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ABSTRACT

The increased usage of hybrid and electric vehicles where waste heat availability is limited has spurred research and development of mobile heat pump systems. Many options exist for heat pump system architectures and refrigerants to be used. Currently R134a use is prevalent in vehicle air conditioning systems but offers poor heat pump performance at low ambient temperatures. Two refrigerants will be explored in this paper, R744 and R445A. Both of these refrigerants are getting attention in vehicle A/C systems because of their relatively low GWP but each offers benefits over R134a in heat pump systems as well. Both refrigerants operate at higher pressures which improves the performance at low ambient temperatures in part due to higher compressor inlet refrigerant densities. R134a (and R445A to a lesser extent) also suffer from the drawback of going into sub-atmospheric pressure operation at temperatures commonly seen in vehicles. Data will be shown for multiple system architectures comparing these refrigerants to R134a. Advantages and disadvantages of each refrigerant will be shown. System control and optimization is important to get the maximum performance from each refrigerant and system. Control exploration will be presented for each alternative refrigerant.

1. INTRODUCTION

Electric vehicle range is greatly limited in cold ambient conditions by the heating requirements for the cabin and batteries of the vehicle. The most prevalent form of heating in electric vehicles is electric resistance heat. The maximum coefficient of performance (COP), defined by the heating capacity divided by the power input, for resistance heating is 1. Implementing a heat pump system can more than double or triple the COP thus greatly increasing the driving range of an electric vehicle. Some electric vehicles on the road today have heat pumps or heat pump options such as the BMW i3, Renault Zoe, and Nissan Leaf. These heat pumps use low pressure refrigerants commonly used in vehicle air conditioning such as R134a and R1234yf. Both refrigerants have the limitation of low performance and sub-atmospheric pressure operation at low ambient temperatures at or below -20°C. R1234yf has been introduced as a drop-in alternative to R134a due to its low GWP (4 compared to 1430). Another low GWP drop-in alternative, R445A (GWP of 135) has been explored and has advantages in heat pump operation due to higher pressures. R744 (GWP of 1) has been shown to be the most promising fluid for heat pump operation among the refrigerants listed above but is not a drop-in due to the requirement for components able to withstand significantly higher pressures. Both R445A and R744 are under the European Union regulatory limit for GWP of 150 which is generally accepted worldwide as the threshold for classifying as low-GWP refrigerants.

R445A is a ternary refrigerant mixture of R1234ze(E), R134a, and R744 in the nominal proportions of 85%/9%/6% respectively. For the purposes of this study, it was not feasible to test with R445A, thus an alternative was used to simulate the properties of R445A. This alternative was chosen to consist of the same percentage of R744 at 6% with the balance being R134a (94%). The proportion of R1234ze(E) in R445A is present to reduce the GWP and has similar performance to R134a thus replacing the R1234ze(E) with R134a was not expected to have a large impact on the overall performance. The 94% R134a, 6% R744 blend will be referred to as the ‘R134a/R744 blend’ for the purposes of simplicity in the remainder of this paper.

2. EXPERIMENTAL FACILITY

The test facility was designed based on the SAE Surface Vehicle Standard, J2765; Procedure for Measuring System COP [Coefficient of Performance] of a Mobile Air Conditioning System on a Test Bench (SAE, 2008). The facility consists of two environmental calorimeters. The outdoor environmental chamber simulated the ambient conditions experienced by the front end vehicle components of the system including the condenser (in A/C operation), internal heat exchanger, and compressor. The indoor chamber simulated the conditions experienced by the evaporator (in A/C mode) and the secondary condenser (in heat pump mode). Each chamber contained a wind tunnel designed according to ASHRAE standard 41.2 (ASHRAE, 1987). In the case of both wind tunnels, the air passes through the heat exchangers, flow mixers, and then flow measuring nozzles. Thermocouples in the nozzle throat are then used in the airflow calculation as well as for the bulk air outlet temperature for each heat exchanger in the energy balance calculations. The setup was designed to replicate the actual relative heights of components in the vehicle. Figure 1 shows a simplified chamber schematic set up for A/C mode. Testing was performed for R134a and the R134a/R744 blend in both A/C and heat pump operation. In the case of heat pump operation, the chambers were equipped with additional heat exchangers connected to a condensing unit capable of pulling both chambers down to -40°C. Three independent methods for calculating cooling or heating capacity were used which exceeds the requirement of 2 independent methods in the SAE standard. The 3 methods used to determine capacity were the refrigerant side energy balance, air side energy balance, and a calorimeter energy balance where all energy entering and leaving the indoor calorimeter is measured with the balance being the capacity of the indoor heat exchanger.

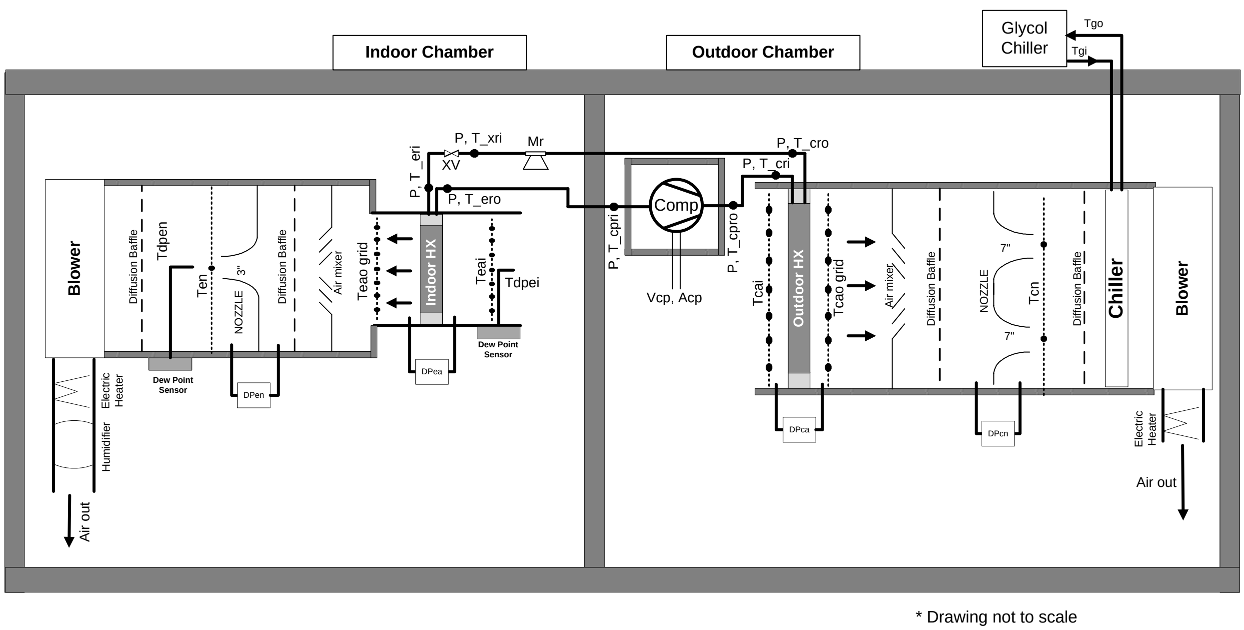

Figure 1: Experimental Facility

3. A/C AND HEAT PUMP SYSTEM ARCHITECTURE AND COMPONENTS

Many architectures for mobile heat pump systems were first evaluated. Wawzyniak (2011) outlines several potential architectures which could be implemented in vehicles. The architecture shown in Figure 2 and Figure 3 was chosen based on architectures used in production vehicles on the market today. Modifications to the current vehicle architectures were made in order to allow for additional laboratory exploration and to accommodate the limitations of available components. The design is based around adding a second heat exchanger in the cabin HVAC module. This heat exchanger functions as the condenser in heat pump operation. This eliminates the need to fully reverse the system and allows for the potential of using the indoor evaporator in heat pump operation for defogging purposes. Typically, in the vehicle the air flow is diverted through the secondary condenser only when heating is needed. In the case of the laboratory experiments, a refrigerant valve was added to bypass the refrigerant flow around the indoor condenser in addition to blocking the air flow in A/C operation. The components, which include the indoor and outdoor heat exchangers and electric compressor, were taken from a production hybrid mid-size sedan. A cross-counterflow microchannel heat exchanger was chosen for the secondary condenser and electronic expansion valves were used for control exploration. A transparent accumulator was added in order to visualize the charge migration between heat pump and A/C modes as well as any problems with oil separation in heat pump mode. The production vehicle components used had been optimized for A/C operation with R134a and were used as a proof-of-concept for the R134a/R744 blend in heat pump operation. Many improvements could be made in future research to optimize the components for both A/C and heat pump operation with R445A as the refrigerant. R445A is a zeotropic blend which exhibits a temperature glide during evaporation and condensation. Thus, the use of counter flow heat exchangers is beneficial to take advantage of (or compensate for) the temperature glide.

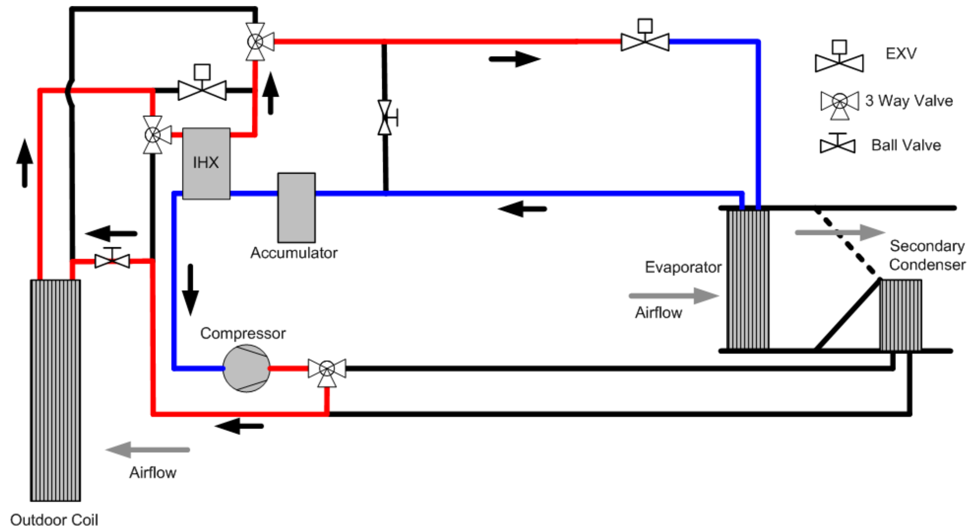

Figure 2: System Architecture in A/C Mode

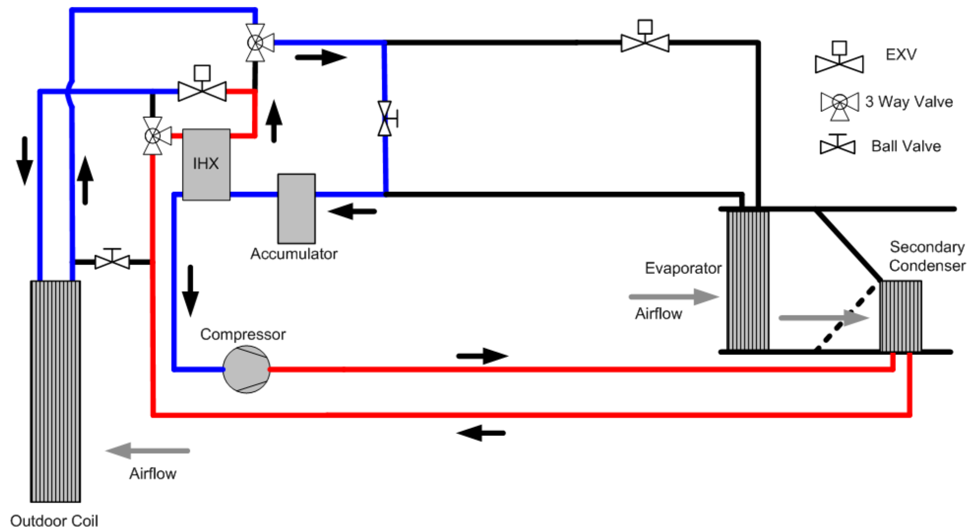

Figure 3: System Architecture in Heat Pump Mode

4. EXPERIMENTATION AND RESULTS

Experiments were performed in heat pump operation based on a test matrix in development for a proposed SAE heat pump standard as shown in Table 1. Ambient temperatures down to -20°C were explored, however, R134a experienced undesirable sub-atmospheric operation at -20°C thus -15°C test points were added in order to compare R134a and the R134a/R744 blend at the lower limits of R134a heat pump operation.

Table 1: Heat Pump Test Matrix

	Outdoor conditions		Indoor conditions		
Test name	$T_{o,air,in}$	Air Velocity	$T_{i,air,in}$	AirFlow rate	Target Temp at outlet
	[° C]	[m/s]	[° C]	[l/s]	[° C]
H-20a / H-15a	-20 / -15	4.0	-20 / -15	50	Max
M-20a / M-15a	-20 / -15	2.5	-20 / -15	50	Max
L-20a / L-15a	-20 / -15	1.5	-20 / -15	50	Max
H-20b / H-15b	-20 / -15	4.0	0	80	40
M-20b / M-15b	-20 / -15	2.5	0	80	40
L-20b / L-15b	-20 / -15	1.5	0	80	40
H-10a	-10	4.0	-10	80	40
M-10a	-10	2.5	-10	80	40
L-10a	-10	1.5	-10	80	40
H-10b	-10	4.0	-10	50	50
M-10b	-10	2.5	-10	50	50
L-10b	-10	1.5	-10	50	50
H-10c	-10	4.0	0	80	50
M-10c	-10	2.5	0	80	50
L-10c	-10	1.5	0	80	50
H0a	0	4.0	0	80	50
M0a	0	2.5	0	80	50
L0a	0	1.5	0	80	50
H0b	0	4.0	10	80	45
M0b	0	2.5	10	80	45
L0b	0	1.5	10	80	45
H10a	10	4.0	10	80	50
M10a	10	2.5	10	80	50
L10a	10	1.5	10	80	50
H10b	10	4.0	15	80	50
M10b	10	2.5	15	80	50
L10b	10	1.5	15	80	50
H15a	15	4.0	15	80	40
M15a	15	2.5	15	80	40
L15a	15	1.5	15	80	40

The two refrigerants were run at maximum compressor speeds for each condition within the limits of allowable compressor discharge temperature and while avoiding sub-atmospheric operation. The R134a/R744 blend produced 15% to 50% higher heating capacities at ambient temperatures of -10°C and below as shown in Figure 4. The R134a/R744 blend also produced capacities of approximately 3.5kW at -20°C where R134a could not reasonably operate. Figure 5 shows the corresponding COP values for the maximum capacity data points. The COP is defined by dividing the heating capacity by the compressor power which is sometimes referred to as the heating performance factor (HPF). Despite the much higher capacities for the R134a/R744 blend, the COP values were very close to R134a with the blend being on average 3% lower. The same low temperature conditions were run where the compressor speed was adjusted for the R134a/R744 blend to match the capacity of R134a. At equal capacities the R134a/R744 blend exhibited 2% to 9% higher COP results.

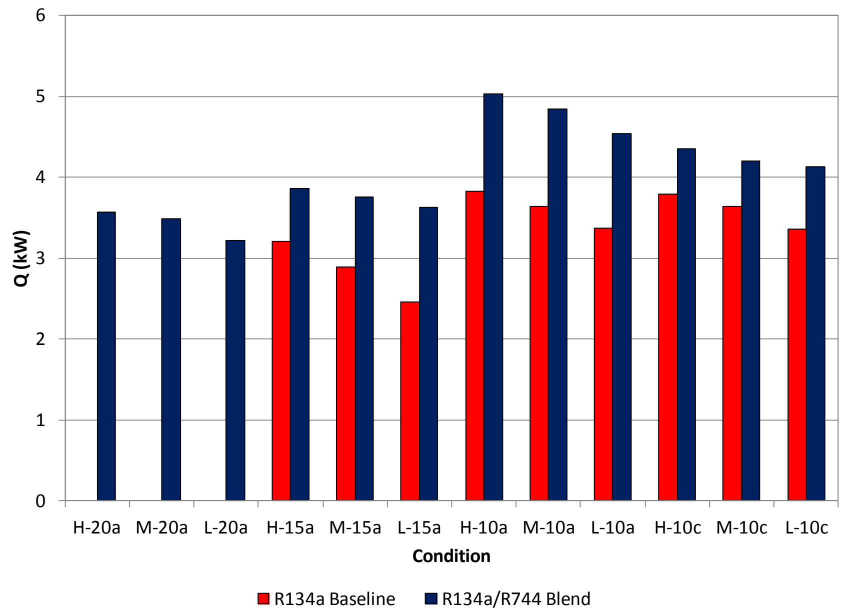

Figure 4: Capacity Comparison Between R134a and R134a/R744 Blend

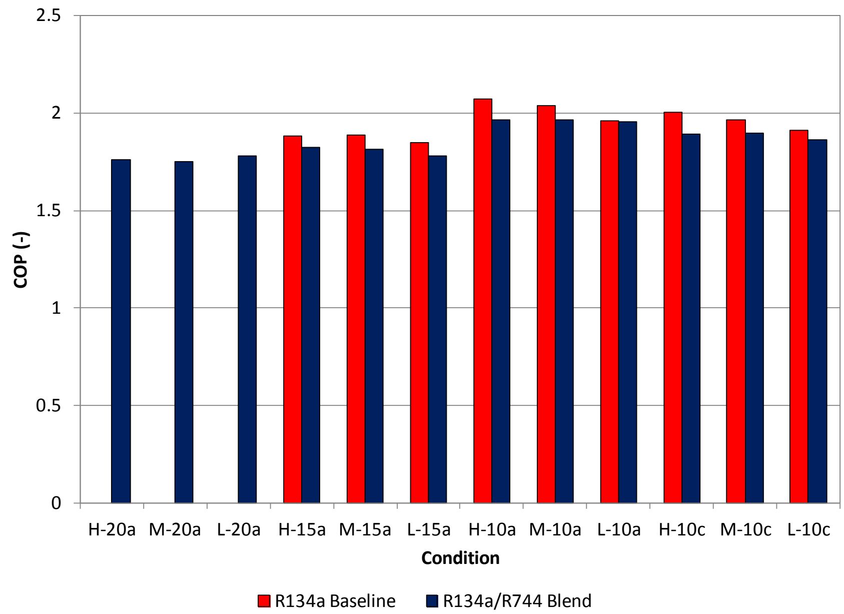

Figure 5: COP Comparison Between R134a and R134a/R744 Blend

Control optimization was performed for the R134a/R744 blend by varying the electronic expansion valve and the compressor speed while maintaining all other conditions constant. The subcooling was increased while reducing the compressor speed to maintain a constant heating capacity as shown in Figure 6. As the subcooling increased the compressor power dropped and the COP increased.

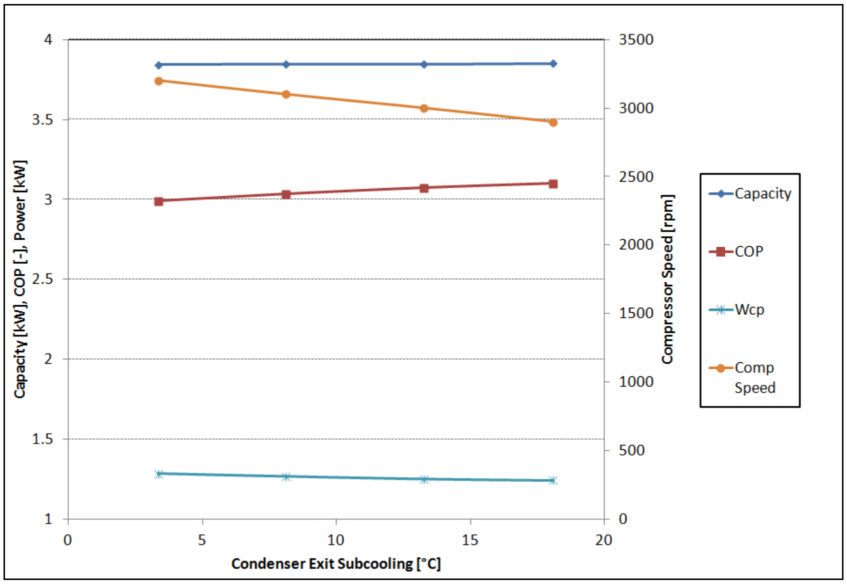

Figure 6: Control Optimization of the R134a/R744 blend at Condition M10a

The above results show the favorable performance of R445A compared to R134a in heat pump operation. Significant study has been performed on R445A as a drop-in for air conditioning as part of a SAE cooperative research program: MAC Refrigerant Blend Cooperative Research Program (MRB CRP). The results have been presented in the white paper, Development and Evaluation of AC5 and AC6 Refrigerants for MAC Applications (SAE, 2013). The study has shown that R445A as a drop-in has similar performance to R134a in A/C operation at high load conditions while there is a loss in COP of 5% to 10% at part load conditions. With the selection of an optimized internal heat exchanger and separated receiver it is possible to improve the A/C performance of R445A relative to R134a at part load and achieve equivalent or better performance relative to R1234yf. Thus with R445A significant performance gains are achievable in heat pump operation while minor shortcomings in A/C operation have been observed.

5. R744 EXPERIMENTATION AND RESULTS

Carbon Dioxide was first explored for use in automotive air conditioning in the 1990s and early 2000s as a replacement for R134a due to the greatly reduced global warming potential (1 compared to 1430). Despite comparable cooling capacities and COP values, R744 was eventually surpassed by new drop-in refrigerants such as R1234yf which require very few changes on the component level compared to R744. Heat pump operation was explored as part of the initial A/C research for R744 at the University of Illinois Air Conditioning and Refrigeration Center (Musser 2005) and those results have been revisited in this paper for comparison to R134a and the R134a/R744 blend. R744 has recently gained traction again in automotive air conditioning, specifically in Europe, due to flammability concerns with R1234yf. If R744 is implemented for vehicle air conditioning, usage in vehicle heat pumps is expected to soon follow. R744 has been used in heat pumps for hot water heating beginning in the mid 1990s and is prevalent in Japan. Use in commercial hot water heating is also being explored (Petersen *et al*, 2012). R744 is also used in many other cooling applications on the market today ranging from light commercial to supermarket refrigeration.

The experimental facility used for the automotive R744 heat pump exploration consisted of 2 calorimeters and is similar in function to the facilities described above. The vehicle components used were designed for a mid-sized sedan as with the other refrigerants discussed but in this case a belt-driven compressor was used. The system consisted of components primarily designed for A/C operation and not optimized for use in heat pump operation. The system used only 2 heat exchangers and is presented in heat pump configuration in Figure 7 below.

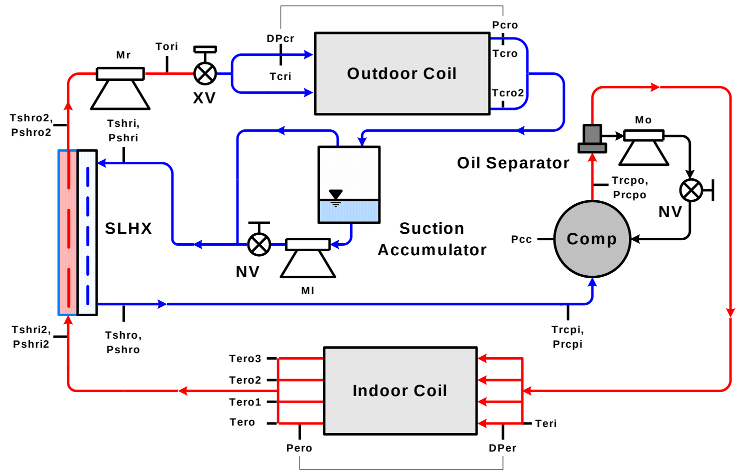

Figure 7: R744 Heat Pump System

The R744 heat pump was tested at several ambient temperatures going down to -40°C. At each ambient condition the indoor temperature was increased from the ambient temperature up to 20°C (in most cases) in a series of steady state points to simulate the warm up of the cabin as shown in Figure 8. All conditions shown in the figure were run at a worst-case compressor idle speed and higher capacities could be achieved at higher vehicle speeds (or compressor speeds in the case of an electric vehicle with variable speed electric compressor). R744 showed good heating capacity of 4kW to 5kW at each of the lowest indoor/outdoor temperature combinations where the greatest heating is needed. Comparing similar conditions of -20°C and -10°C between the 3 refrigerants yields similar heating capacities between the R134a/R744 blend and R744 with R744 being 10% higher at -20°C at 4kW compared to 3.6kW. As shown above, these are both significantly above the R134a capacity at approximately 30% higher at -10°C. The COP of the R744 heat pump was much higher than that of the other fluids. At -10°C the R744 COP was 3.2 compared to R134a and the R134a/R744 blend exhibiting COP values of approximately 2. At -20°C the R744 COP was nearly double that of the R134a/R744 blend at 3.4 compared to 1.8 respectively.

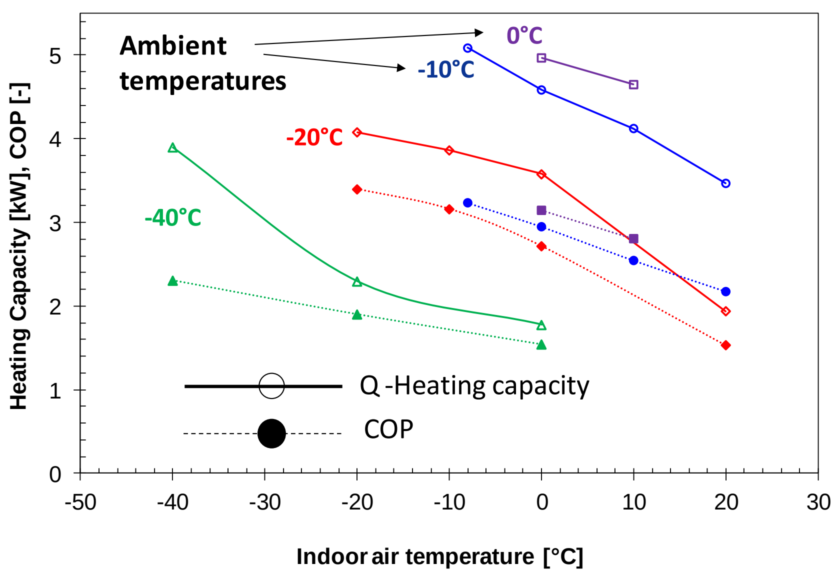

Figure 8: R744 Heat Pump Results

Control optimization was also performed on the R744 heat pump system. Unlike the hybrid system with a variable speed electric compressor used with the low pressure fluids, the belt driven compressor used for the R744 experiments had a fixed speed dependent on the simulated vehicle speed. The most influential control variable explored was the expansion valve. Park *et al*. (1999) have shown using similar systems that maximum COP and capacity can be obtained for a transcritical R744 mobile A/C system by regulating high-side pressure. A relationship between maximum COP and high-side pressure was determined based on Park's study. Giannavola (2001) further showed capacity and COP/HPF maximums were obtainable by regulating high side pressure in both A/C and H/P transcritical operation. The study presented here and originally shown by Musser (2005) extended this work to low temperatures where subcritical operation is expected for the heat pump system. Figure 9 shows high side pressure control exploration for -20°C ambient temperatures and multiple indoor air temperatures. As expected, the compressor power increases as the pressure increases. However, due to the loss of compressor efficiency at higher pressure ratios, the refrigerant mass flow rate and evaporator capacity reaches a maximum and then begins to drop. The initial evaporator capacity increase is due to increased subcooling caused by better condenser performance from higher temperature difference between refrigerant and air side but the loss in mass flow eventually outweighs the gains. The condenser or heating capacity is the sum of the compressor power and evaporator capacity thus it increases to the point at which the evaporator capacity loss becomes greater than the compressor power addition. This heating capacity maximum occurs at subcritical pressures for indoor temperatures of -10°C and -20°C for the -20°C ambient condition. The COP/HPF maximums occur at lower pressures than the capacity maximums due to relatively low heating capacity gains compared to the elevated compressor power input as the pressure increases. Thus, there is a trade-off between maximizing heating capacity and efficiency in subcritical operation and at these low temperatures capacity would likely be chosen over efficiency during the initial warm-up period.

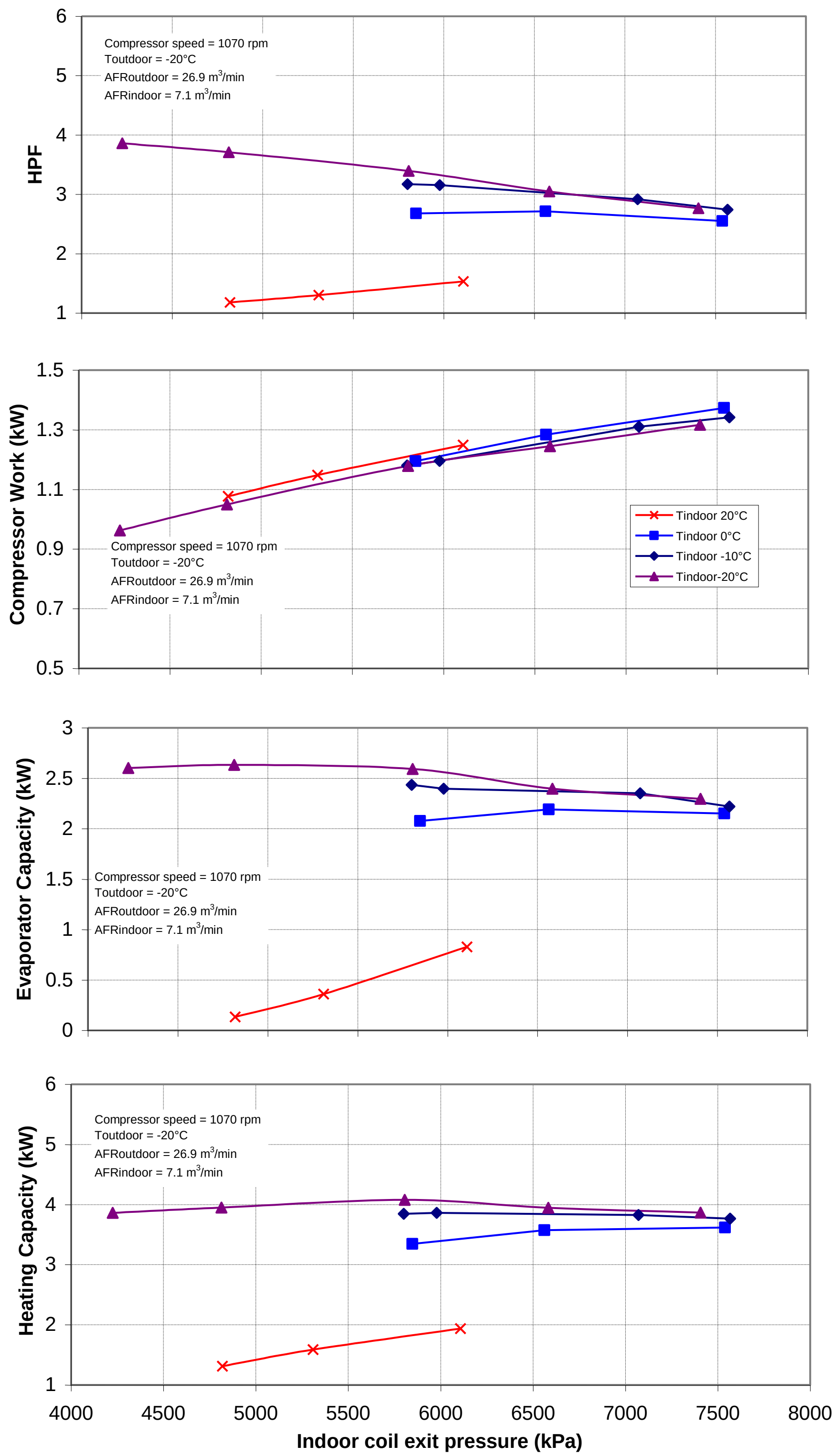

Figure 9: High Side Pressure Control Exploration at -20°C Ambient

6. CONCLUSIONS

Electric vehicle range is largely dependent on heating loads in the winter months. Currently R134a and R1234yf are being used in heat pumps in vehicles on the market. Considerable improvements in heating performance have been shown in this paper for the R134a/R744 blend and R744. The R134a/R744 blend exhibits 15% to 50% higher heating capacities compared to R134a for the conditions tested at -10°C and below while maintaining comparable COP values. R445A has marginally lower performance in A/C operation compared to R134a and is overall a good option for A/C-HP systems based on performance. R744 shows equal or greater capacities compared to the already strong R134a/R744 blend results at -10°C and -20°C despite only operating at idle compressor speeds. At the equal or greater capacities, R744 exhibits much higher COP values up to nearly double that of the R134a/R744 blend at -20°C. Heat pump performance alone will likely not drive the adoption of R445A or R744 in vehicles but the European Union regulations for GWP below 150 combined with flammability concerns for R1234yf may lead to adoption of one of these refrigerants opening the door for improved heat pump performance.

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