EVALUATION OF SEASONAL PERFORMANCE IMPROVEMENTS IN A 3-TON RESIDENTIAL HEAT PUMP SYSTEM USING A NOVEL DESIGN OF INTEGRATED ELECTRONIC EXPANSION VALVE

Chad Bowers, Senior Research Engineer, Creative Thermal Solutions, Urbana, IL, USA;
Dave Wrocklage, Engineering Manager, Parker Hannifin Corporation Sporlan Division, Washington, MO, USA;
Stefan Elbel, Chief Engineer, Creative Thermal Solutions and University of Illinois, Urbana, IL, USA;
Pega Hrnjak, President, Creative Thermal Solutions and University of Illinois, Urbana, IL, USA;

Abstract: With the advent of high efficiency residential heat pump systems, achieving even higher seasonal efficiency is becoming more complex and incremental in nature. For this reason, component modifications that provide improvements of even a few percent can become very attractive. If these component level improvements can also provide secondary benefits, such as a reduced bill of materials or more compact packaging, the likelihood of acceptance and market penetration becomes high. One example of such a component level improvement is the novel integration of a stepper motor controlled electronic expansion valve with the distributor for a multi-circuited round tube plate fin heat exchanger. This paper describes the experimental validation of the potential improvements in seasonal performance achieved by implementing this novel electronic expansion valve design into a high efficiency reversible 3-ton air-residential heat pump system. The implementation of this technology led to increases of 3% in HSPF.

Key Words: Residential Heat Pump, Expansion Valve, Refrigerant Distribution

1 INTRODUCTION

The need to reverse the refrigeration cycle in heat pump systems means that both indoor and outdoor units require both an expansion device and check valve mechanism to bypass this device during the mode of operation in which it is not needed. This assembly then needs to be integrated with the distributor in multi-circuited round tube heat exchangers. One note worthy feature of the system tested was that it used electronically controlled expansion devices on both the indoor and outdoor side of the system. The use of electronically controlled expansion devices is becoming more popular, especially in higher efficiency units as this allows for programmable control of the superheat in many operating modes. While the use of the electronic expansion valve allows for energy saving control strategies, the complexity of this subassembly requires a larger bill of materials and extra effort in fabrication when compared to a simple piston expansion device integrated into a check valve. With these difficulties in mind, an expansion valve manufacturer developed a proprietary and novel electronic expansion valve with both the check valve and distributor integrated into the body of the valve. An example of this valve, referred to as an integrated electronic expansion valve distributor Figure 1. As shown in this figure the valve (with integrated check) and it's wet motor join directly to the refrigerant distributor. One direct difference with the integrated electronic expansion valve distributor is the simplicity of the valve subassembly packaging; another key difference is the proximity of the distributor to the expansion volume. In the integration of the distributor with the valve, the distributor is placed

directly at the outlet of the orifice. This is noticeable different from conventional valves where the distributor is brazed some length downstream of the orifice. The additional length can provide opportunity for the two phases of the refrigerant to separate and unequally distribute among the circuits. In some cases, an additional orifice is put between the expansion device and the distributor to offset this effect.

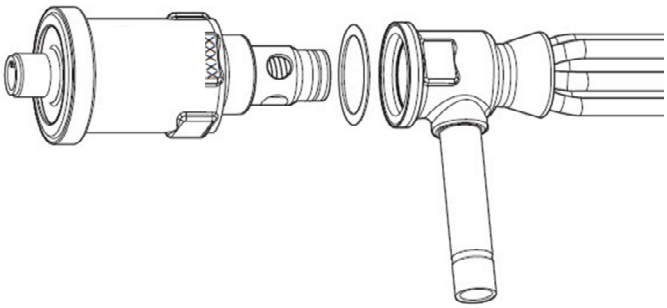


Figure 1: Integrated Electronic Expansion Valve and Distributor with Check Valve

To illustrate the ability to increase build compactness, images of the factory installed electronic valve, distributor, and check valve assembly are compared to the installed integrated electronic expansion valve and distributor with check valve in both the indoor unit and outdoor unit in Figure 2 and Figure 3, respectively. The space savings is much more apparent in the images comparing the two configurations in the outdoor unit. In this case, it is apparent that the expansion valve, distributor, and check valve are three completely independent parts requiring additional assembly during fabrication, and more opportunity for leaky braze joints. While using the integrated package shows that assembly would only require joints between the liquid line and the valve inlet and between the distributor and feeder tubes, joints that need to be made in both configurations.

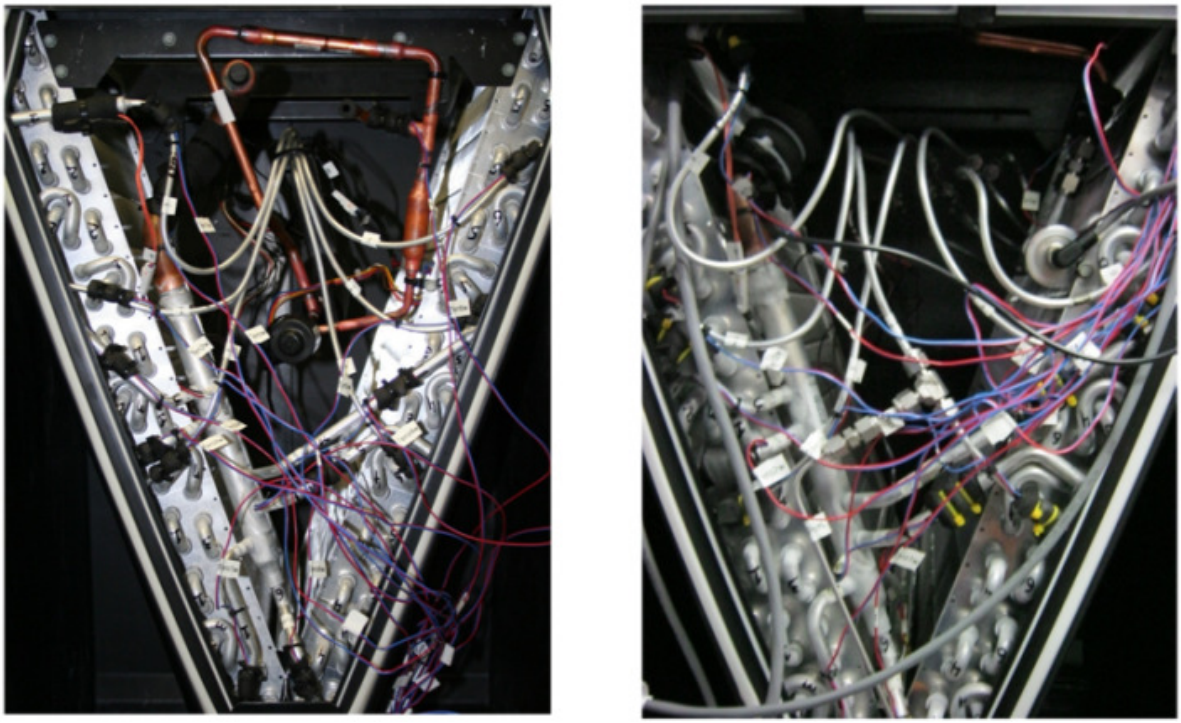


Figure 2: Expansion Valve, Distributor, and Check Valve Assembly from Manufacturer and Prototype Integrated Electronic Expansion Valve and Distributor with Check Valve in Indoor Unit

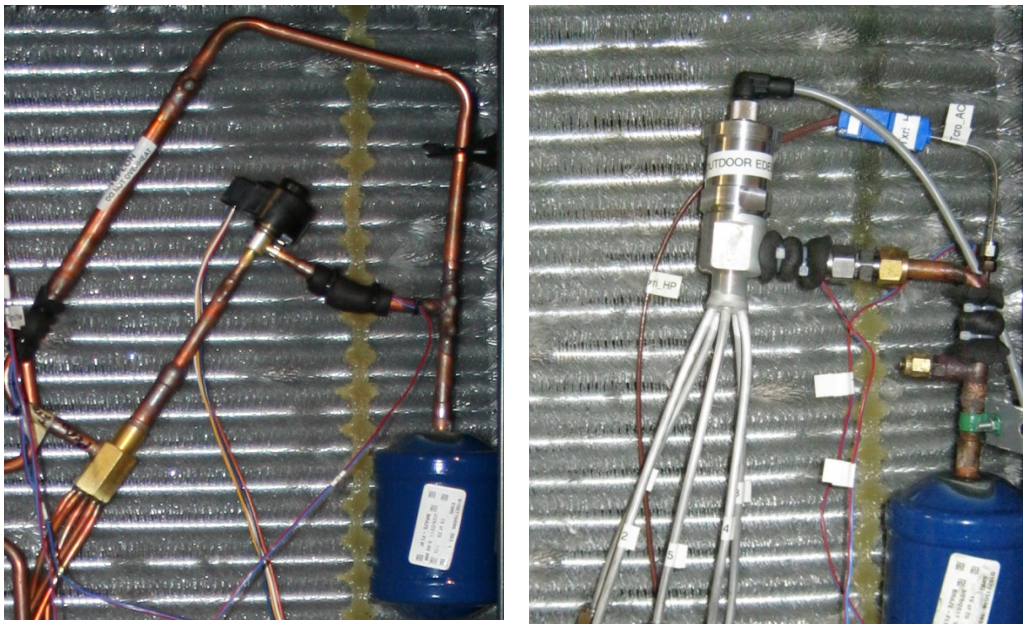
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Figure 3: Expansion Valve, Distributor, and Check Valve Assembly from Manufacturer and Prototype Integrated Electronic Expansion Valve and Distributor with Check Valve in Outdoor Unit

The importance of proper refrigerant flow distribution through a multi-circuited evaporator is well known. Choi et al., 2003, showed that as much as 30% capacity degradation can come from refrigerant flow maldistribution, even at the same superheat setting. Kaern et al., 2013, indicated that better matched individual circuit outlet superheat in an interlaced evaporator can lead to as much as 7% improvement in overall UA and 2.4% improvement in system COP. Fay and Hrnjak, 2011, indicated that a 4% and 5% gain in COP and capacity, respectively, is possible when moving from a refrigerant flow distribution where some circuits have two-phase exit, to a matched superheat condition. To realize these kinds of improvements, active individual circuit superheat control is typically implemented. While a few attempts have been made to automate this control scheme in a single device, this is most often done experimentally through the use of a throttling device placed on each circuit, which is not practical in a production application. Another way to approach uniform superheat distribution, assuming uniform circuit loading, is to more uniformly distribute the flow inside of the distributor

The objective of the current study was to demonstrate that, in addition to the above described advantages for system integration, this technology can improve system level performance metrics such as capacity and coefficient of performance (COP), as well as secondary metrics such as refrigerant distribution. To quantify these effects, a prototype valve with integrated check valve and distributor was provided by the valve manufacturer and installed in both the indoor and outdoor units of a 3-ton high efficiency reversible heat pump system. The indoor unit had a three row six circuit symmetric V-shaped coil, with interlaced circuiting on each side of the coil. Circuits 1-3 were on the left side of the coil and 4-6 on the right. The outdoor unit had 5 separate circuits. Nominal efficiencies of this system, as provided by the manufacturer were a SEER of 18 and an HSPF of 9.8. For configurations with both the original electronic valves and the integrated electronic expansion valve distributor's, a full series of SEER and HSPF tests were performed according to AHRI 210/240-2008 at various superheat settings for a system having a two-capacity compressor. These results were then compared. In addition to recording all the required measurements for capacity and efficiency, both the indoor and outdoor coils were equipped with temperature measurements on all of the circuits to determine the uniformity of superheat among the

circuits and several additional pressure transducers to quantify pressure drop in various components. The instrumentation used on the refrigerant side of the system is shown schematically in Figure 4. In addition to instrumentation installed on the refrigerant side of the system sufficient instrumentation was installed in the air stream of the indoor unit to obtain a capacity determination on this stream in compliance with ASHRAE 37-2009 and ASHRAE 116-2010.

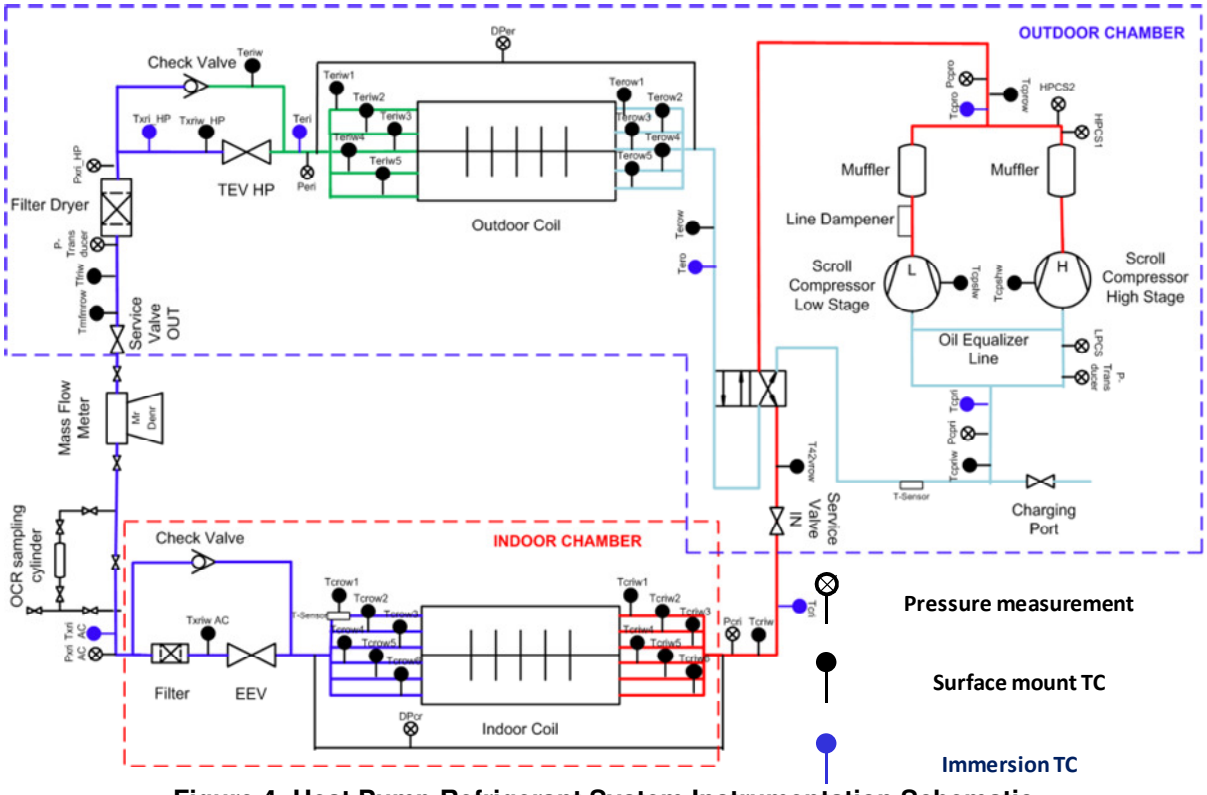


Figure 4: Heat Pump Refrigerant System Instrumentation Schematic

2 COOLING PERFORMANCE

Cooling mode tests were performed on the system in configurations using both valve subassembly options according to AHRI 210/240-2008 Table 7. Steady state data was acquired at the four required wet coil tests conditions, A2, B2, B1 and F1, as well as the two steady dry coil conditions, C2 and C1. Cycling tests, D2 and D1, were also performed to determine cycling degradation coefficient (CD). Testing on the system in the baseline configuration was performed with no modifications to any of the control devices. As the system configuration with the integrated electronic expansion valve distributor could not utilize the original control signal provided to the valve by the manufacturer of the system, a separate control algorithm, developed by the valve's manufacturer, was implemented and a superheat optimization was performed on the system with the integrated electronic expansion valve distributor installed. These superheat optimization consisted of varying the superheat control set point over a large range at required conditions and performing the rating tests at the lowest superheat set point that showed stability over all test conditions. Using this optimization for superheat setpoint resulted in a superheat setting, only slightly lower than the baseline configuration. While the use of different control algorithms makes the comparison between the baseline and integrated expansion valve and distributor systems less direct in cycling tests, the steady state testing should allow for direct comparisons.

The cooling capacity and COP as determined by these test results are shown in Figure 5a and Figure 5b, respectively. In all conditions, both cooling capacity and COP are higher for the system using the integrated electronic expansion valve distributor configuration. The increase in cooling capacity ranged from 3.6%, at condition C2, to 6.0%, at condition B2. Overall efficiency increases varied from 1%, at condition C2, to 8.1% at condition B2. Improvements in COP over the baseline were not directly proportional to the improvement seen in cooling capacity due to changes in system power at the different test conditions. In some cases the power increased and in others it decreased. The largest increase in system power, compared to the baseline occurred at condition C2, with the integrated electronic expansion valve distributor configuration requiring 2.5% more power. This explains why, at condition C2, the COP improvement is actually smaller than the capacity gain when using the integrated electronic expansion valve distributor. Conversely, at condition B2, the COP improvement is two percentage points larger than the gain in capacity because the system power was reduced by nearly 2%. The results from the cycling tests yielded cycling degradation coefficients at both low and high capacity, of 0.0. Using the calculation guidelines set forth for calculation SEER, it was determined that the baseline system achieved an SEER of 18.00, while the system with the integrated electronic expansion valve distributor improved on this by nearly 5%, achieving an SEER of 18.83. This indicates, that in addition to providing a solution that reduces complexity in manufacturing, the integration of this novel expansion valve, check valve, and distributor may also provide significant performance improvement in cooling mode.

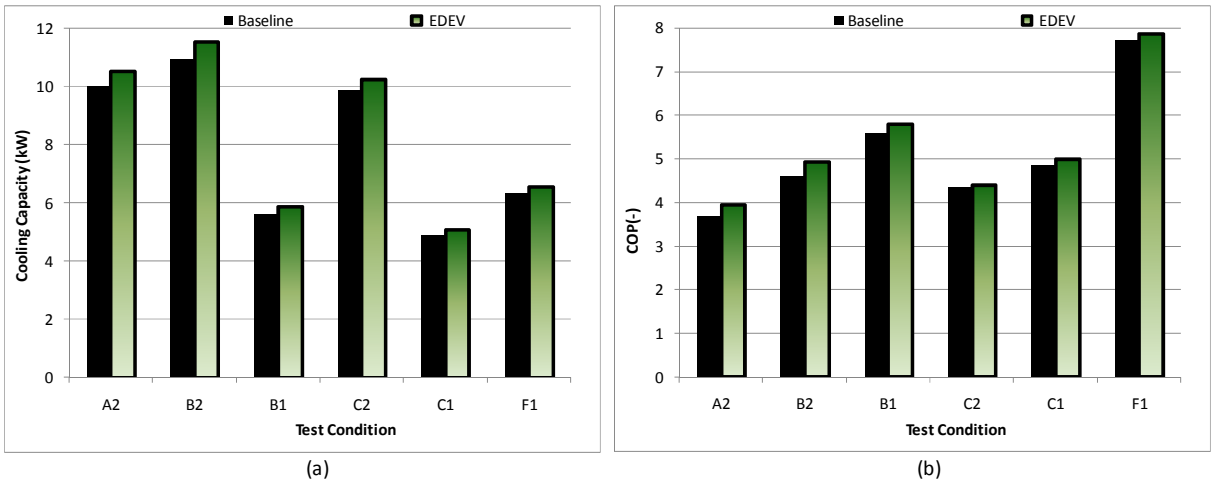


Figure 5: (a) Cooling capacity and (b) COP of Baseline and integrated electronic expansion valve distributor for all steady cooling tests.

As mentioned earlier, one possible “unseen” advantage of integrating the distributor with the expansion valve is improved refrigerant flow distribution among the circuits of the heat exchanger, leading to better matched circuit superheats. This secondary indicator of performance improvement was also seen as a result of integrating the integrated electronic expansion valve distributor in the system during cooling mode. The graphs shown in Figure 6 present the exit superheat in the individual circuits of the indoor coil for all of the steady state conditions tested in both the baseline configuration and with the integrated electronic expansion valve distributor, respectively. In the baseline configuration, Circuit 4 has an exit condition that is not superheated over the majority of the test period. This indicates that this circuit either receives much more liquid refrigerant or is loaded considerably less on the air side of the coil. With Circuit 3 being the symmetric circuit on the other side of the coil, it appears that loading on the air side may not be the primary cause of this maldistribution. As a result of this one circuit with a wet exit, the other circuits must have higher superheats to bring the average superheat up to the set point. The other five circuits have exit superheats

that average between 3K and 5K. The average exit superheat, as determined through a time average of an wall mounted thermocouple at the exit of the common suction was just over 4K. The spread in individual circuit superheats is much more dramatic in the baseline configurations at conditions C1 and C2, which are both dry tests. In these cases, the superheat varies as much as 11K among all six circuits. The results from the tests performed with the integrated valve and distributor show that the individual circuit superheat variation is much smaller, indicating that the flow distribution in these test is much more uniform.

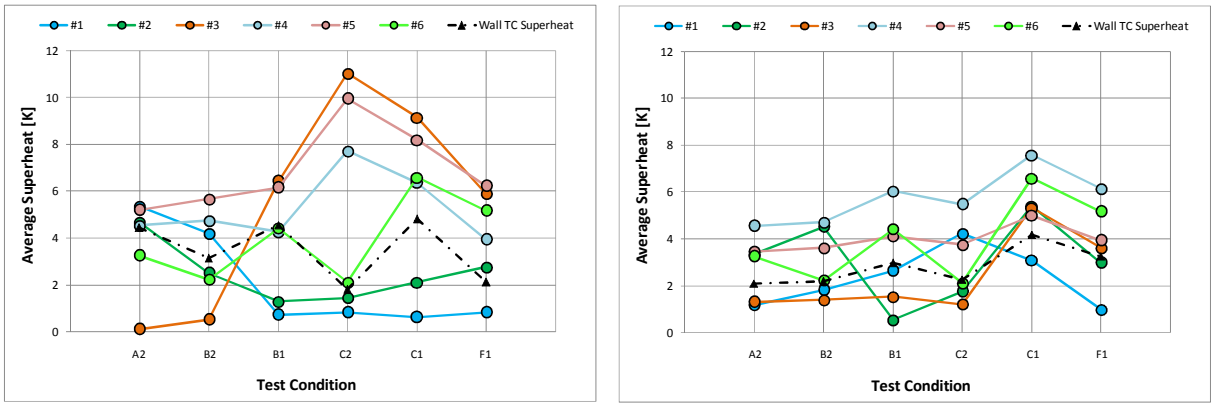


Figure 6: Individual Circuit Superheat Distribution for Baseline (a) and Integrated Electronic Expansion Valve Distributor (b) for All Steady Cooling Tests.

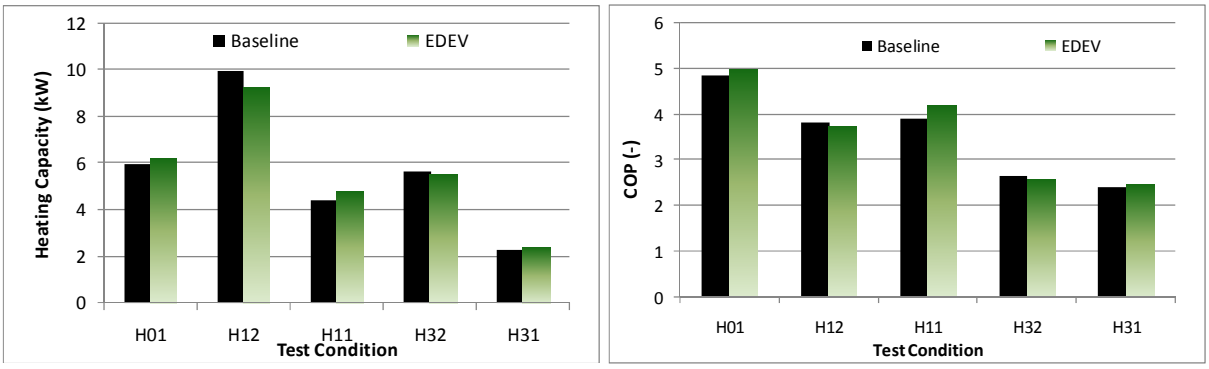
While it may be difficult to quantify, it also appears that the superheat in all of the circuits is more stable with the integrated electronic expansion valve distributor installed. This increased stability could be caused by a variety of things; but is most likely attributable to the controller, the refrigerant distribution, or a combination thereof. While the different control algorithms used to control superheat may have differences that lead to better or worse stability, the act of combining the two phase flow leaving one or more circuits with the superheat vapor leaving the others may contribute to stability as well. This would be a strong function of the amount of liquid present, the degree of superheating present and required, and the length available for these flows to mix prior to measuring the bulk temperature.

3 HEATING PERFORMANCE

Heating mode tests were performed on the system in configurations using both valve subassembly options according to AHRI 210/240-2008 Table 8. One maximum temperature test (H01), two high temperature tests (H12 and H11), two frost accumulation tests (H22 and H221), and two low temperature test (H32 and H32) were conducted. The optional two cycling tests (H1C1 and H1C2) were also performed. As with the cooling mode tests, an optimization on superheat control point setting was performed at each steady test condition. The superheat set point was varied and the lowest stable superheat overall conditions was chosen as the set point for the performance evaluation tests. It should be noted, that at the low capacity conditions, the stable superheat setting was consistently lower. This indicates that further efficiency improvements may be possible by implementing a control strategy that constantly “looks” for the lowest stable superheat as opposed to the fixed superheat set point logic used in this study.

The heating capacity and COP as determined by these tests are shown in Figure 7a and Figure 7b, respectively. In all but the high capacity low temperature condition, the system with the integrated electronic expansion valve distributor installed achieved equal or higher

capacity and COP. The largest improvement in both capacity and COP was at condition H11 where both capacity and COP were increased by 8%. In the single condition in which performance was degraded, capacity was only reduced by 1.5%, while COP was reduced by 3%. The results from the cycling tests yielded cycling degradation coefficients at both low and high capacity, of 0.0. Using the procedures outlined in AHRI 210/240, the HSPF was calculated for both system configurations, assuming the system would be running in climatic region IV as described in AHRI 210/240 Table 17. The system in the baseline configuration achieved an HSPF of 9.79. Integrating the integrated electronic expansion valve distributor assembly into the system resulted an increase in HSPF of approximately 3% to 10.06.



(a) (b)

Figure 7: (a) Heating capacity and (b) HPF of Baseline and the integrated electronic expansion valve distributor for all steady heating tests.

The largest noticeable difference in superheat between cooling and heating mode is that no single circuit appeared to have liquid present at the exit during any steady state test. This is illustrated in the comparison of individual circuit superheats shown in Figure 8. In the baseline configuration at condition H12, the exits of circuits 1, 2, 3, and 5 are superheated by 5K to 7K, and stable. While the superheat at the exit of circuit 4 is approximately 3.5K, on average with much less stability. At the most dramatic condition, the highest deviation between circuit superheats is approximately 3K, which is significantly less than the baseline indoor coil during cooling operation. With the implementation of the integrated electronic expansion valve distributor valve assembly, the deviation between the highest and lowest superheat is reduced from 3K to 2.5K. While not shown here it was observed that no single circuit has the instability noted in the baseline results. This again, is a secondary indicator that integrating the distributor into the expansion device may provide improvements in refrigerant distribution, although much less notable than in the indoor coil. Another indicator of improved refrigerant flow distribution is an increase in evaporation pressure. Typically, evaporation temperature (pressure) will increase as refrigerant is more uniformly distributed because the heat exchanger area is used more effectively. In all conditions tested, the evaporation pressure was increased when the integrated electronic expansion valve distributor was implemented. The largest increase in evaporation pressure, from 1108kPa to 1156kPa, was seen at condition H01. The smallest increase, from 510kPa to 523kPa, was at condition H32.

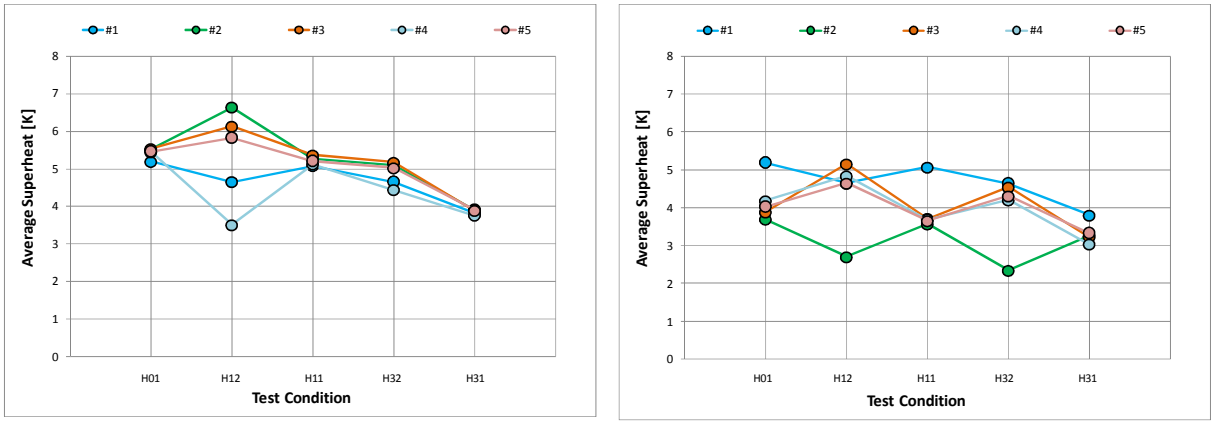


Figure 8: Individual Circuit Superheat Distribution for Baseline and Integrated Electronic Expansion Valve Distributor for All Steady Heating Tests.

4 CONCLUSIONS

Managing the refrigerant flow distribution in a multi-circuited evaporator in a way that optimizes the air side loading of the coil is crucial to obtaining the best performance. The work presented here demonstrated the possibility for performance improvements using a novel electronic expansion device for reversible systems that integrates the electronic expansion valve, the check valve, and the distributor. While such a device has advantages from a manufacturing and packaging point of view, the present work shows that appreciable gains in both system capacity and efficiency can be achieved through the integration of this technology. In the high efficiency 3-ton reversible system investigated, integration of this technology led to increases in SEER and HSPF of nearly 5% and 3%, respectively. For all but one test condition, system capacity (both cooling and heating) was also increased. In addition to the improvement in these primary metrics, secondary metric improvements were also observed. Implementation of this technology also showed that the spread in circuit superheat can be reduced, superheat stability was improved, and in some cases evaporation pressure increased. All of these secondary metrics point towards improved refrigerant flow distribution through integration of the integrated electronic expansion valve distributor technology.

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