler or a fossil-fuel backup boiler. AWHPs are often provided with some form of control equipment or software. These tend to be proprietary systems that allow a broad range of functions, from basic temperature control to independent control and scheduling of multiple zoned emitters. User interfaces can also vary broadly from a basic display with a few buttons and indicators to an elaborate touch-screen interface built into the unit or provided as an external controller. A developing trend includes app-based control, which leverages the home Wi-Fi network to provide wireless connectivity between the heat pump system and the user's smartphone. Cloud connectivity is also a common feature of modern controllers.

Indoor system components that deliver the heating and cooling load within the indoor space are referred to as emitters. AWHP systems are broadly compatible with all hydronic emitters, including hydronic ducted air handlers, cassette-style ductless fan coils, radiant slabs, radiators, and indirect domestic hot water tanks. However, manufacturers often explicitly recommend emitter configurations or their own emitter products. In most cases, radiant floor heating or low temperature radiative emitters are recommended due to the limitations of ASHP supply temperatures.

As of April 2021, 47 AWHP systems were identified through product literature that were available in the Unitied States and met the target rated heating capacity range of residential equipment in the region (2 to 6 tons). Of these 47 systems, comprising 14 product lines from 9 manufacturers, more than half (55%) were from manufacturers outside of the United States. Nearly three quarters of systems (72%) were monobloc type with the remainder split (11%) and third-party split systems (17%). While all systems are thought to be capable of meeting at least a portion of the domestic hot water (DHW) load, 35 units (74% of compatible units) explicitly mention this capability. Forty-four units (94%) provide cooling in addition to heating. The remaining 3 units are heating-only third party split IDUs. Three quarters (76%) of systems list either inverter or variable speed compressor types. Just 10% of systems list single speed compressor type and compressor type is not specified for 17% of systems. The average reported minimum operating temperature was -10 °F but ranged from -31 °F to 13 °F. However, roughly 90% of units did not have reported heating capacity below 17 °F, so additional manufacturer data will be necessary to evaluate most AWHPs for all cold climate applications.

METHODOLOGY

The details of the systems included in this case study are summarized in Table 1. The field demonstration sites in this study were all retrofit installations on homes with existing electric boiler hydronic heating systems. The participating homeowners were provided with new AWHP systems at no cost to them in exchange for facilitating continuous monitoring of the system. Homes with radiant slabs were selected to avoid limitations of undersized radiators and utility billing data was analyzed to ensure the newly installed AWHP would be able to meet more than 50% of the annual load. The installing contractors were identified based on manufacterer's recommendations or by the participating homeowner's preference.

Site A, was retrofitted with a NorAire AWHP unit, manufacturered by Minnesota-based Electro Industries. This is a third-party split IDU AWHP system marketed for having compatibility with multiple ASHP ODUs. The IDU under study was paried with a 5 ton Bosch IDS 2.0 ASHP, a widely available variable speed condenser designed for use in noncommunicating systems. To our knowledge, this unit has not previously been marketed by Bosch for AWHP applications and is not efficiency rated in such a configuration.

The remaining two sites, B and C, were retrofitted with Enertech Advantage EAV060 monobloc AWHPs. The Enertech Advantage EAV060 monobloc ODUs were installed with the manufacturer's accompanying Enertech Advantage EAV060 IDU. The Enertech IDU connects with the ODU through a hydronic loop and contains within a pump, expansion tank, auxiliary electric resistance boiler, and built-in control screen. In this system, connections with emitters are made to the IDU rather than the ODU directly. Both sites with the Enertech monobloc system were outfitted with a hydronic coil interfacing with a centrally ducted air handler and propane furnace. In both cases, the central forced air system was primarily used to heat and cool the second floor of the home. The third site, site C, was additionally outfitted with the Enertech Turbomax indirect domestic hot water (DHW) heater for preheating the potable water supply. All sites had concrete slab radiant floor heating. Site A had no zoning in the radiant slab while site B and C had the separate hydronic coil for forced air delivery. Site B also had two hydronic zones within the infloor basement slab.

Table 1. Test Site Summary

Site	System	Emitters	Thermostat	Home Description
A	NorAire EBH-5-020 and Bosch IDS 2.0	Single zone floor slab	Honeywell FocusPRO 5000	2,600 sqft slab on grade with vaulted ceilings built 2009.
B	Enertech Advantage EAV060 with IDU	Three zone floor slab, hydronic coil with central forced air handler	T771 Pro	4,000 sqft two-story home built in 2009.
C	Enertech Advantage EAV060 with IDU and Turbomax indirect water heater	Single zone floor slab, hydronic coil with central forced air handler	Honeywell T6 Pro	1,300 sqft two-story home built in 2006.

Installation of these systems was completed by third-party contractors in accordance with manufacturer's specification as much as possible. Default control settings were left in place except for the compressor lock out temperature, which was set to the minimum available setting so that performance over all outdoor air temperatures could be evaluated. Each system was installed with a back up electric resistance boiler which can run in conjunction or separate from the heat pump to ensure the system can meet the load regardless of the outdoor air temperature (OAT).

INSTALLATION CONSIDERATIONS

Several observations were noted from the installation process. First, manufacturer support in the first installations by a contractor proved extremely helpful in facilitating a successful installation for these new-to-the-market products. It also proved helpful to work with a contractor company which is familiar with both hydronic heating systems and heat pumps. In the Minnesota market, some companies do provide both plumbing and HVAC services. Alternatively, contractors in the geothermal heat pump market may also well-positioned to install AWHPs, particularly monobloc systems.

Unlike in new construction, retrofit AWHP installs must deal with the limitations of the existing heating system infrastructure. Challenges related to the existing distribution system, original system design size, or the installed thermostat may be difficult to identify prior to the AWHP installation but greatly impact the performance. Notably, existing hydronic radiators in Minnesota's residential housing stock are typically undersized for the discharge temperature provided by AWHPs. The high supply temperatures provided by gas or electric boilers have enabled small radiators that would not provide the same level of comfort if operated with the lower AWHP supply temperatures. To avoid these potential challenges, the study's test sites all had infloor slab heat rather than small radiators.

An additional consideration in retrofits are the thermostats. In most of the study's installs, the existing thermostats were left in place and not replaced, according to the installers' typical preference. However, despite each of the study sites having existing hydronic infloor heat, none of them had thermostats with slab temperature sensors. Slab sensors are considered a best practice recommended by the AWHP manufacturers and may offer better control against short cycling than a thermostat that monitors air temperature alone. Retrofit AWHP installations are also limited by the building envelope design and subsequent heating load. Of all commercially available AWHP systems reviewed in this work, the highest reported capacity rating at 47 °F did not exceed 6 tons, though design heating loads in climate zone 6 or greater may surpass 6 tons due to a combination of home size, poor insulation, or high heat loss. While not all installers may complete a thorough load calculation when completing a retrofit replacement, they are highly recommended for a successful AWHP installation.

A final detail to note for cold climate AWHP installs is preparation of the ODU location. In cold and snowy climates, heat pumps must be raised high enough to avoid snow coverage and require a stable foundation footing of some sort. Awnings to prevent snow accumulation may also improve the AWHP reliability. In this work, one of the participating site installations was delayed due to a steep grade of the site ground that prevented easy installation of a suitable ODU footing until the ground thawed in the spring. At another site, ice ingress in the ODU caused a part failure which might not have occurred in a warmer climate.

MEASURED PERFORMANCE

Third Party Split

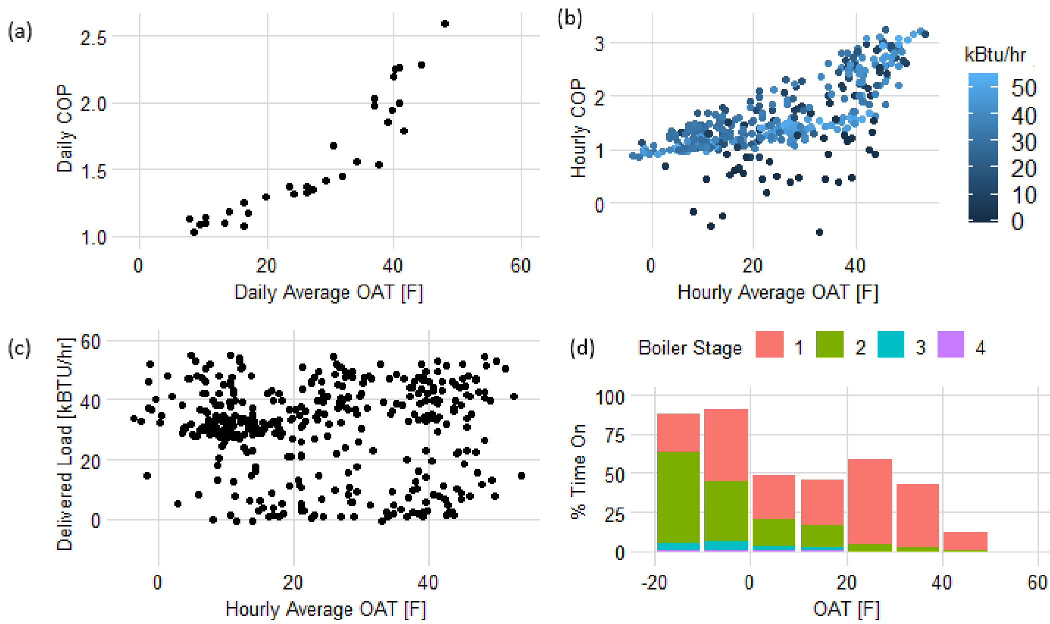

Figure 2 (a) Daily coefficient of performance measured at site A over a range of daily average outdoor air temperatures. (b) The same as (a) on an hourly time interval. Fill shade of each point corresponds to the total load delivered in that hour in kBTU/hr. (b) Total kBTU/hr load measured as delivered from the AWHP over a range of average hourly outdoor air temperatures. (c) Percentage time the back up boiler supplied heat during a heat call in each of its operating stages (5 – 20 kW) over a range of outdoor air temperatures in 10 °F groupings.

The third-party split system installed at site A was monitored from late December, 2021 through the spring of 2022. During the study period, the third-party outdoor condenser unit experienced a part failure due to a design defect related to ice ingress. The manufacturer had recently addressed this issue with a new part design and delivered a replacement part to solve the failure under the product warranty. The repair was completed in early April, but this part failure prevented the heat pump condensor from operating properly for more than three winter months. During this time, the AWHP's backup boiler supplied the heating load without support of the heat pump, resulting in an average daily coefficient of performance (COP) of 0.98. The daily COP is calculated as the total heat energy delivered to the home during a day divided by the total energy consumed by the AWHP and related distribution system during a day. The hourly COP is calculated likewise but over a period of an hour rather than a day. As expected, the COP did not vary with OAT when the heat was produced by the backup boiler alone.

In contrast, when the outdoor heat pump was fully operational, the daily COP was a strong function of the daily average OAT as shown in Figure 2a. Data in Figure a-d show measured performance collected when the ODU was fully operational only. As expected, the measured daily COP increases with OAT, reaching as high as 2.6 measured on a day with an average OAT of 48 °F. For operational days with the average OAT falling below 10 °F, the daily COP approached 1 but did not fall to that of the boiler-only operational efficiency. Examining the performance on a shorter time increment, we observe significant variation in COP on an hourly basis as shown in Figure 2b. Occasionally, the measured COP fell below zero during a single hour. In these cases, the AWHP system extacts rather than supplies heat to the home. These periods of heat loss or very low COP are associated with brief runtimes or repeated short cycling of the AWHP system. The amount of heat loss observed measured at most 900 Btu/h, a fraction of the hourly heat load of the home as shown in Figure 2c. These brief periods did not result in any comfort complaints from the home occupants.

Unlike forced-air ASHPs paired with furnaces upstream of the refrigerant coil, all AWHP systems included in this study are designed with the backup boiler downstream of the refrigerant-hydronic heat exchanger. As a result, the AWHP can operate concurrently with the boiler, preheating the working fluid rather than operating in either heat pump or backup heat mode as most forced-air systems do. As a result, these systems operate the AWHP for all heat calls except when the OAT falls below the condensors' lockout temperature. The manufacturer-specified lockout temperature is -4 °F for the Bosch IDS 2.0 condensor. Once the ODU is locked out due to low OAT, the backup boiler is intended to provide the full heat load.

The boiler is often used during warmer weather than the lockout temperature, however, as the AWHP capacity and heating load are both a function of the OAT. The studied AWHPs have an internal logic controller which decides when to use the back up boiler and when to rely solely on the heat pump. Control strategies typically include a combination of runtime counters and temperature sensors to balance comfort and efficiency priorities. The NorAire AWHP uses both indicators in its control algorithm. Figure 2d shows the percentage of time the boiler was operating at site A during all heat calls. A heat call is defined in this work as anytime the primary hydronic distribution loop was circulating. The installed boiler has four stages of 5, 10, 15, or 20 kW capacities, respectively. The boiler operates at this home mostly in stage 1 (5 kW) and stage 2 (10 kW), infrequently operating at higher capacities. The backup boiler is operated about half the runtime or more, except when the OAT is above 40 °F. Because the COP of the boiler is limited to 0.98, its frequent operation will decrease the total system COP from that of the heat pump alone.

Monobloc with Ducted Coil

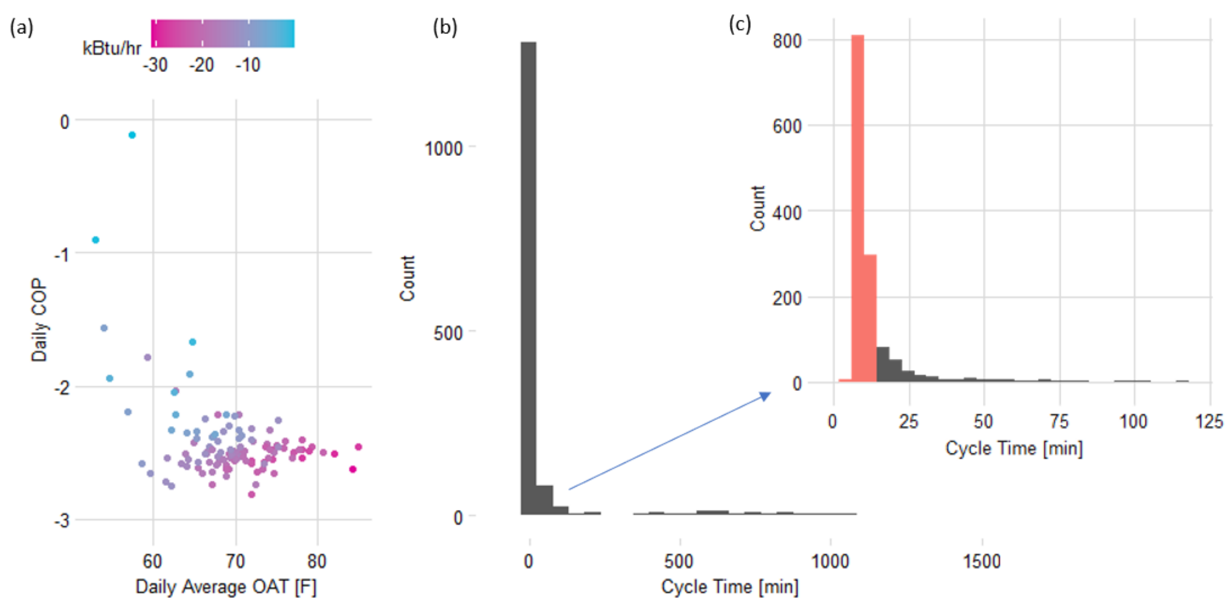

Figure 3 (a) Daily coefficient of performance of cooling measured over a range of outdoor air temperatures, color coded by the daily average hourly load delivered in kBTU/hr. (b) Histogram of observed air-to-water heat pump runtime cycles with (c) inset zoomed into the shortest cycles, with cycles of 15 minutes or less highlighted in red.

Site B's monobloc system with a centrally ducted hydronic coil and radiant in-floor heat was installed at the end of April, 2022. Unlike site A, which was monitored in the heating season, site B was only able to be monitored in the cooling season. Cooling at this site was delivered solely through a hydronic coil to a central forced-air handling unit. Due to limitations of the existing ductwork and comfort concerns of the occupants, the target coil temperature was lowered to 42 °F from the manufacturer's default setting of 50 °F for cooling. As plotted in Figure 3a, the average daily cooling COP from this system is 2.5 for OATs above 70 °F. The cooling efficiency was not a strong function of the OAT. The data in Figure 3a are colored according to the average hourly cooling load delivered that day. Low daily COP is associated with extremely brief runtimes and low total delivered cooling loads. As plotted in Figure 3b, the total operational time of any run cycle spans from a few minutes to most of a day. However, 53% of all runtime cycles observed at site B last 15 minutes or less. These "short cycles" are highlighted in red in Figure 3c.

Monobloc with Ducted Coil and Domestic Hot Water

Site C was installed in late February 2022. This AWHP system's indirect DHW heater was not enabled until late summer that year due to a manufacturer-required part update within the Turbomax tank taking some time to complete. The daily COP measured at this site is presented in Figure 4a, where a positive COP indicates the system delivered net heating to the home that day while a negative COP is calculated when the system delivers net cooling to the home. The days when the AWHP-fed indirect DHW tank was active are denoted by the star symbol. The empty black stars indicate the COP of heating the indirect DHW tank while the empty blue stars are the daily cooling COP on the days where DHW heating also occurred.

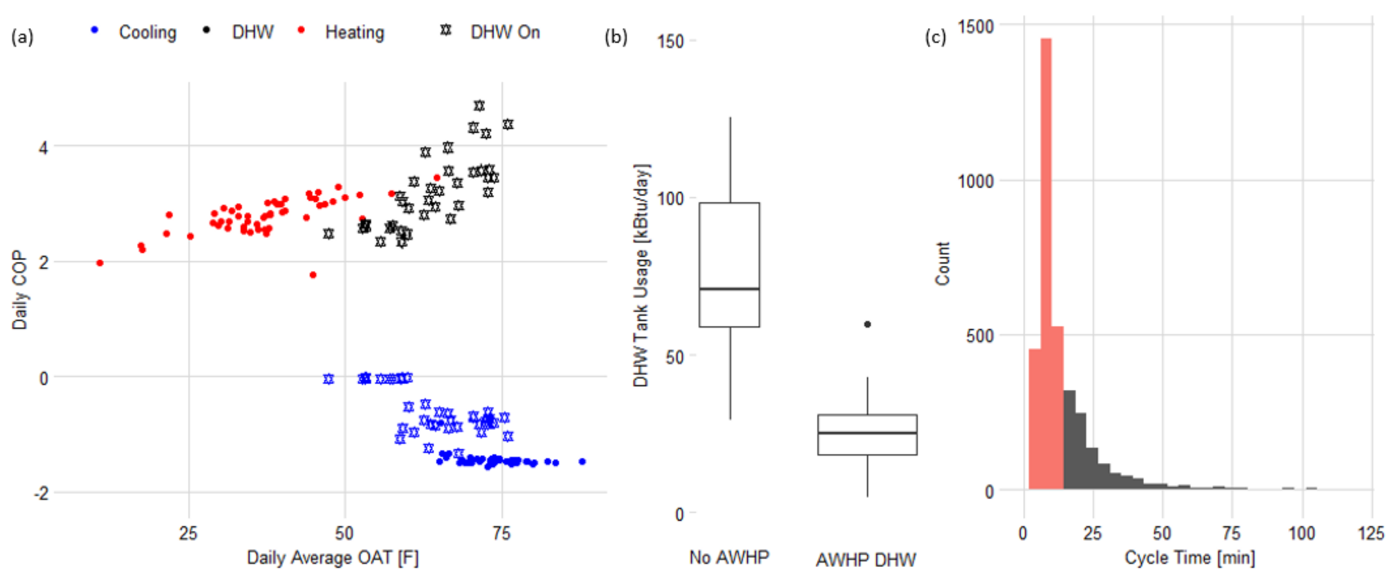

Figure 4 (a) Daily coefficient of performance of cooling measured over a range of outdoor air temperatures, color coded by the system operational mode. Red denotes heating, blue cooling, and black hot water heating. Days where the water heater was running are further indicated by the hollow star shape. (b) Boxplot of total daily energy usage by the pre-existing electric hot water heater with and without preheating from the AWHP. (c) Histogram of observed air-to-water heat pump runtime cycles, zoomed into the shortest cycles, with cycles of 15 minutes or less highlighted in red.

The measured daily heating COPs at site C ranged from 1.5 to 3.4 as a function of temperature. Like at Site B, the cooling efficiency was not a strong function of outdoor air temperature. An absolute COP of less than 1.5 was measured for most cooling days at site C. Operation of the DHW was associated with even lower COPs, but the COPs of heating the DHW approach 5. A significant decrease in the power consumption of the home's existing domestic hot water (DHW) tank was observed once the AWHP system's indirect water heater became operational, illustrated in Figure 4b. The month before the AWHP's DHW tank became operational, the average daily power consumption of the home's pre-existing electric DHW tank was 84 kBtu per day. The DHW consumption dropped to less than a third of the baseline, to 25 kBtu per day, in the month following the addition of the AWHP DHW indirect heater. Shown in Figure 4c is an accounting of most runtime cycle lengths observed at site C. Short cycles of 15 minutes or less are very frequent, accounting for 70% of all observations.

DISCUSSION

The systems studied in this work demonstrate the capability of AWHP systems to retrofit into existing single family housing stock found in Minnesota. All systems were able to be configured to satisfy the heating, and in two cases, cooling loads of the participating homes. Participants at site B reported dissatisfaction with the as-installed cooling performance of their AWHP but reported improved comfort after the supply temperature to the hydronic coil was lowered from the default setting. Comfort complaints at the other participating test sites were related to part failures rather than the systems' operational design.Several factors beyond the AWHP contributed to site B's poor cooling performance. Site B experiences high solar gains through large windows on the upper floor. This, combined with high static pressure in the undersized ductwork, made evenly distributing the cooling capacity available from the AWHP difficult to acheive. Despite these challenges, site B showed better absolute cooling COPs than did site C, which has the same AWHP. Site C's lower cooling efficiency may be related due to the AWHP being more oversized compared to the home's cooling load. The average daily cooling load at site C was 7.9 kBtu/hr while it was 15 kBtu/hr at site B. Overall, the cooling performance from these AWHP systems does not compete with that of a code-minimum air conditioner with cooling COPs above 3. However, the DHW efficiency delivered at site C was excellent in comparison and efficiency gains there may net savings overall, depending on the yearly performance.

The heating performance of these systems did deliver improved efficiencies above that of an electric resistance boiler, yet room for improvement remains. All systems exhibited a significant amount of short cycling, ranging from 86% of cycles being less than 15 minutes long at site A to 53% of cycles being similarly short at site B. Site C had 70% of cycles end short. Because ramping the ODU compressor up and down takes time during every cycle, short cycles are more impacted by these less efficient operational modes and should be avoided. Especially with thermally massive emitters like hydronic slabs, longer runtime cycles at lower compressor speeds should be favorable with AWHPs. Improved thermostat controls may reduce the short cycling; none of these sites' thermostats had integrated slab sensors and thus may be more prone to calling short cycles.AWHP control algorithms also impact heating COPs. For example, how the compressors turn on impacts how quickly the system reaches or overshoots the thermostat setpoint. The AWHP controllers in each of the systems studied here also determine when the backup boiler is turned on to support the AWHP. Usage of the backup boiler to accelerate system responsiveness leads to lower heating COPs. Communicating AWHPs may be better poised to avoid unnecessary use of the back up boiler. These systems can use temperature sensors in the IDU to direct the ODU condenser to ramp up if the load is not being satisfactorily reached. For the third-party split system at site A, however, such call and response controls are not available. The default settings of this systems tend to prioritize fast response of the system, leading to frequent boiler operation. Maintaining comfort is a critical requirement of AWHP systems but maximizing efficiency will be vital in achieving cost-effectiveness for system owners.

CONCLUSION

ASHPs are a rapidly evolving group of technologies and the development of commercially available AWHP systems has further diversified the market. While all AWHPs have some fundamental similarities, the term can apply to an array of remarkably different types of technologies, ranging from all-in-one monobloc systems to noncommunicating indoor heat exchangers with control units that can integrate with a myriad of third-party equipment. Clearly categorizing these systems and their performance specifications is a challenge for the technology's acceptance. To examine AWHPs, this work presents early performance results from three AWHP systems installed in climate zone 6. To maximize the load delivered by these AWHP systems in a cold climate, we tested system with variable speed compressors that were retrofit onto homes with low-temperature slab emitters. All test sites demonstrated an improvement of efficiency compared to an electric resistance boiler system, but the measured COP varied drastically between test sites and OATs. Cooling COPs also varied significantly between the two sites outfitted with hydronic A-coils and did not reach that of a 13 SEER air conditioner. More work is needed to estimate the average seasonal performance of AWHP systems in cold and warm climates alike especially as new models continue to become available.

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