Experimental Evaluation of a High-Performance Cold-Climate Heat Pump Using Tandem Vapor Injection Compressors

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ABSTRACT

A high-performance cold-climate heat pump (CCHP) was developed and experimentally validated through comprehensive laboratory and field testing. The system utilized two equal-size tandem vapor injection (VI) compressors with an inter-stage flash tank to improve performance and capacity retention under subfreezing conditions. Laboratory testing was conducted on a 3-ton prototype in a controlled environmental chamber equipped with calibrated thermocouples, refrigerant-side mass flow and pressure transducers, and precision airflow measurement for energy balance verification. The prototype achieved heating coefficients of performance (COPs) of 4.4 at 47 °F, 3.1 at 17 °F, and 2.0 at –13 °F, while maintaining 88% of its rated heating capacity at –13°F. These results confirm strong low temperature performance and indicate the potential for significant reductions in electric resistance backup use. A field prototype was installed and monitored in a residential building in Fairbanks, Alaska, during the heating season. Instrumentation included real-time power, temperature, and refrigerant state measurements to evaluate performance under dynamic outdoor conditions. The heat pump operated reliably down to –30 °F, delivering 75% of its rated heating capacity with a COP of 1.8, while maintaining stable operation, effective defrost control, and indoor comfort without auxiliary heating. The combined laboratory and field results demonstrate that the tandem VI compressor configuration provides a practical and energy-efficient approach for residential heat pumps designed for cold and very cold climate regions.

Introduction

Reliable heat pump operation in severe cold climates remains a major technical challenge for residential space heating. Space heating represents a substantial share of building energy consumption, as reported by the International Energy Agency (2024) and the U.S. Energy Information Administration (2020). At low ambient temperatures, conventional air-source heat pumps (ASHPs) experience reduced suction pressure, increased compression ratio, elevated discharge temperature, and lower refrigerant mass flow rate. These effects result in diminished heating capacity and declining coefficient of performance (COP).

Vapor injection (VI) has been widely investigated as an effective method to extend the low temperature operating envelope of ASHPs. By introducing intermediate-pressure vapor into the compression process, VI increases condenser mass flow rate, moderates discharge temperature, and enhances heating capacity under sub-zero conditions (below 0 °F). Because it

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modifies the compression process rather than requiring an entirely different system architecture, VI is considered suitable for residential applications.

Experimental studies consistently demonstrate the benefits of vapor injection across refrigerants and system capacities. Ma et al. (2003) and Ma and Zhao (2008) reported significant heating capacity improvement at 5 °F in R22 systems. Liu et al. (2008) validated VI performance enhancement in small-capacity units. For R410A systems, Wang et al. (2009), Xu et al. (2011), Christian et al. (2014), and Zhang et al. (2019) demonstrated stable operation around 0 °F with improved COP and capacity retention. Qin et al. (2015) and Kang et al. (2018) further extended performance evaluation to −4 °F conditions. More recently, Fan et al. (2022) showed that optimized injection control can deliver high COP under moderately cold conditions.

Although these investigations confirm the thermodynamic advantages of vapor injection, most prior work has focused on laboratory-scale evaluations or modified commercial units. Integrated residential prototypes designed specifically for sustained operation below −13 °F, together with field validation under extended sub-zero conditions, remain relatively limited.

The present study develops residential cold-climate heat pump (CCHP) prototype incorporating optimized vapor injection technology. The systems are designed to retain at least 75% of rated heating capacity at −13 °F relative to 17 °F and to achieve a heating COP greater than 4.0 at 17 °F. Performance evaluation combines controlled psychrometric chamber testing with field demonstrations in Fairbanks to assess capacity retention, performance trends, and defrost behavior under realistic operating conditions.

Methodology

Laboratory Setup

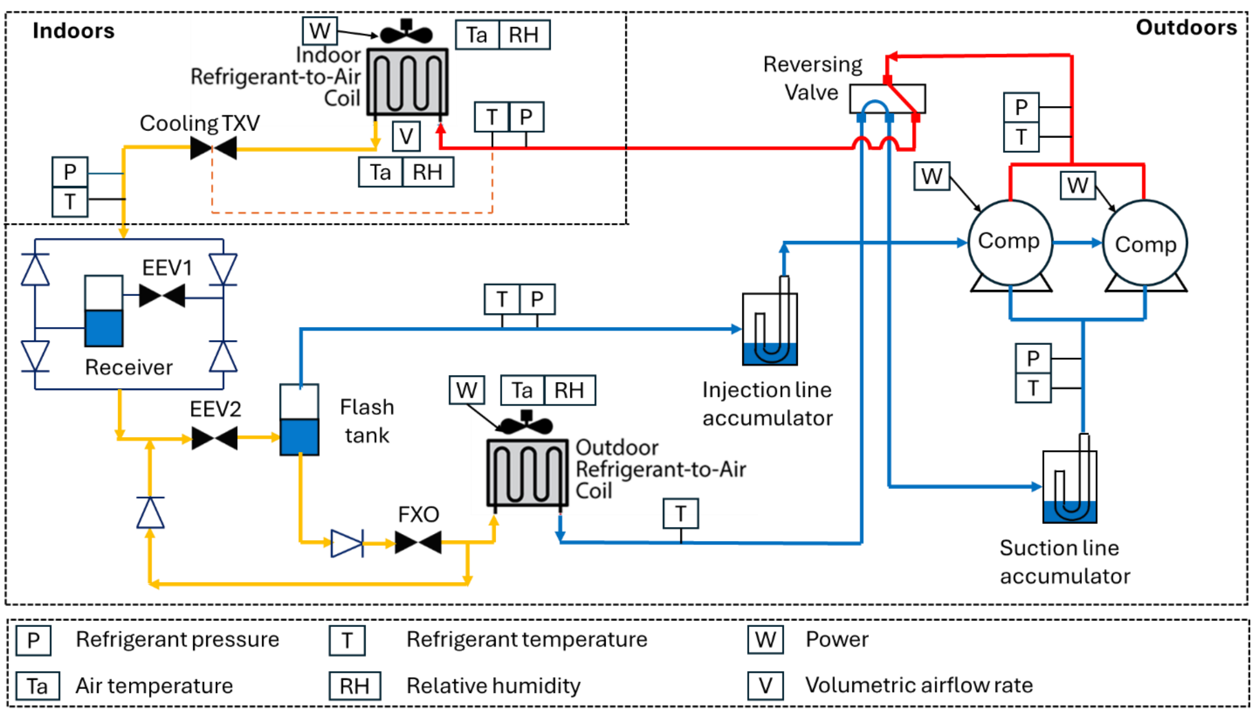

Figure 1. System schematic of the CCHP using tandem compressors with vapor injection (Hu and Shen, 2026)

The layout of the CCHP using tandem compressors with vapor injection is shown in Figure 1. The VI configuration integrates several pieces of hardware along the liquid line: a receiver with an electronic expansion valve (EEV1) to adjust the refrigerant inventory, a flash tank paired with another expansion valve (EEV2) to establish the injection pressure and supply saturated vapor to the compressor's injection port, a fixed-orifice device (FXO) with a check valve for heating operation, and a bypass loop with a check valve for cooling-cycle flow management.

The cold-climate heat pump prototype originated from a conventional 5-ton fixed-speed air-source heat pump (ASHP) rated at 60,000 Btu/hr in cooling and a heating seasonal performance factor (HSPF) of 8.5, equivalent to a seasonal average heating COP of 2.49. For the modified design, the single compressor was replaced with a tandem arrangement consisting of two 3-ton fixed-speed units, each with a rated cooling capacity of 36,000 Btu/hr. The system was designed so that one compressor alone could satisfy a typical 3-ton cooling demand, while the heat exchangers retained their original 5-ton sizing. This intentional oversizing of the coils under single-compressor operation—whether in cooling or in mild-weather heating—reduces thermal resistance and increases both heat-exchange performance and system COP. Indoor supply air was provided by a two-speed indoor blower fan, which delivered 1750 CFM at 460 W in high-speed operation and 1420 CFM at 270 W in low-speed mode. The outdoor fan ran at a constant rotational speed, consuming approximately 300 W.

In the heating mode, the thermostatic expansion valve (TXV) remains open and inactive, enabling EEV1 to fine-tune system subcooling through refrigerant charge control. EEV2 sets the flash-tank pressure to produce the vapor fraction required for injection, while the FXO acts as the main expansion device feeding the evaporator. When cooling, the TXV resumes its throttling function, EEV1 continues to manage liquid-line subcooling, EEV2 closes completely, and the check valve isolates the FXO path so that it remains out of operation.

Table 1. Uncertainty analysis

Name	Parameters (Range)	Uncertainty
Thermocouple	-328-500 °F	±0.5°F
Relative humidity	0-95%	±3%
Refrigerant pressure	0–1000 PSIA	±0.25%
Volumetric airflow rate	0-2133CFM	±2%
Refrigerant mass flow rate	0–1100 lb/hr	±0.2%
Compressor power	0-10 kW	±0.2% F.S.
Indoor blower, outdoor fan	0-1kW	±0.2% F.S.
Capacity	-	4.67%
COP	-	4.75%

Airflow through the indoor unit was determined using a Pitot-tube array positioned at the air-handler outlet. Temperature readings were captured with a nine-point (3×3) thermocouple grid spanning the return and supply air streams, and an additional sensor measured the outdoor air entering the condenser coil. Relative humidity was tracked at the centers of both air streams using dedicated sensors. Electrical energy consumption of each major component—the compressor, indoor fan, and outdoor fan—was monitored separately with precision power transducers. Across the refrigeration loop, distributed pressure sensors and thermocouples provided continuous tracking of temperature and pressure conditions. System heating and cooling capacities were derived from the measured changes in air-side enthalpy. Details of instrument specifications, including ranges, accuracies, and propagated uncertainties in the derived capacity and COP values, are presented in Table 1.

Laboratory Test Matrix

Table 2. Test matrix

Condition	Indoor condition Dry-/wet-bulb (°F)	Outdoor condition Dry-/wet-bulb (°F)	Compressor
1	70.0/60.0	62.0/56.5	1
2	70.0/60.0	47.0/43.0	1
3	70.0/60.0	35.0/33.0	1, 2
4	70.0/60.0	17.0/15.0	1, 2
5	70.0/60.0	-13.0/-	2

Table 2 presents the test matrix for both cold-climate heat pump (CCHP) prototypes, developed following the guidelines of AHRI Standard 210/240 (AHRI, 2024). Test Conditions 1 through 4 correspond to representative heating season scenarios, while Condition 5 reflects system operation under extreme low temperature conditions.

Field Study

Figure 2. Field study of the CCHP using tandem compressors with vapor injection

Figure 2 shows the field-installed configuration of the CCHP equipped with tandem compressors and vapor injection. The prototype was based on a baseline 5-ton R-410A heat pump originally rated at an HSPF of 8.5 and a SEER of 15.5, with identical instrumentation to that used in laboratory testing. Field evaluation was conducted in partnership with the Cold Climate Housing Research Center (CCHRC) in Fairbanks, Alaska, utilizing their controlled testing facility. Although this facility does not replicate a typical residential or commercial setting, it enabled systematic exposure of the heat pump to rigorous sub-arctic winter conditions. The heating trial spanned from September to March, during which the system operated solely in heating mode, consistent with the site's exclusively heating-dominated climate. Field study data were analyzed using 5.0 °F temperature bins.

Results and Discussion

Laboratory Study

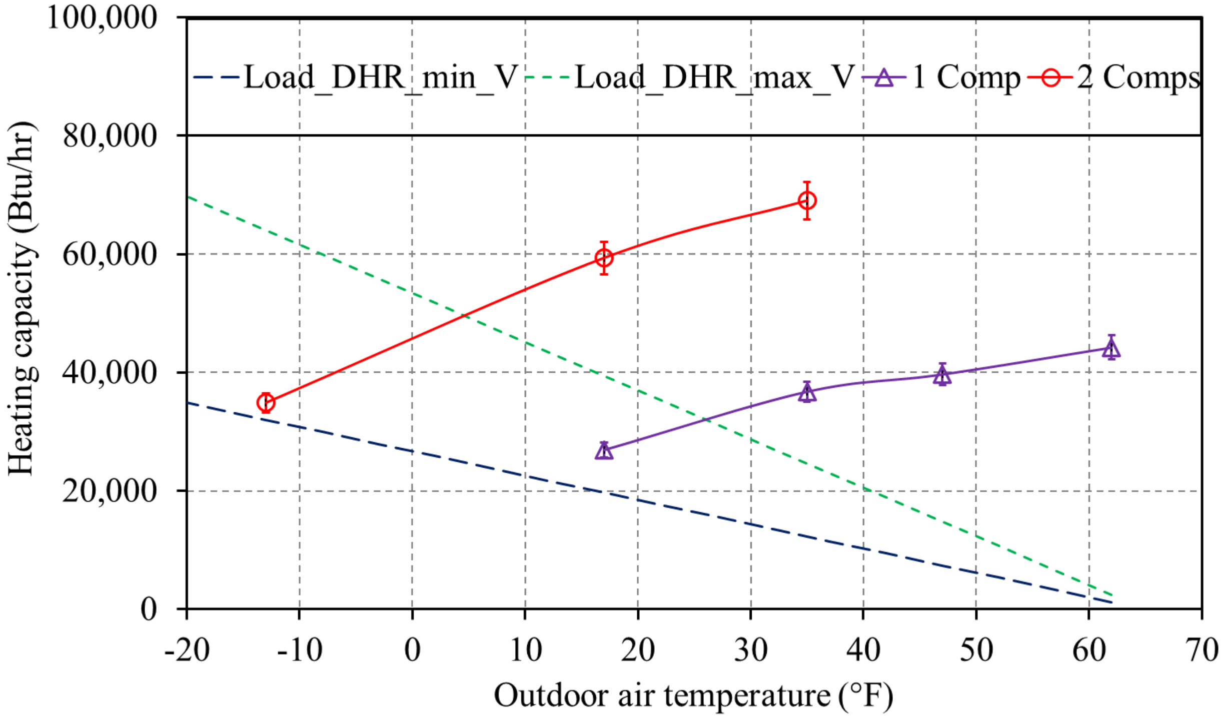

Figure 3. Heating capacity of the CCHP using tandem compressors with vapor injection

Figure 3 presents heating capacity of the CCHP using tandem compressors with vapor injection. Capacity consistently declines as outdoor temperature decreases. When operating with a single compressor, capacity drops by about 35% as the ambient temperature decreases from 47.0 °F to 17.0 °F. Even at the lowest test point of −13 °F, the system preserved more than 75% of the rated capacity at 47.0°F (approximately 39720 Btu/hr). Under the Region V climate scenario, this prototype satisfies the minimum design heating requirement (Load_DHR_min) for well-insulated buildings without the need for auxiliary electric heating.

Figure 4 illustrates how the heating COP of the tandem compressors varies with outdoor temperature. The system demonstrates the expected trend of declining COP as ambient temperature decreases. During two compressors' operation, the COP decreases by roughly one-third (about 33%) when the temperature drops from 17 °F to −13 °F. Despite the harshest test condition, the system n sustains a COP around 2.0, with compressor discharge temperatures remaining below 213 °F—comfortably within the design threshold of 280 °F.

Figure 5 presents the supply air temperatures delivered by the vapor injection (VI) system. The VI prototype produced adequate heating capacity to sustain high-speed airflow throughout the full range of test temperatures, even under extreme conditions. Across all cases, the system maintained supply air temperatures above 88.0 °F at ambient temperatures as low as −13 °F, ensuring acceptable thermal comfort.

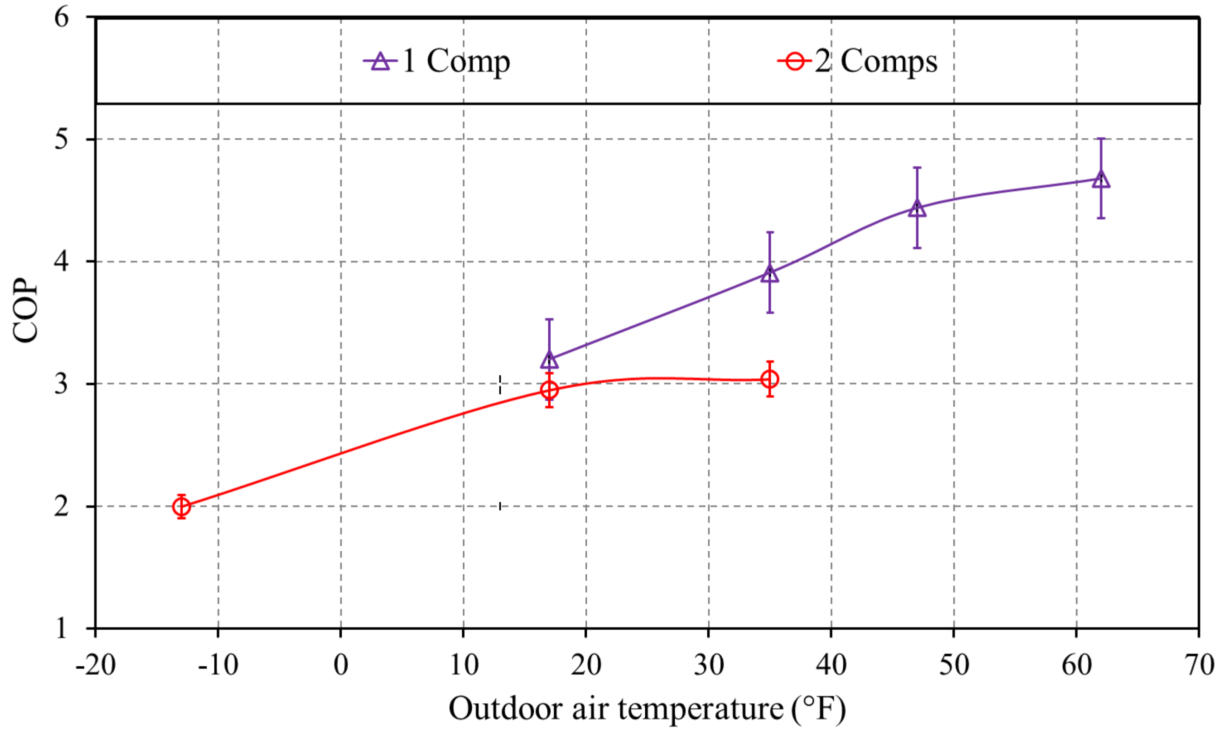

Figure 4. Heating COP of the CCHP using tandem compressors with vapor injection

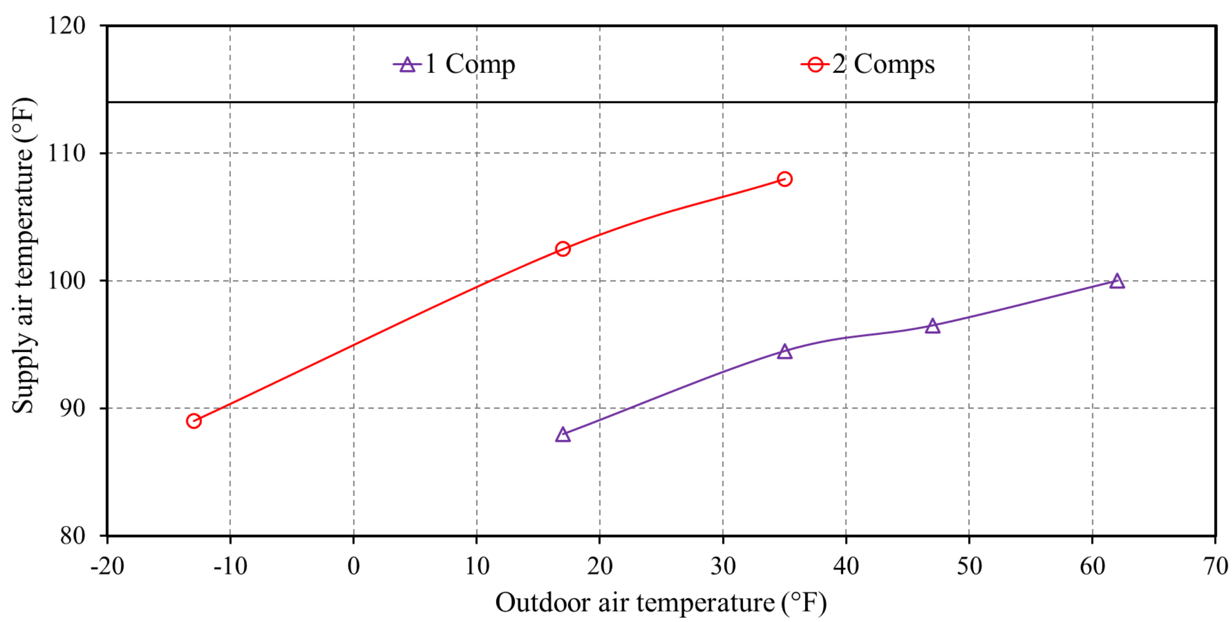

Figure 5. Supply air temperature of the CCHP using tandem compressors with vapor injection

Field Study

For the vapor injection (VI) configuration, heating performance was analyzed over outdoor temperatures ranging from −30.0 °F to 60 °F, grouped in 5.0 °F intervals.

Cooling-season testing was not conducted, as the facility lacked a cooling load. The prototype also omitted electric resistance backup heat since the building was already equipped with a hydronic heating system that served as the auxiliary source.

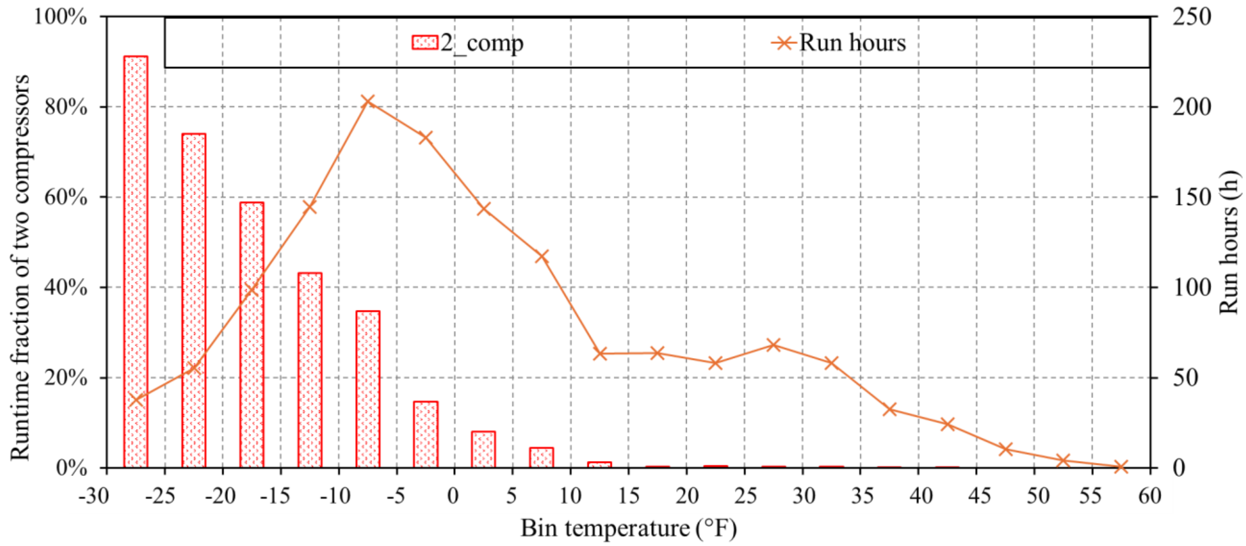

Figure 6. Runtime fraction of two compressors and total runtime of the prototype system

Figure 6 illustrates how the second compressor's operating fraction varied with outdoor temperature. Its share of total runtime rose steeply once ambient conditions fell below 0 °F, reaching approximately 90% at −30 °F. This trend demonstrates that the prototype maintained sufficient reserve heating capacity to satisfy the laboratory load even under the most severe cold-weather conditions.

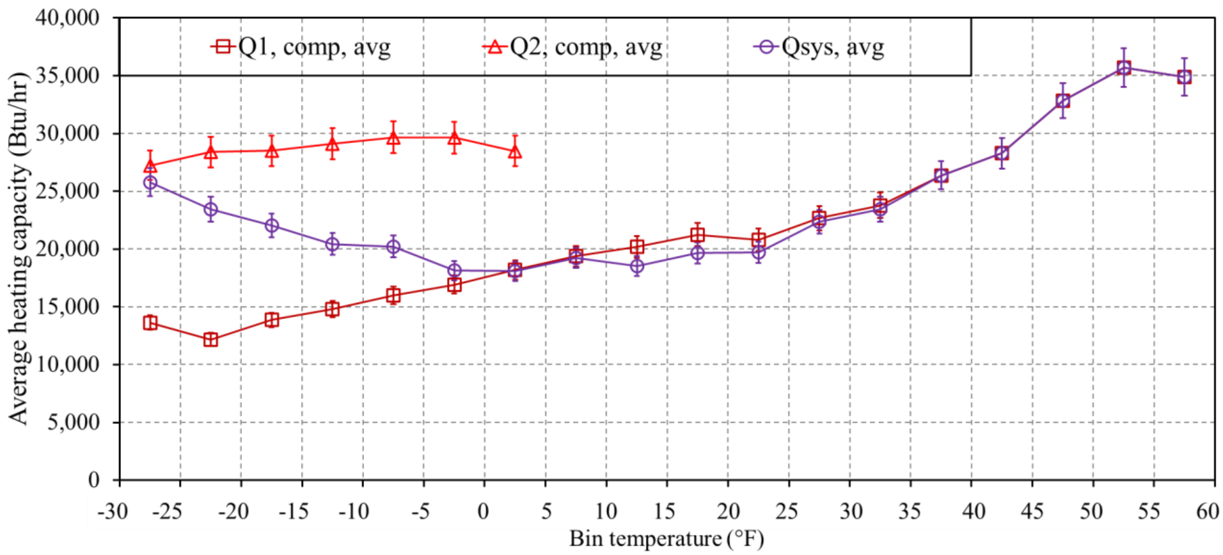

Figure 7. Average heating capacity of the prototype system

Figure 7 compares the average heating capacities achieved during single- and dual-compressor operation. At an outdoor temperature of −30.0 °F, operation with both compressors yielded an average heating capacity of 27, 233 Btu/hr—about 75% of the rated capacity at 47.0 °F (36,000 Btu/hr). As the ambient temperature rose above roughly 0°F, the average capacity declined because single-compressor operation became predominant (see Figure 6). Conversely, at temperatures below 0 °F, the extended operation of both compressors—reaching up to 90% of total runtime at −30.0 °F—allowed the system to maintain heating output consistent with the building's load demand.

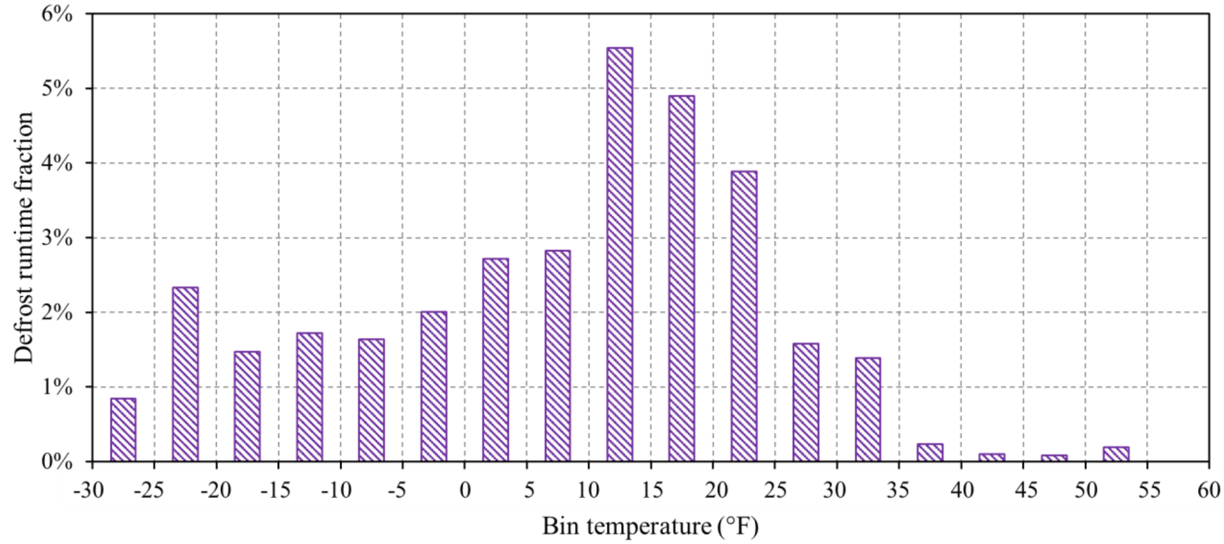

Figure 8. Defrost runtime fraction of the prototype system

Figure 8 illustrates the proportion of time the heat pump spent in defrost relative to total operating time at each temperature bin. As shown, defrost events occurred infrequently. At temperatures conducive to frost formation, the system typically ran one compressor, and the oversized outdoor coil promoted higher evaporating temperatures that slowed frost accumulation. Under colder conditions, where both compressors were active, the extremely low ambient humidity further suppressed frost development, resulting in minimal defrost activity throughout the heating season.

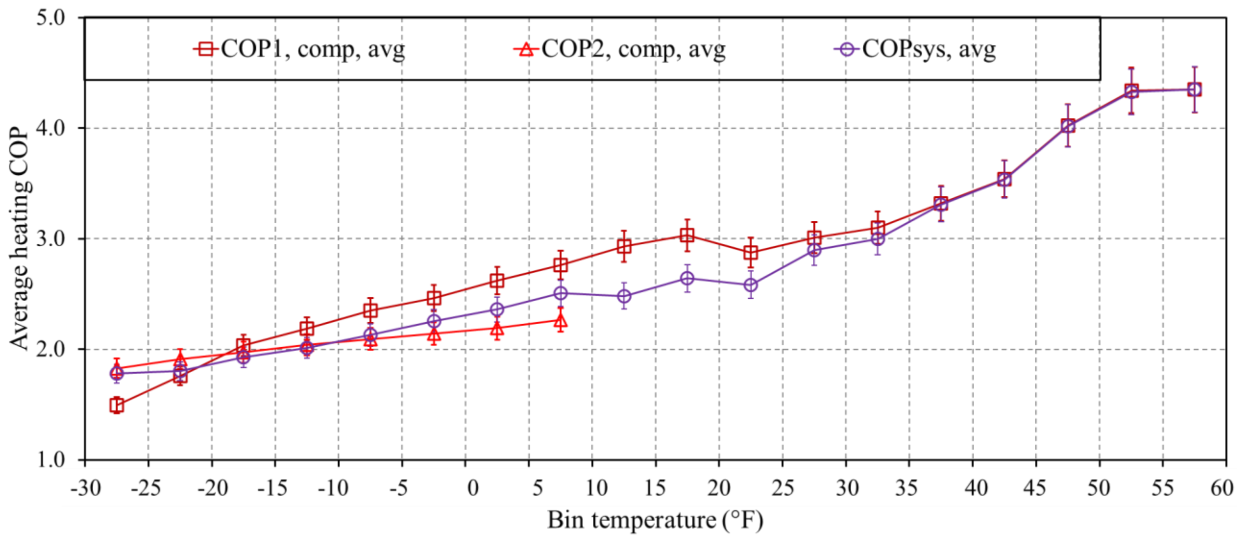

Figure 9. Average heating COP of the prototype system

Figure 9 summarizes the average field COP for single- and dual-compressor operation in each outdoor temperature bin, together with the overall system COP that accounts for cycling, defrost, and compressor staging. During defrost events, both compressors operated in reverse cycle mode. In the 45.0–50 °F bin, the average system COP was 4.0—about 12% lower than steady-state laboratory values due to cycling losses. At −13 °F and −27 °F, average system COP values were approximately 2.0 and 1.8, respectively, which is still around 80% higher in energy performance than electric resistance heating with COP = 1. Interestingly, below roughly −15 °F, dual-compressor operation produced a higher COP than single-compressor operation, underscoring the benefit of vapor injection at extreme low temperatures by improving mass-flow utilization and mitigating thermodynamic losses even as both compressors are engaged.

Conclusions

The combined laboratory and field evaluations demonstrate that the tandem vapor injection cold-climate heat pump meets its primary design goals of high performance, strong capacity retention, and reliable operation across a broad range of subfreezing conditions. In controlled chamber tests, the 3-ton R410A prototype with tandem compressors and an inter-stage flash tank maintained roughly 88% of its rated heating capacity at −13 °F, achieving COPs of 4.4 at 47 °F, 3.1 at 17 °F, and 2.0 at −13 °F, with measurement uncertainties in capacity and COP below about 5%. These results confirm that the combination of vapor injection and oversized indoor/outdoor coils effectively mitigates low-temperature performance degradation typical of conventional air-source heat pumps.

Field monitoring in a residential-scale facility in Fairbanks, Alaska, further verified robust performance under realistic cold-climate operation. The prototype operated reliably down to approximately −30 °F, delivering about 75% of rated capacity with an average COP of 1.8, maintaining comfortable supply air temperatures, and requiring only limited defrost time due to the oversized outdoor coil and low ambient humidity. At very low temperatures, dual-compressor vapor injection operation provided higher COP than single-compressor operation, underscoring the value of optimized injection and staging control in extreme cold. Overall, the results indicate that tandem vapor injection systems can substantially reduce dependence on electric resistance backup in cold and very cold climate zones using a platform that remains compatible with typical residential equipment configurations.

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