Development and Testing of an Advanced Cascaded Thermoelectric Residential Heat Pump

Dr. Sreenidhi Krishnamoorthy, Electric Power Research Institute
Don Shirey, Electric Power Research Institute
Dr. Bo Shen, Oak Ridge National Laboratory

ABSTRACT

Electricity-driven heat pumps using vapor compression cycle are an energy-efficient solution to replace fossil fuel burning and reduce greenhouse gas emissions for space heating in residential buildings. However, heating capacity and Coefficient of Performance (COP) of heat pumps degrade significantly with increasing temperature difference between ambient and indoor environments. Residents and building owners are hence reluctant to fully embrace electric heat pumps. The use of conventional all-electric heat pumps also causes concern for electric utilities due to an increased winter peak demand arising from the use of supplemental electric resistance heaters.

Our research is an attempt to alleviate these concerns by designing and laboratory testing a thermoelectric (TE) heat pump cascaded with a vapor compression cycle to enhance heating capacity and COP. TE modules increase the subcooling in the refrigerant liquid of the vapor compression cycle to enlarge the evaporating capacity and works at an efficiency greater than a conventional electric resistance strip. This results in a simple, affordable, efficient and highly controllable solution to adequately meet space heating needs in dwellings. The laboratory testing of the 3-stage cascaded TE heat pump performed in this research has exhibited a higher heating capacity by above 15%, while maintaining a heating COP of 2.0-3.6 in the ambient temperature range of -18˚C to 8˚C (0˚F to 47 ˚F), which represents more than 60% of winter temperatures observed in US. If successfully commercialized, this technology can advance space-heating electrification by overcoming consumer cost barrier of heat pumps.

Introduction

Electricity-driven heat pumps using a vapor compression cycle are an energy-efficient solution to replace fossil fuel burning and reduce greenhouse gas emissions (Walker et al. 2022; Krishnamoorthy 2023). However, majority of heat pumps being sold and installed in U.S. homes and small commercial buildings are air-source heat pumps that either meet or slightly exceed the federal minimum efficiency standards. When the outdoor air temperature drops below about -1°C (30°F), their heating capacity and COP degrade significantly due to the temperature difference between the source side and demand sides in the cycle. Baxter and Groll (2017) found that the heating capacity of a single-speed heat pump at -25°C (-13°F) outdoor temperature decreases to 40% of the rated heating capacity at 8°C (47°F). Additionally, conventional heat pumps tend to be sized and optimized for cooling operation. Consequently, in the colder months of the year they must be supplemented by another, less efficient heating source, such as electric resistance or a natural gas furnace, in order to provide additional warmth which increases the overall equipment and energy costs. Due to these issues, residents and building owners, particularly those living in colder climates, are reluctant to switch from natural gas, propane, or other fossil fuel furnaces to electric heat pumps for space heating. The use of conventional all-electric heat pumps also causes concern for electric utilities due to an increased winter peak demand arising from the use of supplemental electric resistance heaters.

Industry efforts have resulted in the development of special, advanced cold climate heat pumps that are suited for US cold climates. Various cold climate heat pump solutions such as variable-speed systems, vapor-injected compressors, ground-source heat exchangers, etc. have been outlined in the literature (Chua et al. 2010; Xu, Hwang and Radermacher 2011; Sarkar 2012; Zhang et al. 2018; Valancius et al. 2019; Wan and Hwang 2023). Despite these efforts, large scale adoption of these technologies in the residential sector become difficult since these heat pumps need expensive components that elevate the overall consumer cost, and their sophisticated operation require specialized HVAC contractor training. Retrofittability is another main concern in existing buildings. Simple and cost-competitive technologies must be identified and developed that provide adequate heating energy needs in extreme winter seasons and reduce the reliance on low-efficiency resistance strip or fossil-fuel furnaces for heating.

U.S. Department of Energy is promoting research in non-vapor-compression HVAC technologies (DOE 2014). A potentially revolutionary non-vapor-compression mechanism is to use thermoelectric (TE) technology that can use DC electricity to pump heat from a low temperature heat source to a high temperature sink via the Peltier effect (cooling of one junction and heating of the other when electric current is maintained in a circuit of material consisting of two dissimilar conductors) (Britannica 2021). (Figure 1). TE heat pumps have been widely applied in the electronics cooling industry for several years (Kazmierczak 2008), and manufacturers currently produce TE modules with COP exceeding 3.0 for a temperature lift (ΔT) of 10K (18R) (TE Technology Inc 2021). For heating applications, the TE technology is still fairly new, but has grown appreciably over the past decade. Patel and Gluesenkamp (2017) demonstrated the technical feasibility of TEs for heating through a thermoelectric clothes dryer; while Okuma et al. (2012) incorporated TE modules as an intermediate stage in a two-stage vapor compression system with a vapor injection compressor to enhance space heating capacity of a heat pump in cold climates. The main shortcoming in the use of TE for space heating is the lack of experimental results (Wang, Carlos and YaoDong 2017). The current work of designing a TE based cascaded cold climate heat pump attempts to overcome that shortcoming. Additionally, the fact that TE elements are compact, low-cost, and widely available in the market will render a more affordable cold climate heat pump. As an illustration of cost-efficiency of TEs, a 150 W TE module costs less than $7.0[1]. The current work describes a full-scale prototype design, and laboratory testing of a TE integrated cold climate heat pump, and this research is intended to ultimately increase the body of knowledge in this area.

Design and Experimental Setup

The design of the TE integrated, “vapor-compression – thermoelectric cascade” heat pump developed in this current work is shown schematically in Figure 2. Basically, it consists of a 2-stage conventional split-system vapor compression residential heat pump, whose indoor air handling unit (AHU) has been enhanced with two key components, (1) a supplemental coil and (2)

---

[1] Average market price offered by multiple vendors

a TE subcooler. The supplemental coil (yellow coil in Figure 2) is a one-row microchannel heat exchanger located downstream of the main air handler coil (green coil in Figure 2) and has approximately 60% frontal area as the main air handler coil. It has been added to augment the indoor heat exchanger surface area, and thereby increase condensing capacity and heating efficiency of the heat pump. The TE subcooler consists of an array of forty 60 W TE modules arranged in series, sandwiched between two capillary tube bundles located on either side of the TE array. These capillary tube bundles transport refrigerant in counterflow direction. The TE subcooler is shown in greater detail in Figure 3 and Figure 4. The TE modules act as heat pumps when energized with DC electricity. With a heating COP higher than that of a resistance strip (i.e. COP > 1), they create temperature difference of up to 20K (36R) between the two capillary tube bundles (i.e. renders refrigerant flowing in one side of the capillary tube bundles cold and the refrigerant flowing through the other side capillary tube bundles hot).

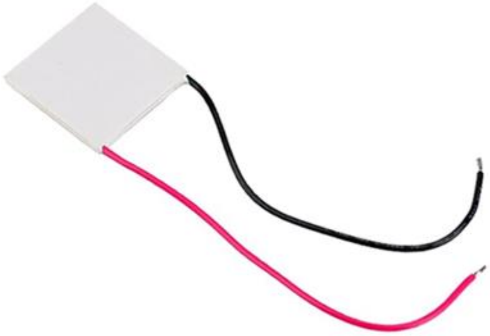

Figure 1. 150 W Thermoelectric module 40mm x 40mm x 3.2mm.

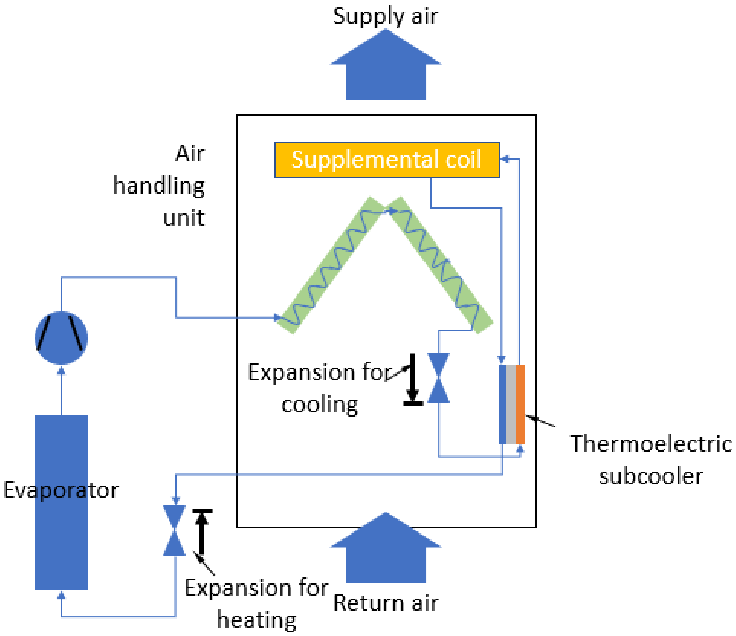

Figure 2. Schematic diagram showing the placement of a TE subcooler and a supplemental coil in AHU

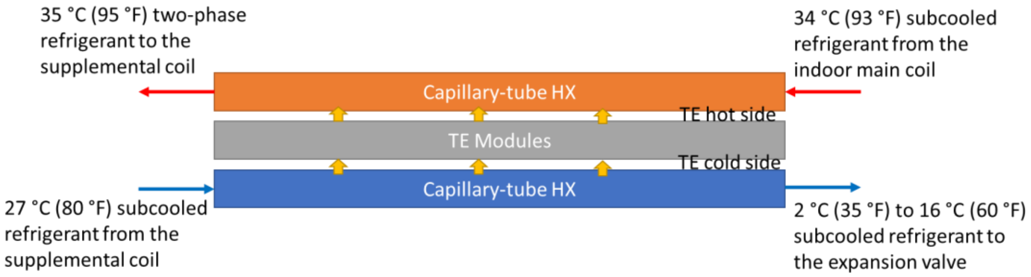

Figure 3. Schematic representation of the TE subcooler

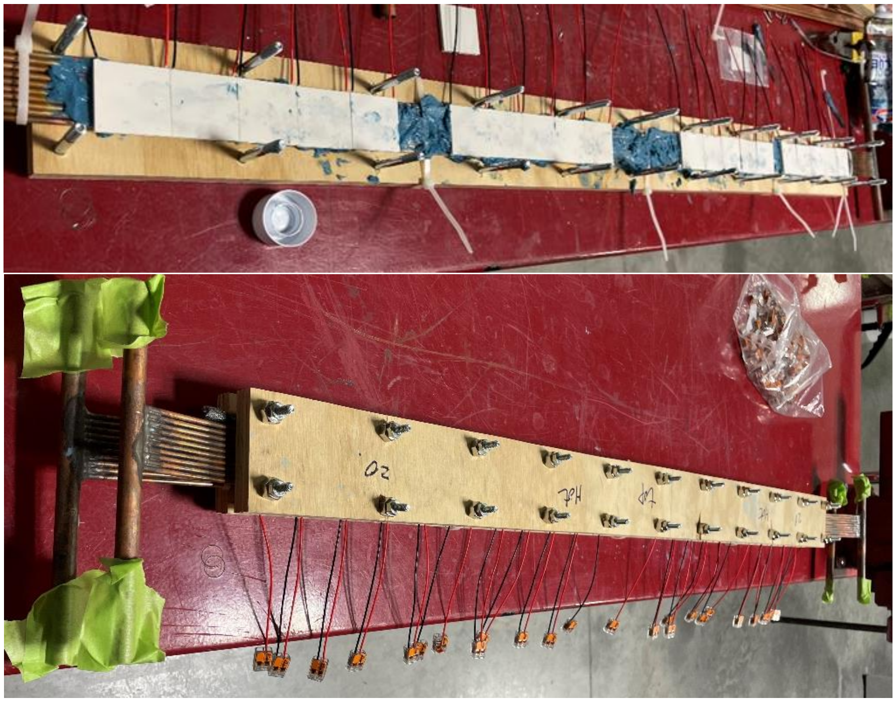

Figure 4. TE subcooler with capillary tube bundles, constructed in the laboratory

From the point of view of the modified AHU (Figure 2), this means that the cold side of the TE subcooler extracts heat from subcooled refrigerant as it leaves the supplemental heat exchanger while the hot side of the subcooler rejects heat to the refrigerant exiting the main air handler coil (indoor condenser coil). Within the hot side of the capillary tube bundles, some of the refrigerant is evaporated, raising its quality. This higher enthalpy refrigerant flows to a supplemental coil to further heat the supply air. In this way, our heat pump consisting of the additional components enhances heating capacity due to reducing the evaporator inlet quality, without needing to use a larger compressor.

Instrumentation and Test Plan

The heat pump that is fabricated and tested in this experimental work is a split system residential heat pump whose outdoor unit has a two-speed scroll compressor, an outdoor coil, an accumulator, and a reversing valve. The heat pump was tested in HVAC chambers fully simulating a residential indoor space and an outdoor space (ambient). Instrumentation on the outdoor unit consists of pressure transducers, temperature sensors, and mass flow meter which are installed for refrigerant side measurements. On the AHU, the power supplied to the TE subcooler and power consumed by the indoor blower are measured. An evaluation of available power sources was performed, and a low-cost AC to DC converter power source was selected and used for powering the TE modules in the TE subcooler, thereby minimizing the total cost of the system. Additionally, the temperature and humidity of the return air, supply air and outdoor air was also measured. These measurements are adequate to calculate the heating capacity and heating COP, using the methods set forth in ANSI/AHRI Standard 210/240 (2008). Heating capacity can be computed using either air-side enthalpy or refrigerant-side enthalpy methods. Because the TE subcooler was primarily intended to enhance heating performance by altering refrigerant state points, the primary method for calculating the heating capacity was based on the refrigerant-side enthalpy, with the air side serving as a validation. The laboratory prototype of the instrumented TE based heat pump is shown in Figure 5.

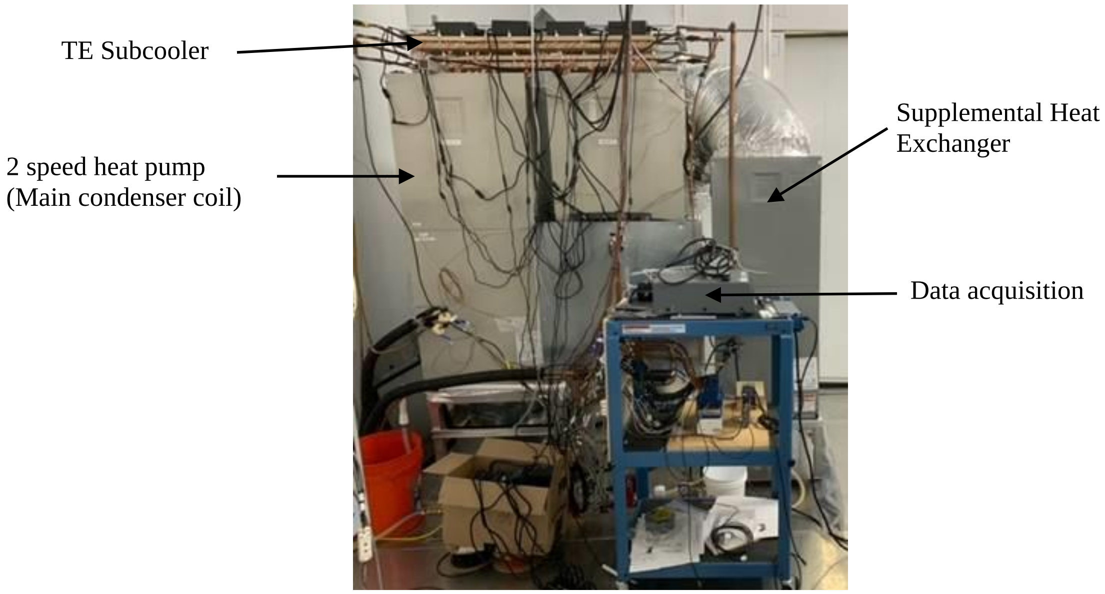

Figure 5. Laboratory prototype of the vapor compression heat pump cascaded with a TE heat pump

Prior to the experimental tests conducted on the TE integrated heat pump, the performance of the conventional heat pump without modifications to the AHU is first recorded through laboratory experiments. Testing is performed at two speeds of operation for the conventional heat pump with the ambient laboratory temperature set at 8˚C (47˚F), 2˚C (35˚F) and -8˚C (17˚F). For the TE integrated heat pump, additional testing is conducted at lower ambient temperatures of -15˚C (5˚F) and -18˚C (0˚F), besides the three test points at which the conventional heat pump is tested. All measurements are recorded during steady state operation of the heat pump and the data is recorded during a half-hour period after the unit has achieved a steady state lasting more than half an hour.

Experimental Test Data Analysis

Figure 6 shows the measured heating capacity in the experiments plotted as a variation of the measured ambient laboratory temperature for multiple stages of operation. Two sets of plots are shown. One set is for a baseline, conventional heat pump that does not have the enhancements of the TE integrated heat pump (purple and green dots in Figure 6). The second set of plots is for the TE integrated heat pump (grey, orange, and blue dots in Figure 6). For the conventional heat pump, the graph is plotted for two stages of operation, namely, (1) low speed (purple dots) and (2) high speed (green dots); while the TE integrated heat pump plot contains an additional third stage, namely “high speed with TE on” (blue dots), apart from the “low speed TE off” (grey dots) and “high speed TE off” (orange dots) stages.

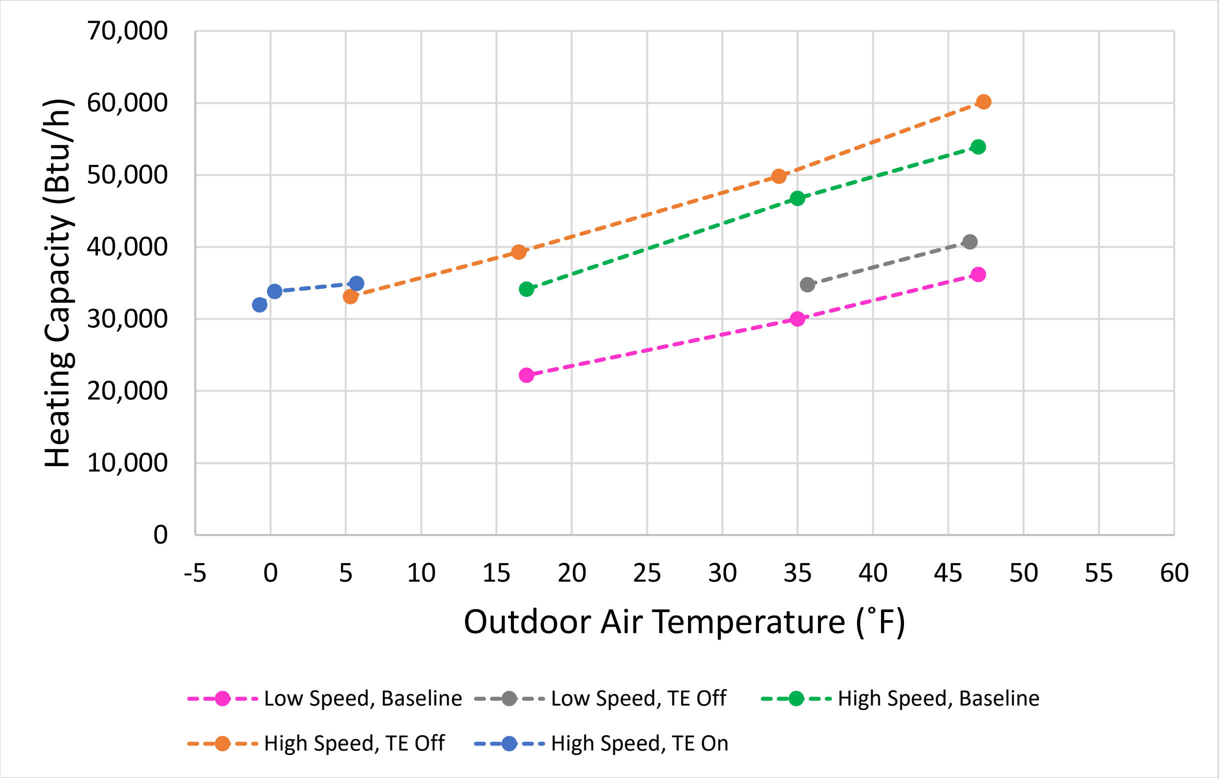

Figure 6. Heating capacity versus outdoor air temperature for the cascaded TE heat pump

Heating Capacity Impacts

The measured heating capacity trend reveals a boost for the heating capacity of the TE integrated heat pump system ranging from 7% to 15% even when the power to the TE subcooler turned off. This is because the extra heat exchanger area provided by the supplemental coil boosts capacity (more convective heat transfer surface area). TE modules are energized with electricity at or below -15˚C (5˚F), and data points are recorded at -15˚C (5˚F) and -18˚C (0˚F). At these low ambient temperatures, additional increase in the heating capacity by 5% to 8% is seen. The key reason for this increase is that the TE subcooler integration allows the liquid refrigerant to undergo additional subcooling than the degree of subcooling observed in conventional heat pump, before entering the evaporator coil. It is noteworthy that the strategy of creating additional refrigerant subcooling to increase heating capacity at lower outdoor air temperatures is already being incorporated into current commercial cold climate heat pumps that use vapor injection. A vapor injection compressor coupled with an economizer decreases the liquid refrigerant temperature by expanding part of the refrigerant liquid to an intermediate pressure/temperature to absorb heat from the liquid refrigerant. The expanded refrigerant stream comes back to the compressor injection port while the remaining refrigerant enters the evaporator with lower quality. This results in higher capacity and efficiency than conventional heat pumps at low ambient temperatures. However, this a complex and expensive method. The TE integrated heat pump achieves the same effect of reducing the evaporator inlet enthalpy without needing the complicated vapor-injection configuration, phase separation and associated control devices. Ultimately, both the extra heat exchanger and TE elements will be able to boost capacity of the TE integrated heat pump compared to a conventional heat pump by more than 15%. Finally, considering that the nature of small percentage changes, follow up testing is recommended to check the variability in experimental data.

Impact of TE Input Power on Heating Capacity

To analyze the sensitivity of the input power supplied to the TE subcooler on the total heating capacity, the third stage of the TE integrated heat pump is tested with two different input power values. The resulting heating capacities obtained are shown in Figure 7. At the lower input power supply setting of 286 W (975 Btu/h) to the TE subcooler, the heating capacity output by the TE subcooler is 730 W (2,500 Btu/h) when the ambient temperature is -18˚C (0˚F), and it is 500 W (1,700 Btu/h) when the ambient temperature is -15˚C (5˚F). However, when the power input to the TE subcooler is increased to 862 W (2,950 Btu/h), heating capacity output is 1,170 W (4,000 Btu/h) at -18˚C (0°F) ambient. Therefore, an increase in TE power input by a factor of three times yields only 60% more heating capacity compared to lower TE power input. In other words, tripling the power input lowers the incremental COP of the TE subcooler significantly. It means that the TE performance degraded fast with increasing the electric current. A goal of the future work is to determine whether a different TE subcooler configuration (increasing the total number of TE modules used as well as changing their arrangement from series to parallel) will alter the sensitivity of the heating performance and yield a higher incremental COP.

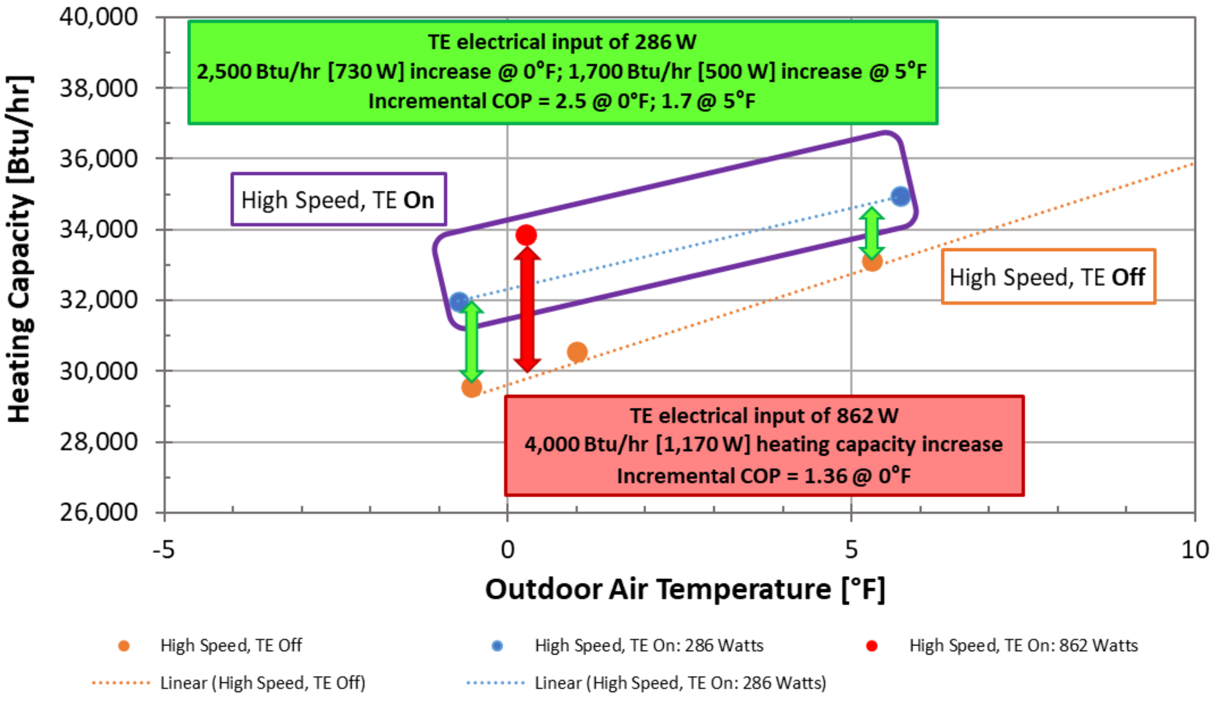

Figure 7. Sensitivity of TE input power on heating capacity output provided by TE subcooler

Heating COP Impacts

The output performance of the TE integrated heat pump system was examined further by plotting the COP versus the ambient laboratory temperature. The COP for the measurements recorded at multiple air temperatures ranging between -18˚C (0˚F) and 8˚C (47˚F), as shown in Figure 8. The overall system COP is approximately ~2.0 at the ambient temperature of -18˚C (0°F), and it increases to 3.6 COP at the ambient temperature of 8˚C (47˚F). The incremental COP obtained by energizing the TE modules of the TE subcooler is calculated based on the data measurements recorded during the "High Speed, TE On" stage. The incremental COP provided by the TE subcooler ranges from 1.36 to 2.5 (also shown in Figure 7). Note that this range of COP output is greater than the COP of an electric resistance strip ($COP_{\text{resistance strip}} = 1$) or a gas furnace ($0.8 < COP_{\text{gas furnace}} < 1$) which are the backup heat sources used in conventional heat pumps, and usually switch on below 0˚C (32˚F). The temperature range -18˚C (0˚F) to 8˚C (47˚F) represents more than 60% of the winter season temperature observed in the US, while the overall system COP range of 2.0 to 3.6 for this temperature range is comparable to the heating efficiencies observed in cold climate heat pumps currently on the US market. Therefore, the TE integrated heat pump illustrated in this paper clearly delivers a multi-stage residential heat pump system that provides (1) enhanced heating capacity and (2) higher seasonal heating efficiency than a conventional heat pump, and (3) comparable heating efficiency to the current commercially available cold climate heat pumps.

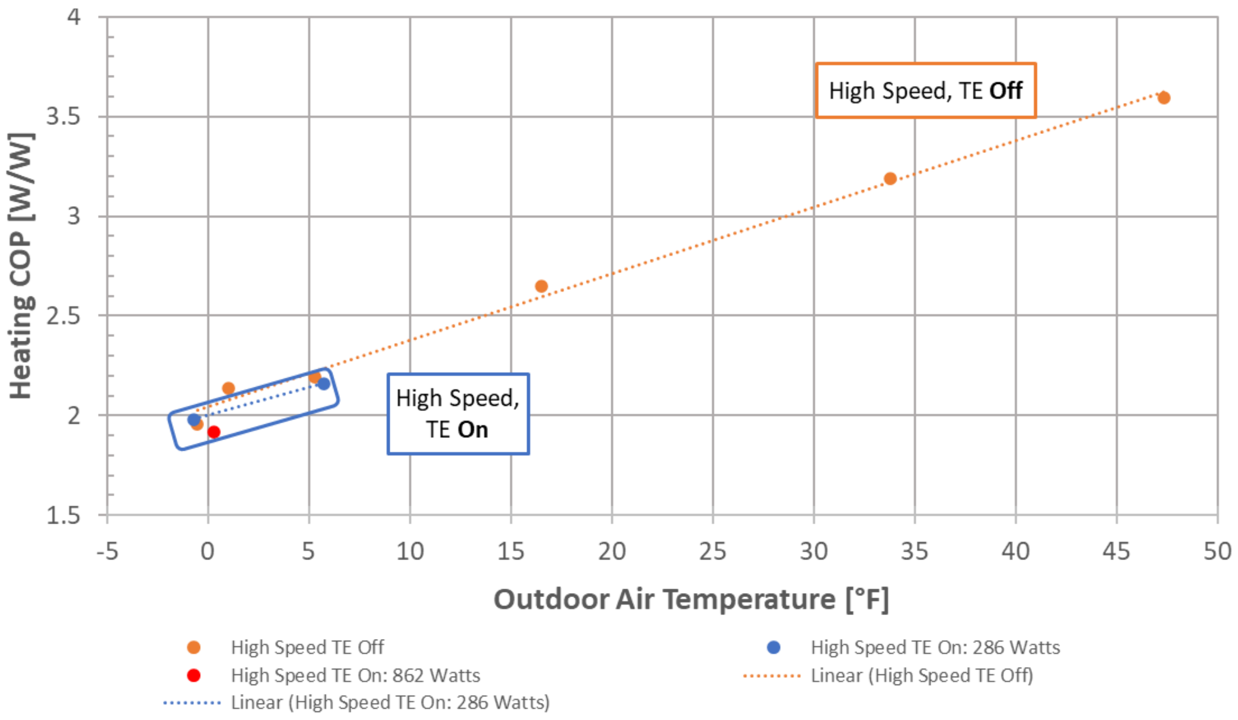

Figure 8. Heating COP versus ambient laboratory temperature for TE integrated heat pump

Understanding the Costs of TE Heat Pump

The proposed thermoelectric-integrated heat pump consists of additional components compared to a standard air-source heat pump, namely the supplemental heat exchanger coil, the TE modules, the TE assembly, and AC to DC converters to power the TEs. These components will increase the capital cost of the system. The cost of TE modules per ton of the heat pump's nominal rating capacity is expected to be approximately $200-$300 ($5-$7 per module x 40 modules). The AC to DC conversion can be accomplished using a standard single-phase 24V DC, 5A power source which can cost between $20-$100 depending on the make. Adding in the costs of other components, e.g. supplemental heater coil (whose required size and cost will vary the capacity needed) and the supplies required to build the TE assembly, we anticipate a total of 20% upfront cost increment over the conventional single-speed air source heat pump (i.e. $100-$150 per kW). As mentioned earlier, commercially available cold climate heat pumps require expensive components such as vapor injection variable-speed compressors which significantly elevates the capital cost (additional incremental cost of $400-$650 per kW compared to a conventional single-speed air source heat pump), With this significant upfront cost reduction, and combining with the energy savings obtained compared to a conventional single-speed heat pump using electric resistance backup heating, it is practical for the proposed TE to be cost-effective. Successful commercialization could render payback period within 5-10 years depending on the prevailing fuel rates in the region of installation.

Other Benefits of TE Heat Pump

Specifically with regards to cold climate heat pumps, this TE integrated heat pump offers additional benefits in terms of the characteristics that the system is much more controllable, simpler and affordable. The current supplied to the TE modules can be varied over a wide range and thereby allow for a very granular operating envelope. For low temperature heating, the TE subcooler that is placed in the AHU can achieve the same effect of reducing the evaporator inlet enthalpy without needing the complicated vapor-injection configuration, phase separation, and associated control devices.

Conclusions and Future Work Recommendations

A vapor compression residential heat pump cascaded with a thermoelectric heat pump has been studied experimentally in the laboratory with the data collected showing the performance characteristics of the enhanced system operating in the heating mode. The results highlight the potential use of thermoelectric technology for residential space heating, which is more affordable than currently available cold climate heat pumps in the market and at the same time more efficient compared to conventional air-source heat pump with a backup resistance strip or a backup fossil fuel furnace. The key takeaways from this work are briefly summarized below:

- The TE integrated heat pump consists of a 2-stage vapor compression heat pump whose AHU is modified by adding a supplemental coil as well as a TE subcooler. The heat pump therefore harvests energy saving from two perspectives. One is that the supplemental coil increases the condensing capacity and operation efficiency. The other is that the TE subcooler further subcools the refrigerant liquid entering the outdoor coil to enlarge the evaporating capacity and total heating capacity.
- The introduction of TE integration into the conventional heat pump results in an augmentation of the overall heating capacity of the system. Activation of the TE heating capacity has the potential to elevate the capacity by up to 1.2 kW for the current configuration, observed at an ambient temperature of -18°C (0˚F).
- TE heat pump’s increased heating capacity at low ambient temperatures is obtained without impacting the total heating COP. The COP of the TE subcooler component at -15°C (5˚F) is about 1.75, which is greater than the COP of conventional back up heating technologies at low ambient temperatures used in today’s single-speed heat pumps, namely electric resistance (COP ~1) and fossil fuel furnace (COP ~0.8). As a result of integrating the TE subcooler, the heat pump system has a high COP of 2.2 at 5˚F and a COP of around 2 at -18°C (0˚F).
- The overall COP of the TE integrated heat pump ranges from 2 at -18°C (0˚F) to 3.6 at 8°C (47˚F). These values are comparable to currently available cold climate heat pumps in the U.S. market. The TE integrated heat pump able to achieve the improved capacity and COP performance, particularly at low ambient temperatures than a conventional air source heat pump without needing to use sophisticated techniques currently employed in cold climate heat pumps.
- The COP of the TEs is sensitive to the input power. In general, higher power input decreases the COP due to the increasing the temperature differential across the TEs. At -18°C (0˚F), the lowest ambient temperature at which testing was conducted, tripling the

power input yields only 60% more heating capacity. This, however, is likely attributed to the total number and series arrangement of the TE modules in the TE subcooler.

- On a mass production scale, the incremental cost of the TE heat pump is expected to be \$100-\$150 per kW compared to a conventional single-speed heat pump with electric resistance backup. The upfront cost increase can be up to 35% lower than today's commercially available cold climate heat pumps, thus resulting in a favorable payback for the customers. It is anticipated that successful commercialization could render payback period as low as 5 years but no more than 10 years depending on the prevailing fuel rates in the region of installation.

Future work will focus on modifying this protype to test alternative configurations of the TE subcooler, i.e. doubling the number of TE modules from 40 pieces to 80 total modules, and investigating the arrangement of the modules in parallel capacity tube bundles instead of series. These alternative configurations will allow for examination of the sensitivity of the heating performance and allow to check whether a higher incremental COP is achieved. The examination of parallel configuration arrangement will also help elevate the performance by reducing pressure drop of the refrigerant in the capillary tube bundles of the TE assembly before it enters the supplemental coil. Additional future work will involve testing the TE integrated heat pump for cooling operation and long-term field study of this heat pump protype in cold climate regions.

Acknowledgments

This work was carried out under a contract DE-EE0009687 between the U.S. Department of Energy and the Electric Power Research Institute (EPRI), for the project: “Cold Climate Heat Pump using Vapor Compression Cycle Cascaded with a Thermoelectric Heat Pump. The results provided in this article are a portion of the overall Task 2 laboratory testing performed under that contract. DOE's technical guidance and support for successful conduct of the work is deeply acknowledged.

References

ANSI/AHRI Standard 210/240. 2008. *Performance rating of unitary air-conditioning and air-source heat pump equipment.* Arlington, VA: Air-Conditioning, Heating, and Refrigeration Institute.

Britannica. Accessed on February 20, 2024. *Peltier effect.* https://www.britannica.com/science/Peltier-effect

Chua, K. J., S.K. Chou, and W. M. Yang. 2010. “Advances in heat pump systems: a review.” *Applied Energy* 87 (12): 3611–24.

Groll, E. A., and V.D. Baxter. 2017. *IEA HPT ANNEX 41–Cold climate heat pumps: US country report*. ORNL/TM-2017/146. Oak Ridge, TN, Oak Ridge National Lab.(ORNL).

Kazmierczak, M. J., S. Krishnamoorthy, and A. Gupta. 2009 "Experimental testing of thermoelectric-based hydronic cooling/heating device with transient charging of sensible thermal energy storage water tank." *Journal of Thermal Science & Engineering Applications* 1(4): 1-14.

Krishnamoorthy, S. 2023. "Opportunities for Rural Electrification of Space Heating in USA" *ASHRAE Transactions* 129.

Okuma,T., R. Radermacher, Y. Hwang. 2012. "A novel application of thermoelectric modules in an HVAC system under cold climate operation." *Journal of Electronic Materials* 41.

Patel, V. K., and K. R. Gluesenkamp. "Development of Packaging and Modular Control of Thermoelectric Clothes Dryer, With Performance Evaluation." *Proceedings of International Electronic Packaging Technical Conference and Exhibition* 58097: V001T04A009, American Society of Mechanical Engineers.

Sarkar, J. 2012. "Ejector enhanced vapor compression refrigeration and heat pump systems—a review." *Renewable and Sustainable Energy Reviews* 16: 6647–59.

TE Technology Inc. Accessed on February 20, 2024. *High-Temperature Modules* https://tetech.com/peltier-thermoelectric-cooler-modules/high-temperature/

U.S. Department of Energy. 2014. *Energy Savings Potential and RD&D Opportunities for Non-Vapor-Compression HVAC Technologies.*

Valancius, R., R. M. Singh, A. Jurelionis, and J. Vaiciunas. 2019. "A Review of Heat Pump Systems and Applications in Cold Climates: Evidence from Lithuania." *Energies* 12: 4331.

Walker, I.S., B.D. Less, and N. Casquero-Modrego. 2022. "Carbon and energy cost impacts of electrification of space heating with heat pumps in the US." *Energy and Buildings* 259. https://doi.org/10.1016/j.enbuild.2022.111910.

Wan, H., and Y. Hwang. 2023. "A Review of Recent Residential Heat Pump Systems and Applications in Cold Climates." *14th IEA Heat Pump Conference*. Chicago, Illinois.

Wang, C., C. Carlos, and W. YaoDong. 2017. "An experimental study of a thermoelectric heat exchange module for domestic space heating." *Energy and Buildings* 145: 1-21.

Xu, X., Y. Hwang, R. Radermacher. 2011. "Transient and steady-state experimental investigation of flash tank vapor injection heat pump cycle control strategy". *International Journal of Refrigeration* 34 (8): 1922-1933.

Zhang, L., Y. Jiang, J. Dong, Y. Yao. 2018. "Advances in vapor compression air source heat pump system in cold regions: A review" *Renewable and Sustainable Energy Reviews* 81: 353–365.