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Cold Climate Integrated Heat Pump

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ABSTRACT

This paper introduces development of a residential air-source integrated heat pump for cold climates (CCIHP). The heat pump is multi-functional to meet all the home comfort demands, including space cooling, space heating, domestic water heating and energy storage. The CCIHP 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 in heat pumps, 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. 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 of 35.0 EER and required only 25 minutes to heat a 50-gallon tank of water. The CCIHP can heat 1.7 GPM water from 58 to 125°F in a direct flow-through, when the ambient temperature is above 47°F. In a dedicated water heating mode using outdoor air source, the heat pump operated down to 17˚F, achieving a COP > 2.6, and heated 50-gallon water within 1 hour.

1. INTRODUCTION

The earth continues to see record increase in temperatures and extreme weather conditions largely driven by anthropogenic emissions of warming gases such as carbon dioxide and other more potent greenhouse gases such as refrigerants. The cooperation of 188 countries in the 21st Conference of the Parties in Paris 2015 (COP21), resulted in an agreement aimed to achieve universal agreement on climate, with the goal of keeping global warming below 2°C by the end of the century. President Biden set an ambitious goal to reduce 52% greenhouse gas (GHG) by 2035 compared to GHG pollutions levels from 2005. The goals will brighten the future and create sustainable living for coming generations.

To achieve the quick decarbonization, one key is to minimize natural gas consumption in residential sectors. Natural gas is a valuable non-renewable resource, which has high grade of energy with burning temperature of 2000°C. It should not be used for home comfort needs, where the required supply temperature is only about 50°C. Huge energy exergy is wasted in the process. Natural gas is a valuable resource that should be utilized more efficiently in power plants with central pollution control than distributed uses at homes. The modern living style has tripled the energy consumption than 50 years ago, in which, 40% home comfort consumptions are from natural gas. On the other hand, consumption of renewables, e.g., solar and wind, is minimal. 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 GHG emissions can be decreased by half.

To replace fossil fuel uses at home, the users need solutions for space heating and water heating. Electricity-driven vapor compression heat pumps are an energy-efficient solution to replace fossil fuel and reduce greenhouse gas emissions. However, residents in northern climates are reluctant to switch from natural gas to electricity. Efficient heating is a necessity with frequent winter ambient temperatures below 0˚F. A typical heat pump doesn't work in cold climates, because: 1) High discharge temperature limits: low suction pressure and high compression pressure ratio at low ambient temperatures cause significantly high compressor discharge temperatures, exceeding the maximum limit for many of the current compressors on the market. Furthermore, system charge of a heat pump is usually optimized in cooling mode, which leads to overcharged conditions in the heating mode, further increasing the discharge temperature. 2) Insufficient heating capacity: a typical heat pump is sized to meet the building design cooling load. However, the building cooling and heating loads in a northern climate are severely unbalanced, with average household space heating consuming 56% energy while space cooling consumes <10%. Heating capacity of a single-speed heat pump decreases with ambient temperature. The heating capacity at -13°F typically decreases to

40% of the rated heating capacity at 47°F (~equivalent to the rated cooling capacity at 95°F). As such, a single-speed heat pump, sized to match the building cooling load, is not able to provide adequate heating capacity to match the building heating load at low ambient temperatures, and supplemental resistance heat must be used, which degrades the overall efficiency quickly. 3) Low coefficient of performance (COP): heating COP degrades significantly at low ambient temperatures due to the temperature difference between the source side and demand side. These issues become more challenging for air source heat pump water heaters, because the water supply temperatures are higher, up to 125˚F.

The study 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. CCIHP is a multi-functional heat pump, that uses one set of components for space cooling, space heating, and water heating. It recovers the condenser waste heat for domestic hot water in summer. In winter, it can do dedicated water heating, or a combination of water heating and space heating to serve customer demands.

The development comprises technical points as below:

1) Multi-stage scroll compressor: Emerson recently developed three-stage (3S) compressors, having 100%/67%/45% capacity stages. It is the first in-the-kind, with one compressor delivering more than two capacity levels without an expensive inverter. The 3S compressor will reduce the compressor cost in comparison to a variable-speed compressor. It has great over-capacity potential at lower cost, which is important for cold climate heat pumps (CCHPs) at low ambient temperatures.
2) Capacity modulation strategy: The 3-stage compressor will have controls developed to allow it to be operated by a typical 2-stage thermostat. To allow capacity modulation in cooling mode and overcapacity at low ambient temperatures in heating mode, the 67% displacement volume is selected to deliver the nominal (rated) cooling capacity for the unit at 95°F ambient temperature, 80°F/67°F indoor dry bulb and wet bulb temperatures, as well as the rated heating capacity at 47°F/44°F ambient dry bulb and wet bulb temperatures and 70°F indoor dry bulb temperature. Thus, during the cooling operation below 90°F and heating operation at moderately low ambient, the unit can decrease the capacity to 67% of the rated value (= 45%/67%). For enhanced heating, the unit can deliver overcapacity to 149% (= 100%/67%). An ambient temperature sensor on the outdoor unit will be used along with the low (Y1) and high (Y2) signals from a 2-stage thermostat to determine the appropriate staging from the 3-stage compressor. The Low (Y1) signal from a 2-stage thermostat will call the 45% compressor capacity. On the other hand, the High (Y2) signal will activate the 67% compressor capacity at ambient temperatures above 20°F; at ambient temperatures below 20°F, the 100% compressor capacity will respond to the Y2 call.
3) Utilization of condenser waste heat and extra compressor capacity for producing domestic hot water: It is necessary to size the compressor for a CCHP to meet the peak heating load. This leads to excessive compressor capacity for space conditioning during the cooling season and the heating season when ambient temperatures are moderately low. It is a natural fit to combine a CCHP and an air-source integrated heat pump (ASIHP) together to be a CCIHP. This maximizes compressor use by deploying the extra capacity with condenser heat to make hot water. Innovative control and configuration facilitate allocating the spacing heating and water heating capacities and match various loads seamlessly.
4) Cost reduction by combining a CCHP and an ASIHP to create an innovative CCIHP: CCIHPs maximize the use of the compressor and heat exchangers, in one integrated unit to compete with two separate units, i.e., a heat pump and a water heater. The proposed CCIHP shall be a cost saver, and the marginal higher cost can be recovered quickly through energy savings. The innovations in less expensive control and operation mode management will assist in lowering operational cost to provide energy savings.
5) Heating mode discharge pressure (subcooling degree) control, which uses an electronic expansion value (EXV), coupled with a suction line accumulator, is intended to optimize the active charge in the system over an extensive operation range. This mitigates the typical charge imbalance problem between cooling and heating modes and reduces the discharge temperature by maintaining saturated vapor entering the compressor.
6) Integration of enhanced thermal storage, grid-responsive, and weather-forecast control technologies: a thermal storage element will enable the heat pump to operate during grid off-peak periods or when renewable generation resources are available, storing energy for space heating or water heating needs. The extra thermal storage enables the heat pump to work preferably when the ambient conditions are favorable. The stored hot water can be used for space heating when the heat pump efficiency is low at cold ambient temperatures. A grid-responsive control system will be integrated to signal the system in advance of peak demand periods and/or periods of high renewable generation availability for transactive control. The size of the thermal storage tank will be optimized to minimize the payback period.

2. SYSTEM CONFIGURATION

A CCIHP is a multi-functional unit, capable of meeting all home comfort requests, including space cooling, space heating, domestic water heating and energy storage. It has two air-to-refrigerant heat exchangers and one brazed plate 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 unused heat exchangers and optimize active system charge as needed for individual working modes. As shown in Figure 1, the innovative configuration aims to solve the typical charge migration problem in integrated heat pumps, which will actively adjust charge allocation and thus, optimize the operation efficiencies in all the operation modes. The connections lines from 1 to 12 are labelled. It combines three four-way reversing valves (RV1, 2 and 3), two electronic expansion valves (EEV1 and 2), two one-way check valves in line 4, and between RV1 and RV2. A suction line accumulator optimizes charge allocations in individual operation modes for a CCIHP. Three four-way valves switch modes and control 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 the suction line accumulator by controlling an optimum subcooling degree.

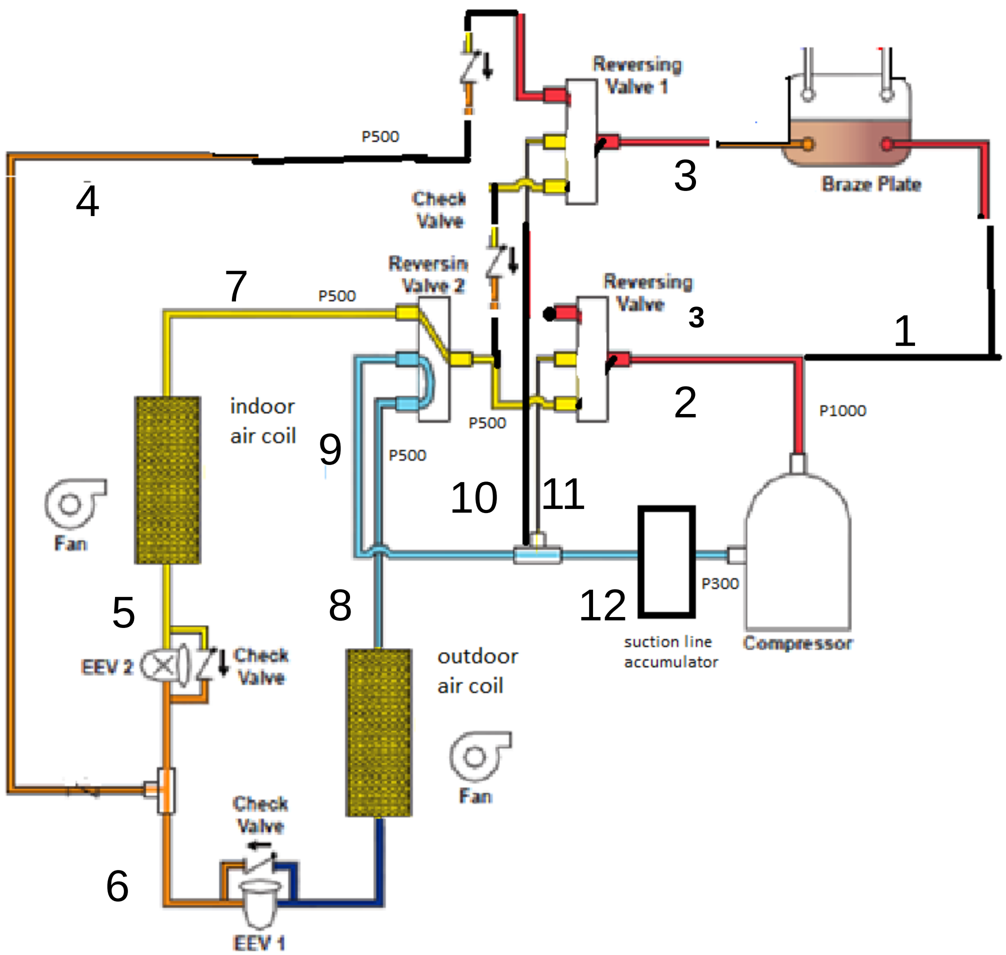

Figure 1: Physical Schematic: Charge Migration Mechanism, including three four-way valves, two electronic expansion valves, two one-way check valves, and a suction line accumulator to optimize charge allocations.

3. WORKING MODES AND FLOW PATHS

This configuration and related controls facilitate seven working modes: 1) Space cooling – SC; 2) Space heating – SH; 3) Dedicated water heating – DWH; combined space cooling with water heating (most efficient mode), including 4) water heating in full condensing – SCWH, 5) water heating in desuperheating - SCDWH; combined space heating with water heating, including 6) water heating in parallel condensers- SHPWH; 7) water heating in desuperheating-SHDWH

1) Space cooling mode – SC

The SC mode operates when there is a single call for space cooling. The compressor mass flow goes through two parallel discharge lines of 1, and 2, RV1 and RV3, and merges at the entrance of RV2. Controlled by RV2, the outdoor coil serves as a condenser, and the indoor coil serves as an evaporator. The refrigerant returns to the compressor suction side through the lines 7, 9 and 12. The line 4 is blocked by a one-way check valve in the line. 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 line flow resistance. EEV1 is fully open, while EEV2 control the superheat degree exiting the indoor evaporator coil.

2) Space heating mode – SH

The SH mode operates when there is a single call for space heating. The compressor mass flow goes through the parallel discharge lines of 1, and 2, and RV1 and RV3, and merges at the entrance of RV2. Controlled by RV2, the indoor coil serves as a condenser, and the outdoor coil serves as an evaporator. The refrigerant returns to the compressor suction side through the lines 7, 9 and 12. The line 4 is blocked by the one-way check valve. In the mode, the water flow in the brazed plate water heater is OFF. Both the indoor blower and outdoor fan are ON. EEV2 is fully open, while EEV1 control an optimum subcooling degree exiting the indoor air coil. The subcooling degree control adjusts excessive charge stored in the suction line accumulator and optimizes active charge in the system.

3) Dedicated water heating mode – DWH

The dedicated water heating mode uses outdoor air as the source. It operates when there is a single call for water heating. The compressor discharged gas through line 1, brazed plate heat exchanger, line 3, RV1, line 4, and expanded by EEV1, goes through the outdoor coil, and returns to the compressor suction through the lines 8, 9 and 12. 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. EEV2, connected to the indoor coil is closed, while EEV1, connected the outdoor coil, controls an optimum subcooling degree. The compressor runs at the top stage.

4) 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 like 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 an optimum subcooling degree. EEV1 manages the excessive charge located in the outdoor coil and suction line accumulator.

5) Combined space cooling and water heating in desuperheating - SCDWH

The combined space cooling and water heating mode in desuperheating operates when there is a single call for space cooling. In the meantime, the return water temperature at the tank bottom should be higher than the condensing temperature resulted by the space cooling operation, but lower than the compressor discharge temperature. Its flow path and operation are the same as the space cooling mode, while just having the water flow ON. Both the indoor blower and outdoor fan run. EEV1 is fully open while EEV2 controls the superheat degree at the indoor evaporator exit. This mode utilizes free desuperheater heat to slowly heat up the tank water without interrupting the major space cooling operation. The SCDWH mode is allowed when the tank top temperature is below a certain setting, e.g., 140˚F, and the tank bottom water temperature is below the compressor discharge temperature.

6) combined space heating and water heating in parallel condensing - SHPWH

The combined space heating and water heating mode operates when there are simultaneous calls for space heating and water heating. In the case, the return water temperature should be less than 70˚F. The refrigerant flow path for water heating goes through: compressor discharge, line 1, brazed plate heat exchanger, line 3, RV1, line 4; the space heating path goes through line 2, RV3, RV2, line 7 and has the indoor coil as an air heating coil; the water heating and space heating paths merge, expanded through EEV1, and has the outdoor coil as an evaporator, returns to the compressor through lines 8, 9 and 12. The water flow in the brazed plate heat exchanger is ON. Both the indoor blower and outdoor fan run. EEV2 is fully open. EEV1 control the discharge saturation temperature around 95˚F to 100˚F. The compressor runs at its top speed.

7) 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. The refrigerant flow path is like the SH mode. The water flow in the brazed plate heat exchanger is ON. Both the indoor blower and outdoor fan circulate air. EEV2 is fully open. EEV1 control an optimum subcooling degree.

This configuration will facilitate seamless mode transition on most occasions, with two notes. 1). the sequence to alter the flow directions in the three four-way valves should follow: Reversing valve 3→reversing valve 1→Reversing valve 2. 2). When switch from the SC mode to the SCWH mode, there could be a mismatch between the control behaviors between the two electronic expansion devices. It is suggested to hold EEV1 at a fixed opening for about 30 seconds before starting its subcooling degree control.

4. LABORATORY TESTS

A prototype CCIHP system, using R-410A, was built for laboratory testing. The prototype was built using a 4.5-ton two-stage heat pump rated at 54500 Btu/h cooling capacity, 16.0 SEER, 55000 Btu/h high heating capacity, and 9.0 HSPF; 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 Emerson. Three stages are achieved by using a typical two-stage scroll compressor in combination with a speed controller, as depicted in Figure 2. 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. Figures 3 and 4 illustrates the laboratory setups of the indoor and outdoor units. 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.

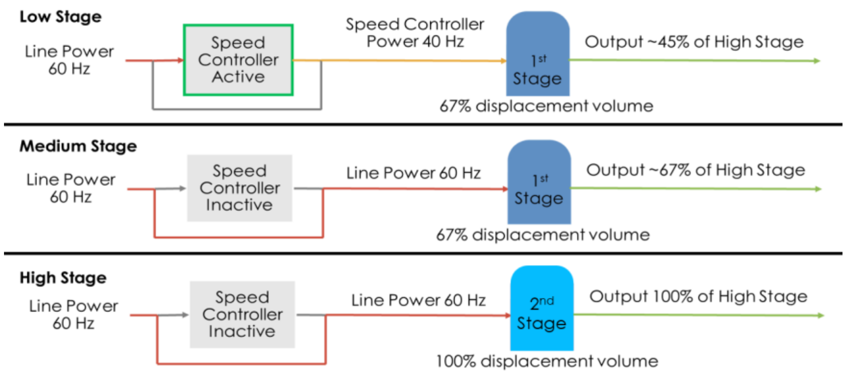

Figure 2: Diagram of speed controller and two-stage heat pump configuration used to achieve 3-stages of operation

Figure 3: Outdoor Unit Connected to Air Sampling Trees

Figure 4: Indoor Air Hander, Compressor, Suction Line Accumulator, Brazed Plate Heat Exchanger, and 50-gallon Water Tank

4.1 Space Cooling Performance

Table 1 presents the measured steady-state cooling performance results 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.

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

4.2 Space Heating Performance

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.

	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 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

	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

4.3 Combined Space Cooling and 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. Figure 5 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 6 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.

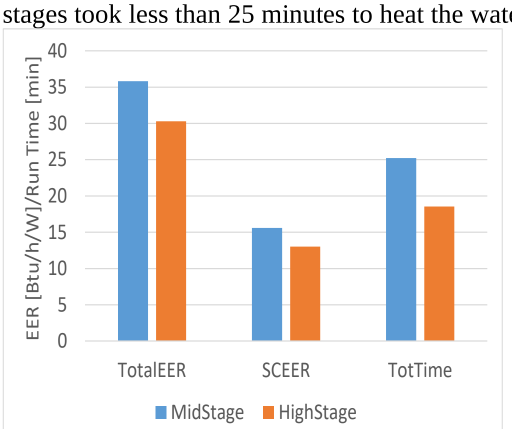

Figure 5: Space cooling and total EERs during SCWH mode.

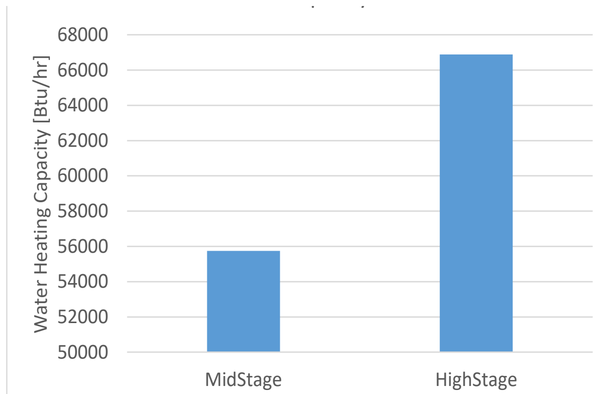

Figure 6: Water heating capacities during SCWH mode.

4.4 Dedicated Water Heating Performance

Figures 7 and 8 illustrate the performance of the dedicated water heating mode (DWH) using outdoor air source. Figure 7 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 8 shows the water heating COP, from 58˚F to 125˚F, water heating delivered) / (compressor power consumption + outdoor fan power consumption).

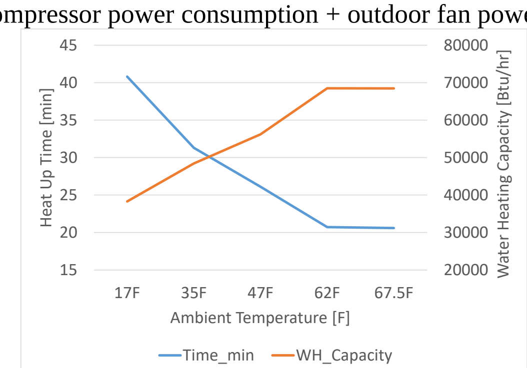

Figure 7: Water heating capacity and time of DWH, changing with ambient temperature.

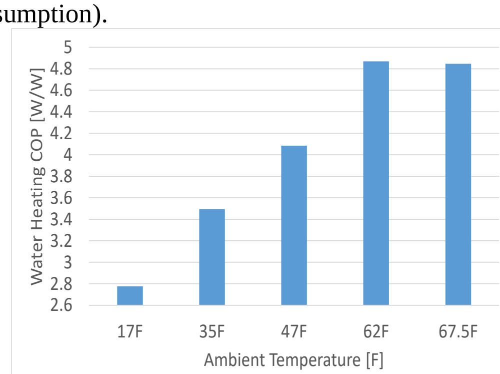

Figure 8: Water heating COP of DWH, changing with ambient temperature.

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, excluding the hot water circulation pump power.

4.5 Mode Transition

Figure 9 below depicts a mode transition from a space cooling mode to a combined space cooling and water heating mode in full condensing. The transition completed within one minute, indicating that the charge migration mechanism was successful.

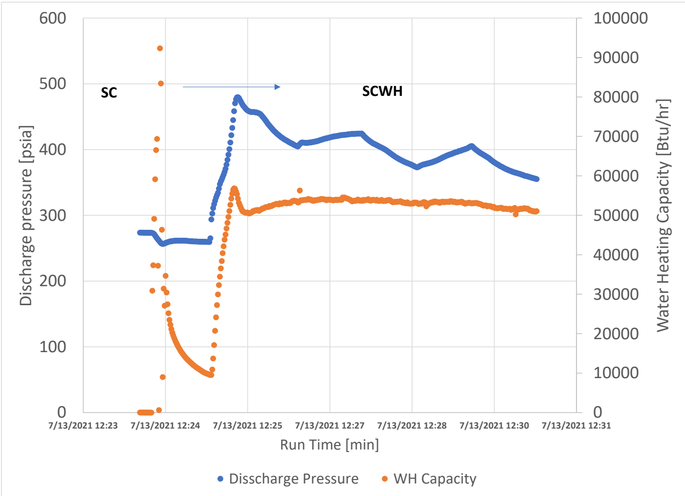

Figure 9: Mode Transition from SC mode to SCWH mode.

Figure 10 below depicts the transition from a SHPWH mode to a SHDWH mode. It plots the water heating capacity, compressor suction and discharge pressures as a function of the entering water temperature to the brazed plate heat exchanger. The working mode was changed from the parallel condensing to the desuperheater water heating operation smoothly when the return water temperature is higher than 70˚F. The water heating capacity dropped noticeably after switching to the desuperheater mode.

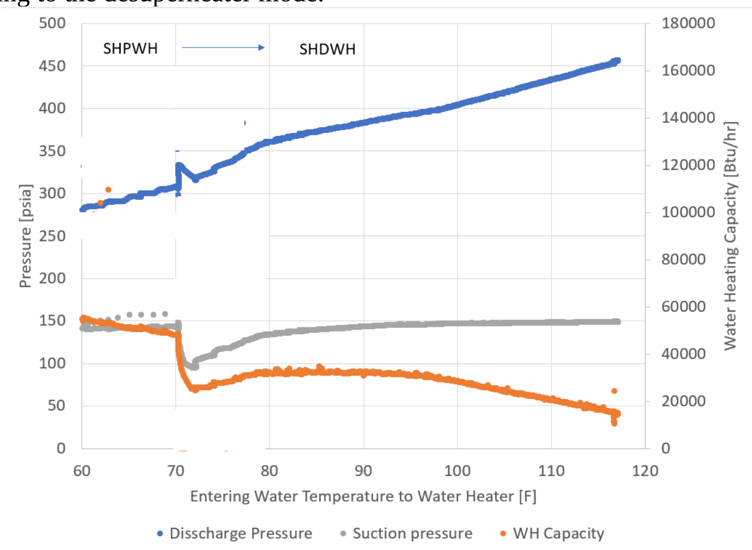

Figure 10: Mode Transition from SHPWH to SHDWH mode.

5. SUMMARY

Air-source integrated heat pumps are multi-functional, capable of meeting all home comfort requests, including space cooling, space heating, domestic water heating and energy storage. 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.

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 compressor discharge pressure as a function of the entering air and water temperatures.

The proposed multi-functional heat pump is capable of seven 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, DHR_{min}, Region IV). In the most efficient mode (combined space cooling and water heating mode), the unit reached a total energy efficiency of 35.0 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, 10 times faster than stand-alone heat pump water heaters. The heat pump water heating operated down to 17˚F, achieving a COP > 2.6, and heated a 50-gallon water within 1 hour.

NOMENCLATURE

ASIHP	Air source integrated heat pump
CCIHP	Cold climate, air source integrated heat pump
COP	Coefficient of Performance [W/W]
DHR	Design heating requirement
EER	Energy efficiency rating [Btu/hr/W]
EEV	Electronic expansion valve
HSPF	Heating Seasonal Performance factor [Btu/hr/W], following DHR_{min} load line, AHRI 210/240
HSPF2	Heating Seasonal Performance factor [Btu/hr/W], Appendix M1 load line, AHRI 210/240
RV	Four-way reversing valve
SEER	Cooling seasonal performance factor [Btu/hr/W]

REFERENCES

ASHRAE Standard 37, Methods Of Testing For Rating Electrically Driven Unitary Air-Conditioning And Heat-Pump Equipment, https://webstore.ansi.org/standards/ashrae/ansiashrae372009r2019

ANSI/AHRI Standard 210/240 (2017), Performance Rating of Unitary Air-Conditioning & Air-Source Heat Pump Equipment, Air Conditioning, heating and refrigerating institute.

COP 21 - Decisions | UNFCCC, 21st Conference of the Parties in Paris 2015, https://unfccc.int/process-and-meetings/conferences/past-conferences/paris-climate-change-conference-november-2015/cop-21/cop-21-decisions

DOE cold climate heat pump challenge, 2022, https://ene.org/wp-content/uploads/2021/12/DOE-CCHP-Tech-Challenge-Fact-Sheet-10-25-2021-FINAL.pdf

DOE, 2013, water heater test procedure rulemaking, https://www1.eere.energy.gov/buildings/appliance_standards/pdfs/water_heater_test_report_111413.pdf

New York, 2021, Statewide Greenhouse Gas Emissions Report, https://www.dec.ny.gov/energy/99223.html#:~:text=These%20requirements%20and%20goals%20include,70%25%20renewable%20electricity%20by%202030

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