Residential Integrated Heat Pump to Meet All the Home Comfort Needs

Bo Shen, Kyle Gluesenkamp, Yifeng Hu, Zhenning Li
Oak Ridge National Laboratory

ABSTRACT

This paper will introduce development and field trial of a residential air-source integrated heat pump for cold climates. The heat pump is multi-functional to meet all the home comfort demands, including space cooling, space heating, domestic water heating. The integrated heat pump is an ideal solution to decarbonize northern homes via providing efficient space heating and water heating to replace natural gas. It uses a three-stage compressor and a single set of heat exchangers and valves to deliver all the functions, and thus achieve cost reduction. We developed an innovative system configuration and related controls to solve typical charge unbalance, accelerate charge migration and smoothen mode transition in integrated heat pumps. Laboratory investigations were conducted for individual modes and verified the control functions. Laboratory tests demonstrated that the unit delivered outstanding performance. In laboratory, it achieved 17.0 SEER (seasonal cooling energy efficiency rating) and 11.0 HSPF (heating seasonal performance factor). In the most efficient mode (combined space cooling and water heating mode), the unit reached a total energy efficiency > 30.0 EER and required only 25 minutes to heat a 50-gallon tank of water. One heat pump prototype is going through a field trial since April, 2023 in Syracuse, New York. The one-year field test results are summarized.

Introduction

U.S. government set an ambitious goal to reduce 52% greenhouse gas (GHG) by 2035 compared to GHG pollutions levels from 2005. To achieve the quick decarbonization, one key is to minimize natural gas consumption in residential sectors. The US Environment Protection Agency summarized that the modern living style has tripled the energy consumption since 1950, in which, 40% home comfort consumptions are from natural gas. Natural gas at home is mostly used for space heating and water heating. If the natural gas consumption at homes can be replaced with heat pumps, the direct greenhouse gas (GHG) emissions can be decreased by half.

The paper addresses the problem of developing an attractive low-carbon solution for replacing fossil-fuel-fired appliances for residential space heating and domestic hot water in northern climate zones. The project addresses this problem by developing and demonstrating an innovative cold-climate integrated heat pump (CCIHP) that provides space heating and cooling and domestic hot water. Successful commercialization of the proposed concept will advance national goals of reducing greenhouse gas (GHG) emissions and reducing energy consumption in buildings. The largest impact on GHG reduction will be achieved when CCIHPs are sufficiently attractive to replace both space and water heating appliances that are currently fired with fossil fuels. A recent analysis found that there is both technical and economic potential to replace nearly all (99%) of petroleum-fueled space heating in New York State over the next 20 years.

An air-source integrated heat pumps (ASIHP) is multi-functional, capable of meeting all home comfort requests, including space cooling, space heating, domestic water heating and energy storage. It has many working modes and tends to use a variable-speed or multi-speed compressor, has two air-to-refrigerant heat exchangers and one water-to-refrigerant heat exchanger. In some modes, there could be internal volumes and a heat exchanger unused. It is difficult to allocate refrigerant charges between the working and idle heat exchangers and optimize active system charge as needed for individual working modes. Prior ASIHPs' charge management mechanism degrades operation efficiencies and impairs the reliability, as introduced in Van et al. 2015. This project aims to solve the typical charge migration problem in ASIHPs, which will actively adjust charge allocation and thus, optimize the operation efficiencies in all the operation modes.

Trilogy ground integrated heat pump, made by Climate Master INC, is a commercialized product, co-developed by Climate Master and ORNL, as introduced by Richard et al. 2007. It uses ground or water source and provide space cooling, space heating and water heating. The system configuration from the manufacturer’s literature is given in Figure 1.

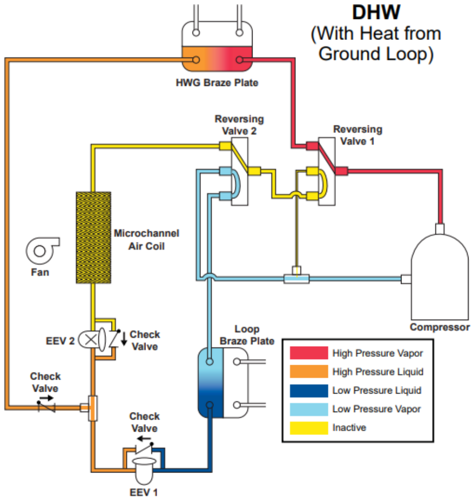

Figure 1: System Configuration of a Ground-Source Integrated Heat Pump Made by Climate Master.

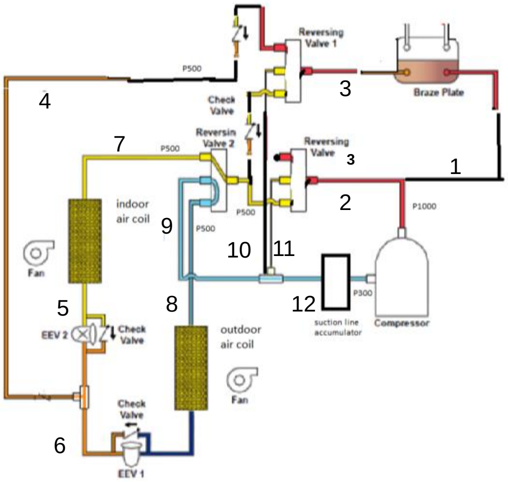

Figure 2: Physical Schematic: Charge Migration Mechanism, including three four-way valves, two electronic expansion valves, two one-way check valves, and a suction line accumulator to optimize charge allocations.

The system uses two four-way valves and two electronic expansion valves to manage the charge migration in numerous modes. The heat pump heats domestic hot water in full condensing either using the indoor air coil or the loop brazed plate heat exchanger as the evaporator. If this configuration is used for an air-source integrated heat pump with one air-to-refrigerant coil replacing the loop brazed plate heat exchanger, low ambient water heating operation would be very limited due to the use of low outdoor air temperature and high-water supply temperature resulting in high compression pressure ratio and compressor discharge temperature. This paper introduces an innovative configuration of air source integrated heat pump illustrated in Figure 2, to smooth charge allocation in multiple modes and result in superior space heating and water heating performance at low ambient temperatures.

System configuration and operation modes

Innovative system configuration and control enable seamless mode transition and optimize charge allocation among numerous operation modes: The new innovative configuration combines three four-way valves, two electronic expansion valves, two one-way check valves, and a suction line accumulator to optimize charge allocations in individual operation modes for an air-source integrated heat pump. Three four-way valves dictate mode switches and refrigerant flow directions. The two electronic expansion valves automatically allocate refrigerant mass in active components, and store excess charge in an idle heat exchanger and suction line accumulator by controlling the compressor discharge pressure as a function of the entering air and water temperatures. In comparison to Figure 1, adding one four-way valve will facilitate a desuperheater mode for water heating. This configuration and related controls have been proven to solve all the issues in the existing integrated heat pump products. It facilitates five working modes: 1. Space cooling – SC; 2. Space heating – SH; 3. Dedicated water heating – DWH; 4. combined space cooling with water heating (most efficient mode) – SCWH; 5. Combined space heating and water heating in desuperheater-SHDWH.

Space cooling mode – SC: Figure 3 below shows the refrigerant flow path in space cooling mode, regulated by the three four-way valves. The SC mode operates when there is a single call for space cooling. In the mode, the water flow in the brazed plate water heater is OFF. Both the indoor blower and outdoor fan are ON. The water heater becomes a parallel flow path to the discharge line, which reduces the discharge side flow resistance, compared to the single discharge line. The arrows show refrigerant flow directions. EEV1 is fully open, while EEV2 control the superheat degree exiting the indoor evaporator coil.

Space heating mode – SH: Figure 4 below shows the refrigerant flow path in space heating mode. The SH mode operates when there is a single call for space heating. In the mode, the water flow in the brazed plate water heater is OFF. Both the indoor blower and outdoor fan are ON. The arrows show refrigerant flow directions. EEV2 is fully open, while EEV1 control the subcooling degree entering the outdoor evaporator coil and extra charge is stored in the suction accumulator.

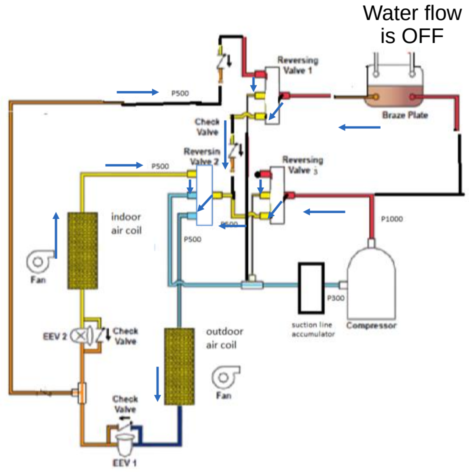

Figure 3: Flow path of Space Cooling Mode

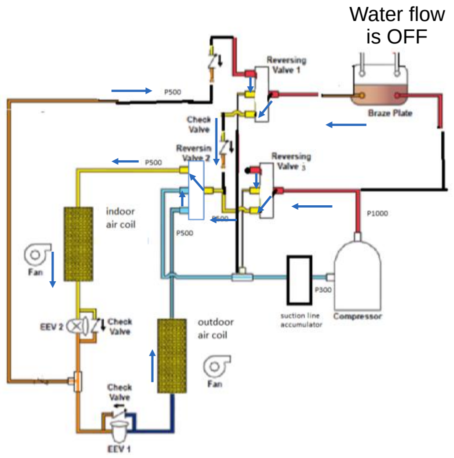

Figure 4: Flow path of Space Heating Mode

Dedicated water heating mode – DWH: The dedicated water heating mode uses outdoor air as the source. If operates when there is a single call for water heating. In the mode, the water flow in the brazed plate water heater is ON. The indoor blower is OFF, but the outdoor fan is ON. In Figure 5, the arrows show the refrigerant flow direction. EEV2, connected to the indoor coil is closed, while EEV1, connected the outdoor coil, controls the condenser subcooling degree. The subcooling degree control adjusts excessive charge stored in the suction line accumulator and optimizes active charge in the system.

Combined space cooling and water heating in full condensing – SCWH: The combined space cooling and water heating mode in full condensing operates when there are simultaneous calls for space cooling and water heating. In the mode, the water flow in the brazed plate water heater is ON. Its refrigerant flow path is the same as the dedicated water heating mode. Yet, the air flow paths and EXV controls are different. In the SCWH mode, the indoor blower is ON, while the outdoor fan is OFF. EEV2 controls a target superheat degree at the indoor evaporator exit, while EEV1 control the condenser subcooling degree. EEV1 manages the excessive charge located in the outdoor coil and suction line accumulator.

Combined space heating and water heating in desuperheating – SHDWH: The combined space heating and water heating mode in desuperheating operates when there is a space heating call, regardless of a water heating call. The return temperature, i.e. tank bottom temperature should be above 80˚F but below a maximum setting temperature, e.g. 140˚F. And the return water temperature shall be lower than compressor discharge temperature resulted by the single space heating mode. The refrigerant flow path is indicated in Figure 6. The water flow in the brazed plate heat exchanger is ON. Both the indoor blower and outdoor fan circulate the air. EEV2 is fully open. EEV1 control the condenser subcooling degree.

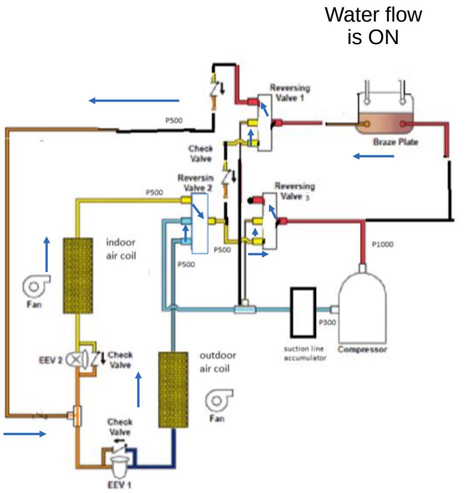

Figure 5: Flow path of Dedicated Water Heating Mode – DWH & Combined space cooling and water heating mode in full condensing - SCWH

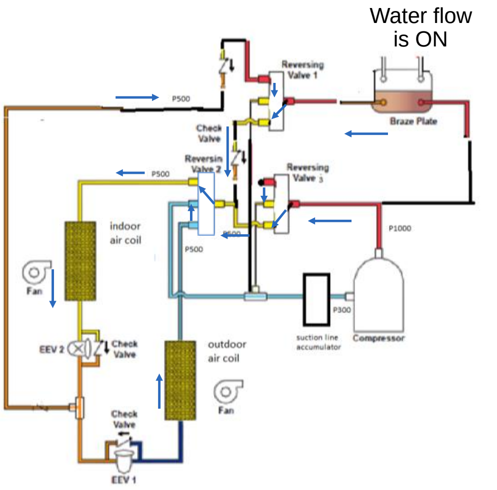

Figure 6: Flow path of Combined Space Heating and Water Heating in Desuperheating

Laboratory Tests

A prototype CCIHP system, using R-410A, was built for laboratory testing. The prototype was modified from a 4.5-ton two-stage heat pump rated at 54500 Btu/h cooling capacity, 16.0 SEER, rated cooling EER at 95˚F of 11.4, 55000 Btu/h high heating capacity, and 9.0 HSPF, rated heating COP at 47˚F of 4.0; both the indoor and outdoor units use microchannel heat exchangers. The compressor was replaced with a prototype 3-stage, 51K Btu/hr (at the high stage) compressor that was provided by Copeland. Three stages are achieved by using a typical two-stage scroll compressor in combination with a speed controller, as depicted in Figure 7. When activated, the speed controller provides power at 40 Hz frequency to run the compressor at a lower speed than the typical 60 Hz power frequency when the speed controller is bypassed. The three stages of the compressor provided capacity output at approximately 100%, 67%, and 45% of full capacity. Cooling and heating capacity were calculated using the indoor air enthalpy method and the refrigerant enthalpy method as described in ASHRAE Standard 37. Tests were run at conditions specified for rating tests of the unit. The compressor stage, outdoor fan speed (low, medium, or high), indoor fan speed (low or high), and outdoor expansion valve opening were controlled manually for the laboratory testing.

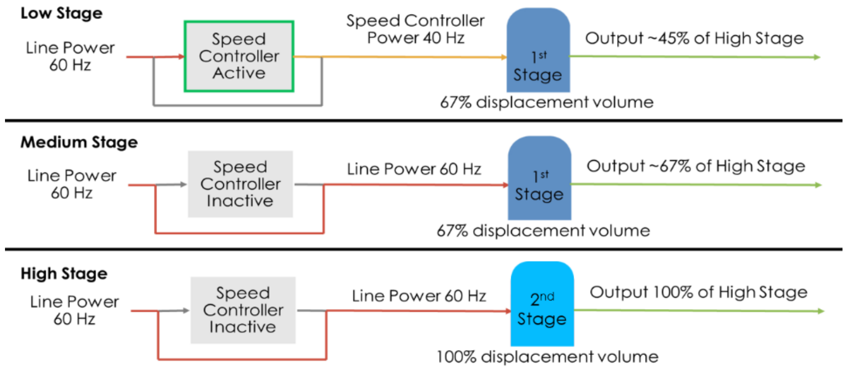

Figure 7: Diagram of speed controller and two-stage heat pump configuration used to achieve 3-stages of operation

Space Cooling and heating Performance

Table 1 presents the measured steady-state cooling performance results at 80˚F dry bulb/67˚F wet bulb indoor temperatures, responding to thermostat low and high calls, including air side space cooling capacities, total power consumption, cooling EERs (energy efficiency ratings), corresponding indoor air flow rates measured by a ASHRAE standard code tester, the compressor suction and discharge saturation temperatures.

Table 1: Measured Cooling Performance Indices of CCIHP.

Test	Capacity	Power	Compressor	EER	Indoor Air Flow	Cond Fan Speed	Suction Saturation T	Discharge Saturation T
Temp (F)	Btu/h	(W)	Capacity	[Btu/hr]	[CFM]	[-]	[F]	[F]
95	42758	3521	Middle	12.14	1550	High	52.1	115.2
82	47394	2812	Middle	16.85	1550	High	50.7	100.7
95	27619	2255	Low	12.25	1050	Low	55.2	111.0
82	31228	1733	Low	18.02	1050	Low	53.7	97.0

Table 2 reports the measured steady-state heating performance results. Recent DOE residential cold climate heat pump challenge, 2022, requires a CCHP reaching a heat pump capacity > 100% rated at 5˚F with a heating COP > 2.4, and HSPF2 in Region V > 8.5.

Table 2: Measured Heating Performance Indices of CCIHP.

	Ambient T	Capa_Air	power	Compressor	COP	Indoor Air Flow	Outdoor Fan Speed	Suction Sat T	Discharge Sat T	Discharge Vap T	Supply Air T
	[F]	[Btu/hr]	[W]	Capacity	[W/W]	[CFM]	[-]	[F]	[F]	[F]	[F]
T-stat High	47	42214	2913	Middle	4.25	1550	High	36	100	135	98
	35	35423	2990	Middle	3.47	1550	High	25	94	141	93
	17	36449	3522	High	3.03	1550	High	5	95	148	94
	5	33192	3696	High	2.63	1550	High	-4	91	164	91
T-stat Low	62	36193	1888	Low	5.62	1550	High	52	96	119	94
	47	29320	1889	Low	4.55	1550	High	38	91	119	91
	35	24656	1876	Low	3.85	1550	High	28	88	120	86
	17	36449	3522	High	3.03	1550	High	5	95	148	94

The laboratory test data was used to estimate the seasonal performance in terms of seasonal energy efficiency ratio (SEER) for cooling performance and heating seasonal performance factor (HSPF) for heating. Estimates of the SEER, HSPF according to the Appendix M heating load lines of AHRI 210/240, and HSPF2 according to the Appendix M1 heating load lines of AHRI 210/240, are shown in Table 3. The triple-capacity northern heat pump rating procedure was followed for calculating the SEER and HSPF values for the 3.5-ton nominal cooling case. For the 2.5-ton nominal cooling case, a single stage cooling bin method calculation was used for estimating the SEER and the triple-capacity northern heat pump rating procedures was used for the HSPF calculation. The values are only estimates because the test procedures for ratings were not strictly followed. One notable deviation is that the external static pressure of the indoor unit was not controlled specifically according to either Appendix M or Appendix M1 values of AHRI 210/240. The only differences between the HSPF and HSPF2 values were the building heating load lines and associated modifications to the outdoor ambient bin hours due to different zero heating load ambient temperatures. Rating the system with one stage of cooling instead of two reduces the estimated SEER by approximately 4%. This is due to additional cyclic losses that offset any gains from operating at a lower compressor capacity. The estimated HSPF for both Region IV and Region V decrease as well. However, the HSPF2 values, with updated building heating loads, for Region IV and Region V increase by 1% and 10%, illustrating the benefits of having higher heating capacity available in very cold climates like those in Region V.

Table 3: Estimated seasonal efficiencies based on laboratory test data of CCHP

	3.5-ton nominal cooling 2-stage cooling 3-stage heating	2.5-ton nominal cooling 1-stage cooling 3-stage heating
SEER (Btu/Wh)	17.15	16.38
HSPF Region IV (Btu/Wh)	10.97	10.54
HSPF Region V (Btu/Wh)	9.47	8.96
HSPF2 Region IV (Btu/Wh)	10.15	10.29
HSPF2 Region V (Btu/Wh)	8.19	9.03

Water heating performance

We ran combined space cooling and water heating operations, respectively at the compressor middle and heat stages, setting the indoor air temperature at 80 ˚F dry bulb/67˚Fwet bulb, and heating a 50-gallon tank of water from 58˚F to 125˚F with circulating 5.3 GPM (gallons per minute) water between the brazed water heater and the water tank. The supply water temperature was monitored at the exit of the brazed plate heat exchanger. Figure 8 depicts the process space cooling EER, i.e., total space cooling delivered / (compressor power consumption + indoor blower consumption); and the total EER (cooling delivered + water heating delivered) / (compressor power consumption + indoor blower consumption); as well as time durations to heat the 50-gallon water. Figure 9 shows the time-average water heating capacities of the two stages. Combined space cooling and water heating mode, running the compressor middle stage, reached a total energy efficiency of 35.0 EER. Both stages took less than 25 minutes to heat the water to 125°F.

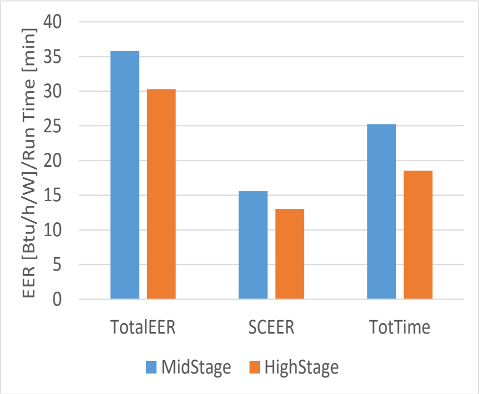

Figure 8: Space cooling and total EERs during SCWH mode.

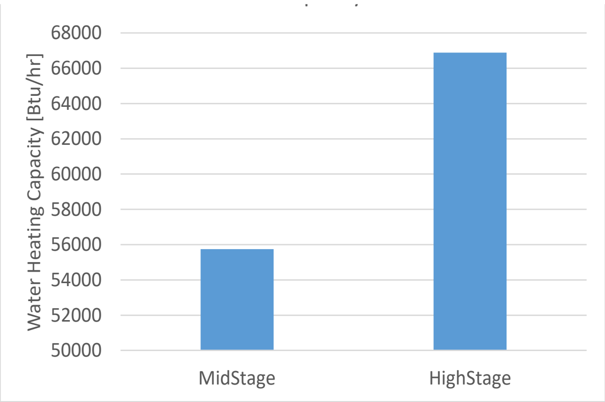

Figure 9: Water heating capacities during SCWH mode.

Figures 10 and 11 illustrate the performance of the dedicated water heating mode (DWH) using outdoor air source. Figure 10 presents the water heating capacity and time to heat a 50-gallon water to 125˚F at the tank top as a function of the ambient temperature. Figure 11 shows the water heating COP, from 58˚F to 125˚F, water heating delivered) / (compressor power consumption + outdoor fan power consumption). This COP an average over the duration of the water heating period.

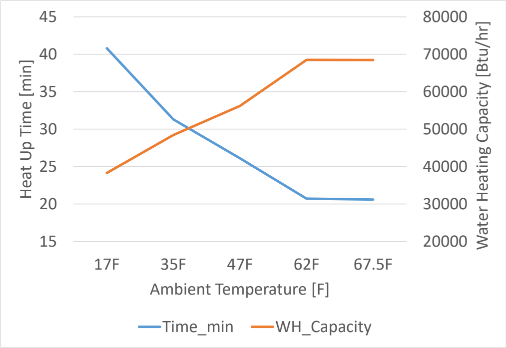

Figure 10: Water heating capacity and time of DWH, changing with ambient temperature.

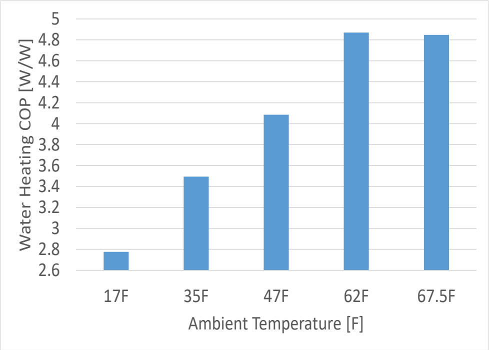

Figure 11: Water heating COP of DWH, changing with ambient temperature.

The dedicated water heating mode provides fast and efficient domestic water heating. It can serve as a tankless water heater, considering that the CCIHP can heat 1.7 GPM water, i.e., the max water draw for a 50-gallon residential Uniform Energy Factor rating procedure, regulated by DOE 2013, from 58 to 125°F in a direct flow-through, when the ambient temperature is above

47˚F. It is 10 times faster than a typical stand-alone HPWHs, e.g., having 4000 Btu/hr capacity. The other outstanding point is that the DWH worked down to 17˚F ambient temperature without violating the compressor discharge temperature, suction, and discharge pressure limits. It heated up the entire tank of water within 40 minutes and reached a process water heating COP > 2.6, not including the hot water circulation pump power.

Field Demonstration

The laboratory prototype was improved with automatic control and fully instrumented to start a field demonstration in Syracuse University, New York since April/2023. The CCIHP was installed in a lab space, as illustrated below. The indoor side has a wooden box containing a 3-stage compressor, two EXVs, three four-way valves and a brazed plate water heater, as well as a Compbell Scientific CR1000X data logger to control and monitor the field trial. The indoor air handler is connected to an exit duct, with returning air to the bottom and supplying air at the top. It has a 2-stage indoor blower and a microchannel coil. A 50-gallon water tank is connected to city water at the return port at the bottom, and the supply port at the top connected to a drain. A 160 watts pump circulating 4.6 GPM hot water from the tank bottom to the brazed plate water heater and back to the tank top. The outdoor unit only contains a -3stage fan and an outdoor microchannel coil. In the wooden box, all the compressor shell, brazed plate heat exchanger and refrigerant pipes were insulated with thick foams, to reserve energy for water heating, and prevent water condensate inside the box. These measures warrantee good energy balance between the water and refrigerant sides.

Figure 12: Compressor box, indoor air handler and a 50-gallon water tank

Figure 13: outdoor unit containing a fan and a microchannel coil

<u>Instrumentations:</u>

At air side, two grids of thermocouples were placed at the inlet and outlet of the indoor air handlers to measure sensible heating/cooling capacity, where two temperature/relative humidity sensors indicate return and supply air relative humidity to calculate the total and sensible cooling capacities. One barometric pressure sensor measures real time air pressure to correlate psychrometric properties. The indoor blower has two speeds and uses an electronically communicated motor, featured to maintain a constant volumetric flow rate at each speed level. It was measured at the field using an air flow monitor (pitot tube array), that the high stage drives around 1480 CFM and the low stage drives 890 CFM, which are used to calculate the air side capacities along with the measured inlet and outlet air enthalpies. In the outdoor unit, a probe thermocouple was placed beneath the outdoor control box to record ambient temperature through the whole year.

At water side, two surface RTDs (thermos-resistance) were placed on the inlet and outlet cooper tubes of the brazed plate water heater. A flow meter measured the circulation flow rate, which was rather constant at 4.6 GPM, consuming 160 Watts. The water flow rate, inlet, and outlet water temperatures, plus the pump power, were used to calculate the water heating capacity. Two thermocouples were tied to surface of return and supply pipes of the water tank and insulated with foam tapes. It should be mentioned that the measured water side capacities are more credible. And thus, space cooling capacity in the combined space cooling and water heating mode is calculated using the water heating capacity subtracting the total power consumption.

At refrigerant side, pressure transducers were inserted into the compressor discharge line, suction line, liquid line out of the indoor air handler. Wire thermocouples were tied at the compressor discharge line, suction line, liquid line of the indoor air handler, and mixed liquid temperature between the water heater exit and indoor air handler coil exit.

Three watt transducers were installed to measure power consumptions of the compressor, indoor blower, and outdoor fan, separately.

Control implemenations:

The CR1000X data logger communicated with an off-the-shelf two-stage thermostat, which sent Y1/Y2 24 VAC signals to call low and high stages of cooling/heating operations, respectively. In heating mode, if the temperature was between 69˚F to 71˚F, it called the first stage heating, when the temperature was below 69˚F, it called the second stage heating. In cooling mode, temperature between 73˚F to 75˚F was related to the first stage cooling, above 75˚F, it called the second stage cooling.

A solenoid valve was installed at the supply side of the water tank. It opened to draw hot water and damped it to a drain for 10 minutes every hour, having estimated daily draw around 200 to 250 gallons from energy balance. If the thermocouple at the supply pipe indicated a temperature below 95˚F, it called water heating. Because the thermocouple is outside the water pipe, the actual hot water temperature tends to be 10 R higher than measured surface.

When it calls for space heating only, if the ambient temperature is below 20˚F, the compressor runs at the high stage regardless of Y1 or Y2. If the ambient temperature is above 40˚F, Y1 calls the compressor low stage and Y2 calls the compressor middle stage. If the ambient temperature is between 20˚F to 40˚F, Y1 calls the compressor middle stage and Y2 calls the compressor high stage. In space heating, the indoor blower always run at the high stage. The outdoor fan runs at the high stage except when the ambient temperature is above 58˚F, and Y1 call the low stage and Y2 calls the middle stage. This aims to limit the compressor suction pressure within the operation envelope.

When it calls space cooling only, Y1 is related to low stages of the compressor, indoor blower, and outdoor fan. Y2 is related to middle stages of the compressor and outdoor fan, the high stage of the indoor blower.

When there is a water heating demand, if the zone temperature is above 70˚F and ambient temperature is above 65˚F, it activates the combined space cooling and water heating mode, when the compressor operates at the middle stage and indoor blower operates at the high stage, the outdoor fan is off. If the ambient temperature is below 25˚F, and the tank return (bottom) water temperature is above 80˚F, and there is a simultaneous space heating call, the combined space heating with water heating mode will operate until the tank supply (top) temperature reaches 140˚F. At all other moments when there is a water heating demand, it calls the dedicated water heating mode using the outdoor air source. During the combined space heating and water heating mode, the compressor runs the high stage, the outdoor fan runs at the high stage and the indoor blower runs at the low stage to elevate the condensing temperature for high temperature water heating. During the dedicated water heating mode, both the compressor and the outdoor fan run the high stage, while the indoor blower is off. Because the dedicated water heating can heat a whole tank of water within half hour above 25˚F ambient temperature, it has a higher priority. It means that the space heating will resume after a dedicated water heating operation completes.

In both the dedicated water heating mode and the combined space cooling and water heating mode, the water heating operates until it reaches the compressor condensing temperature limit as shown in Figure 28 as a function of the evaporating temperature, or the compressor discharge temperature reaches 250˚F.

The outdoor unit control board senses the outdoor coil surface temperature via a thermistor. When the differential between the surface and the outdoor air temperature reaches a threshold, the outdoor board calls defrosting operation. The unit instantly responds to a defrosting call regardless of any ongoing operation mode, when the outdoor fan is off, the compressor runs at the high stage, the same as the indoor blower to draw heat from the indoor air and heat the outdoor coil until the surface temperature reaches 70˚F. After the defrosting completes, the operation logics resume.

The charge migration heavily depends on subcooling degree control using an EXV and storing extra refrigerant in the suction line accumulator. A logic check was implemented in the controller to screen wet compression if the discharge superheat degree is less than 20R after the unit runs longer than 5 minutes. However, this check was never activated during the whole year field test, indicating no wet compression occurred in various modes.

Data validation:

Through the one-year field demonstration, the field data were averaged and recorded every minute. The EXV control always met the subcooling degree target with saturated suction vapor. It indicates no charge loss in the process. Because of every hourly, 10-minute, intensive water draws demanded water heating operations often, i.e., every two or three hours. The frequent dedicated water heating operations can serve as a validation to calculate the compressor mass flow rate via energy balance between the hot water and condensing refrigerant. Figures 14 and 15 plot relative residuals of compressor map predicted mass flow rate and power consumption at the measured suction and discharge saturation temperatures, subtracting the field measured refrigerant mass flow rate (via energy balance) and compressor power, i.e. Residual_mr and Residual_Pow at the compressor high stage, in the whole year. The compressor consistently delivered measured performance within +/-5% to the compressor map.

Figures 16 and 17 shows energy balances by minutes between the air side and refrigerant side, using map-predicted refrigerant mass flow rate in space heating mode when the compressor operated at the high stage and the measured subcooling ranged from 8R to 15R. The minute-level energy balances are mostly within +/10% and centered at zero.

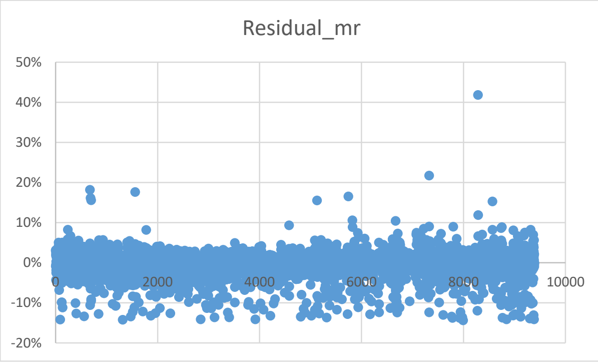

Figure 14: Residual of (energy balanced refrigerant mass flow rate – map predicted mass flow rate)/map predicted flow

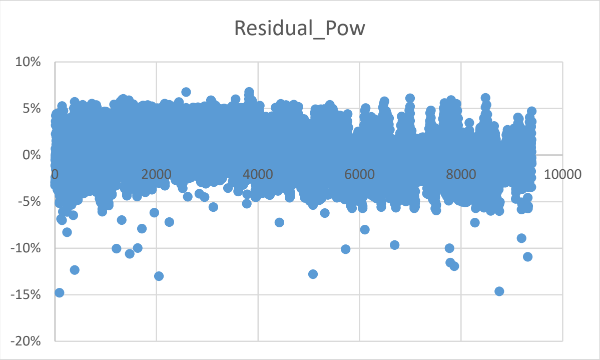

Figure 15: Residual of (measured compressor power – map predicted power)/map power

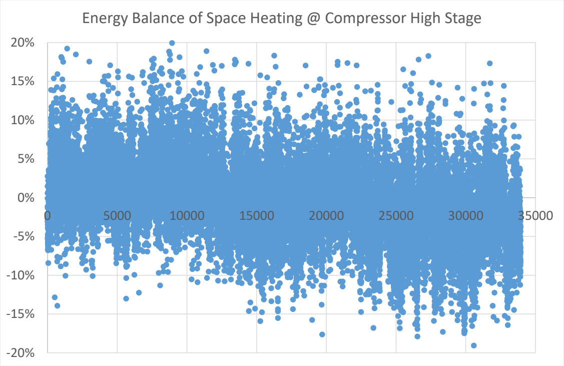

Figure 16: Energy balances by minutes in space heating running compressor high stage

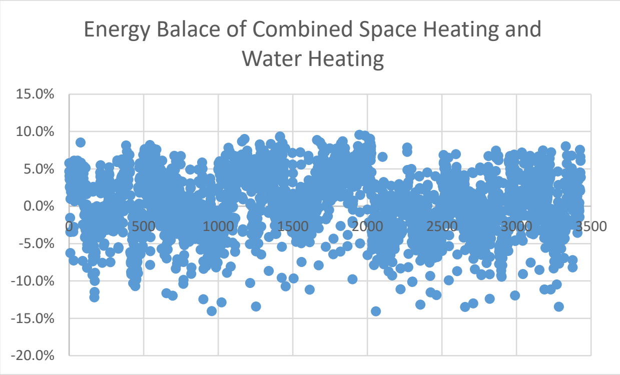

Figure 17: Energy balances by minutes in combined space heating and water heating mode

The building has a backup gas furnace, which turns on at 58˚F and turns off at 60˚F zone temperature. The CCIHP appear undersized for the building load. Figure 18 depicts the controlled zone temperature in winter, decreasing to 60˚F, when the ambient temperature approached 10˚F. Figure 19 shows the zone temperature in summer, which ascended to 78˚F at 90˚F ambient temperature.

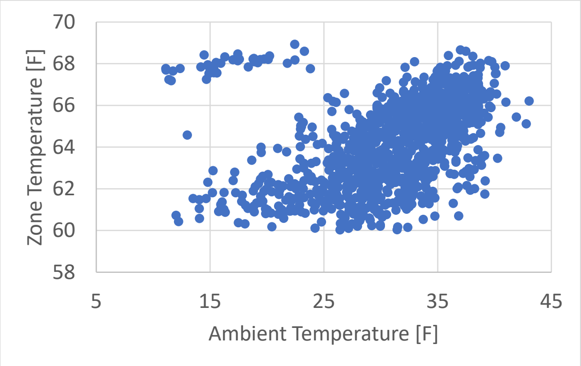

Figure 18: Zone temperture in winter

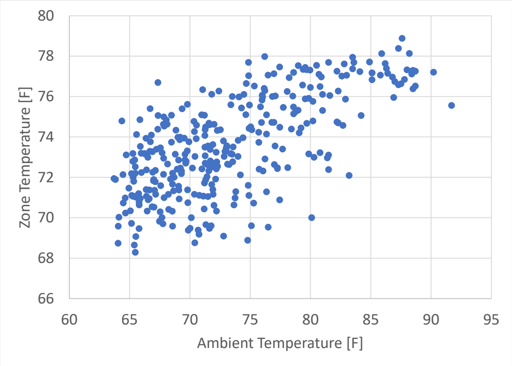

Figure 19: Zone temperature in summer.

Space Heating:

Figure 20 depicts hourly average space heating capacities at the three compressor stages, when the running time is larger than 15 minutes to minimize impact of cyclic loss. Figure 21 shows space heating COPs. At 47˚F ambient temperature, the heat pump delivered approximately 3.5-ton rated capacity, i.e. 42000 Btu/hr. The measured COPs repeated the values obtained from the laboratory tests. The COPs at low ambient temperatures stay around 3.0, because the zone return air temperature was as low as 60˚F.

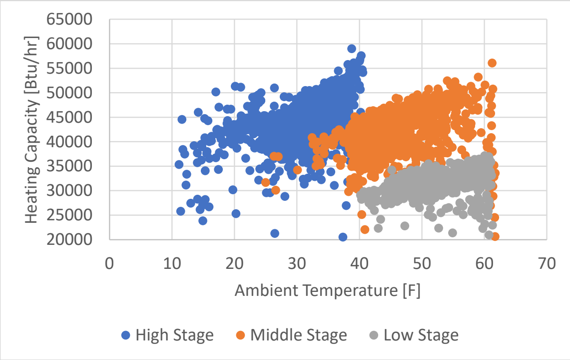

Figure 20: Space heating capacities

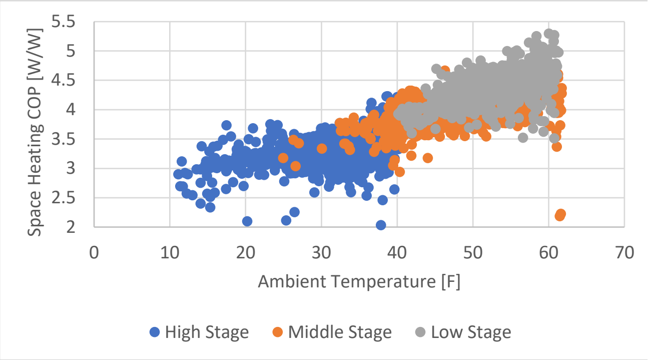

Figure 21: Space heatig COPs

Space Cooling:

The figures below illustrate hourly-average space cooling capacities and EERs with running time larger than 15 minutes. It is counter intuitive to see that the cooling capacity and EER increases with the ambient temperature, which is caused by the ascending zone temperature, shown in Figure 19.

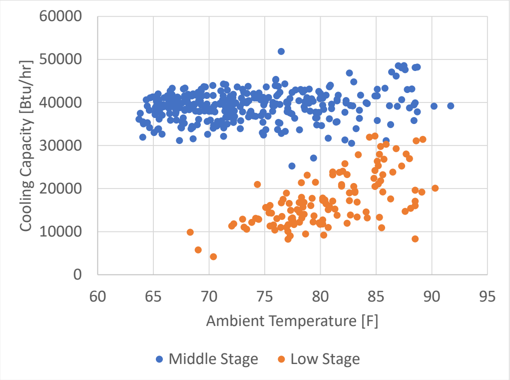

Figure 22: Space cooling capacities

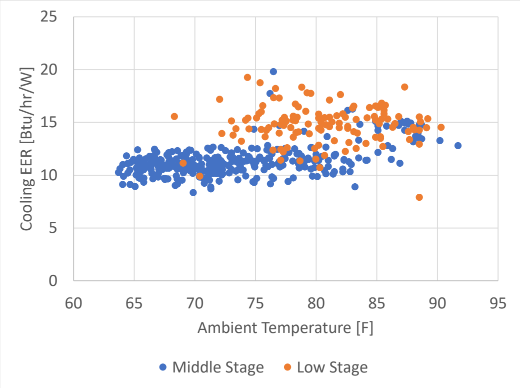

Figure 23: Space cooling EERs

Combined space cooling and water heating:

Figure 24 presents the water heating capacity as a function of the zone air temperature at the compressor middle stage. Figure 25 illustrates the operation time to satisfy a water heating call, which are all below 30 minutes. Figure 26 depicts the total COPs, i.e., water heating capacity + space cooling capacity, divided by the total power consumption. Figure 27 shows the max water supply temperatures. The forced flow water heater increases the water temperature to 128˚F, even with a R410A compressor.

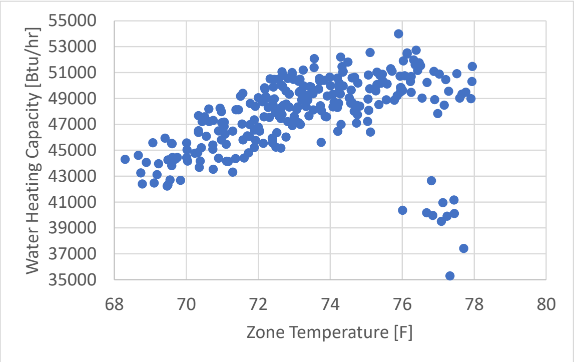

Figure 24: water heating capacities in SCWH mode

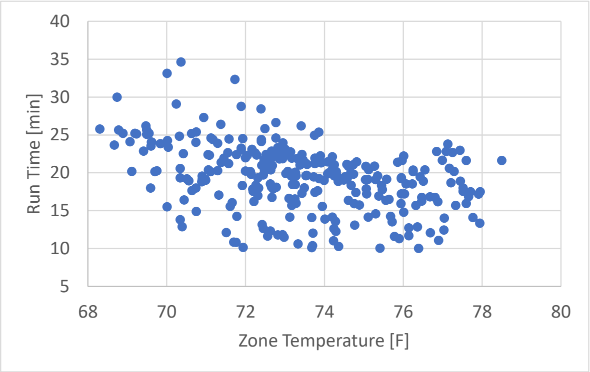

Figure 25: required water heating time in SCWH mode

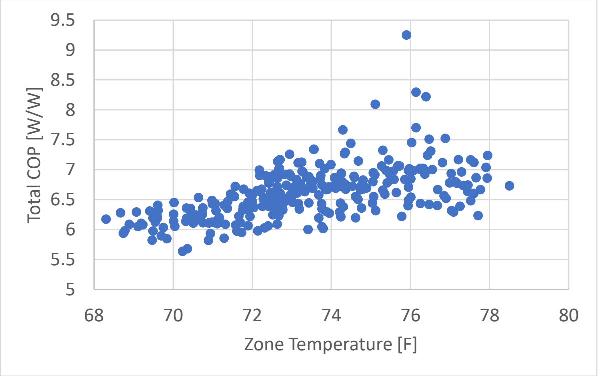

Figure 26: Total COPs combining space cooling and water heating capacities

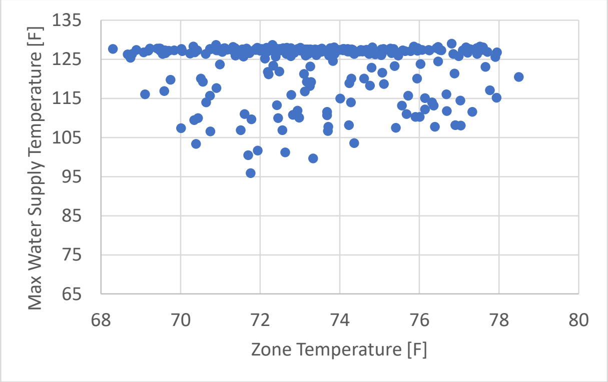

Figure 27: Max water supply temperature as a function of the zone temperature

<u>Dedicated water heating mode:</u>

The unit control raised the water supply temperature out of the brazed plate water heater until the condensing temperature reached the compressor limit as shown in Figure 28. Therefore, max outlet water temperatures in minutes follow a similar profile as the compressor operation envelope, depicted in Figure 29. The dedicated water heating mode met the water heating demand from 25˚F to 70˚F ambient temperatures. At 25˚F, the full condensing still can heat the water up to 110˚F.

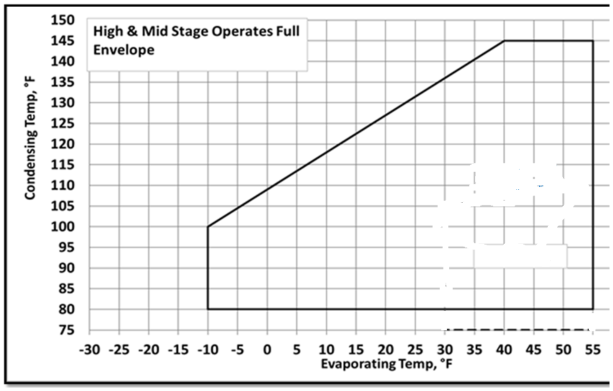

Figure 28: compressor operation envelope

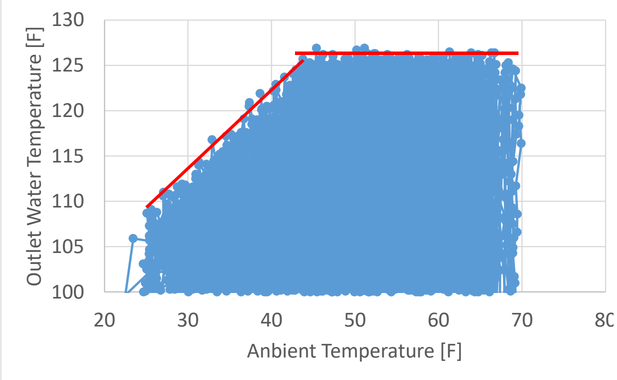

Figure 29: supply water temperatures out of the brazed plate heat exchanger

Figures 30 and 31 depict hourly average water heating capacity and COP as a function of the ambient temperature. The full condensing, DWH mode still operated down to 10˚F, when it approximately heated the water to 80˚F before violating the compressor limit. After that, the combined space heating and water heating mode took over to heat the water with the desuperheating brazed plate heat exchanger.

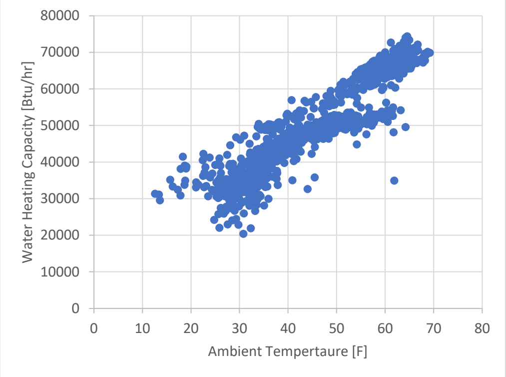

Figure 30: Hourly average water heating capacities in DWH mode

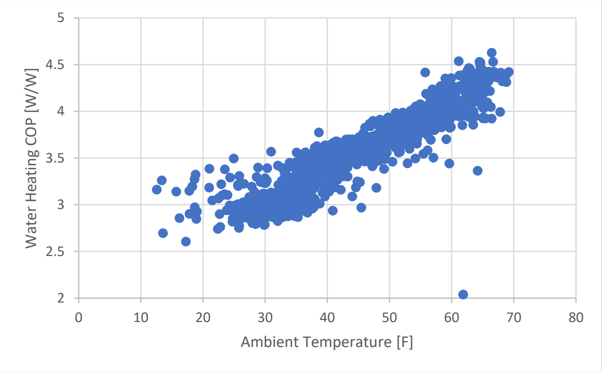

Figure 31: Hourly average water heating COPs in DWH mode

Figure 32 depicts the run time of dedicated water heating changing with the ambient temperature. The required run time increases with decreasing the ambient temperature above 35˚F ambient, temperature due to the water heating capacity drop with the ambient temperature. However, below 35˚F, the run time decreases with the ambient temperature, because it starts violating the compressor operation limit and can't heat the water up to 125˚F.

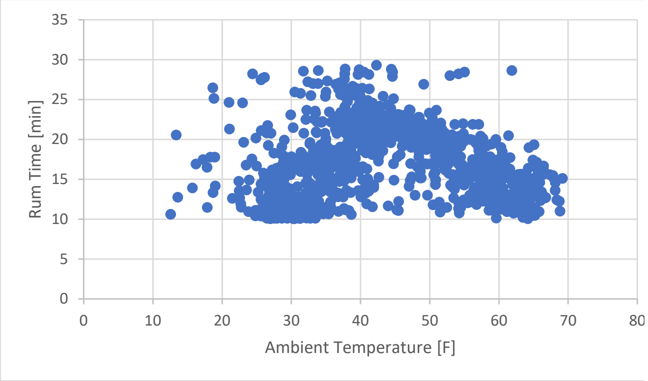

Figure 32: water heating run time in DWH mode

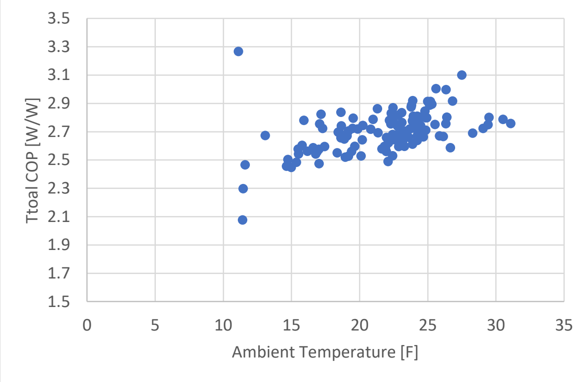

Figure 33: total COP of combined space heating and water heating mode

Combined space heating and water heating mode:

Figure 33 illustrated total COPs of the combined water heating and space heating capacities. They are lower than the COPs of the space heating mode at the compressor high stage because the reduced indoor air flow rate elevated the condensing temperature, to augment high temperature water heating capacity. Figure 34 shows the water heating capacities, which are much less than the full condensing DWH and SCWH modes, but still adequate for a typical single-family use. Figure 35 illustrates maximum supply water temperatures. The desuperheater operation has no compressor limits to heat the water up to 140˚F. However, for the occasions lower than 140˚F, the desuperheater capacity was not adequate to cover the hourly, 10-minute water draws.

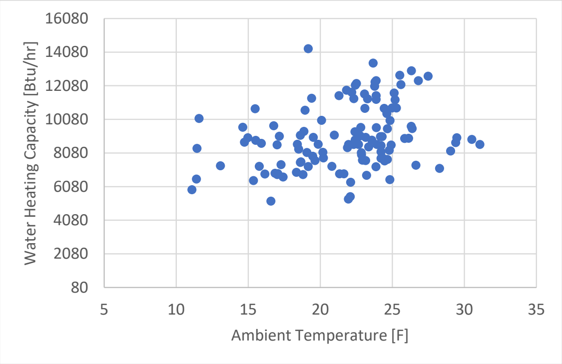

Figure 34: hourly water heating capacities in combined space heating and water heating mode

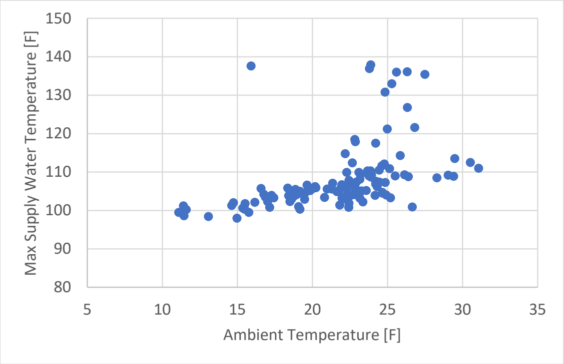

Figure 35: max water supply temperature in combined space heating and water heating mode

Summary

Air-source integrated heat pumps are multi-functional, capable of meeting all home comfort requests, including space cooling, space heating, domestic water heating. They have many working modes and tend to use a variable-speed or multi-speed compressor, have two air-to-refrigerant heat exchangers and one water-to-refrigerant heat exchanger. Despite these advantages, some modes can include unused internal volumes, causing difficulties in allocating refrigerant charge. To date, charge management strategies employed in existing integrated heat pumps degrade efficiency and impair the reliability, as introduced by Van et al. 2015.

This investigation solved the typical charge migration problem in integrated heat pumps by actively adjusting charge allocation and thus optimizing the operation efficiency in all the operation modes. The innovative configuration combines three four-way valves, two electronic expansion valves, two one-way check valves, and a suction line accumulator to optimize charge allocations in individual operation modes for an air-source integrated heat pump. Three four-way valves dictate mode switches and refrigerant flow directions. The two electronic expansion valves automatically allocate refrigerant mass in active components and store excess charge in an idle heat exchanger and suction line accumulator by controlling the condenser subcooling degree.

The multi-functional heat pump is capable of various working modes with smooth transitions. We used a 3-stage compressor targeting to cold climate application, i.e., having the middle capacity sized to match the building peak cooling load, and the top capacity reserved for enhanced heating at low ambient temperatures. Laboratory tests demonstrated that the unit delivered outstanding performance. It achieved 17.0 SEER (seasonal cooling energy efficiency rating) and 11.0 HSPF (heating seasonal performance factor, DHRmin, Region IV). In the most efficient mode (combined space cooling and water heating mode), the unit reached a total energy efficiency > 30.0 EER, and required only 25 minutes to heat a 50-gallon water from 58°F to 125°F. The cold climate air source integrated heat pump can heat 1.7 GPM water (max water draw for the medium draw UEF rating procedure) from 58 to 125°F in a direct flow-through, when the ambient temperature is above 47°F, that is 10 times faster than stand-alone heat pump water heaters.

The laboratory prototype was further instrumented and embedded with automatic control, and successfully went through a whole year field demonstration in Syracuse, NY. Control logics and implementations enabled all five modes in the field. The field test produced high quality, real-world data and delivered outstanding performance close to the laboratory results.

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