2014

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ABSTRACT

This paper presents technical assessment of environmentally friendly refrigerants as alternatives to R410A for window air conditioners. The alternative refrigerants that are studied for its replacement include R32, R600a, R290, R1234yf, R1234ze and a mixture of R32 (90% molar concentration) and R125 (10% molar concentration). Baseline experiments were performed on a window unit charged with R410A. A detailed heat pump design model (HPDM) was calibrated with the baseline data and was used to assess the comparative performance of the WAC with alternative refrigerants. The paper discusses the advantages and disadvantages of each refrigerants and their suitability for window air conditioners.

1. INTRODUCTION

Window air conditioners (WAC) are cheap and sold in large numbers internationally as alternatives to central air-conditioning systems for space cooling and supplemental cooling to improve comfort in older buildings that lack ducted systems, and in cases where a central system upgrade is first-cost prohibitive [Nogueira (2013), Winker et al. (2013)]. There are nearly 57 million WACs currently operating within the United States alone that account for approximately 1.5% of the total US residential energy use or about 0.33 quads per year. Due to global warming and other environmental concerns, there is a pressing need to find an alternative with smaller Global Warming Potential (GWP) to the currently used refrigerant R410a in WACs in order to reduce the greenhouse gas emissions and protect the environment. There are several alternative refrigerant options available, including R32, R600a, R290, R1234yf and R1234ze; however, all of these are either flammable or slightly flammable.

Due to the compact size configuration and small refrigerant charge of R410A in a WAC, the flammability of the refrigerant is less of a concern. Because of this, these potential refrigerants can be evaluated as an alternative to R410A. This study documents the details of a WAC unit charged with R410A, its testing in the laboratory environment, specifically the effectiveness of the sub-merged sub-cooler and the slinger in the performance improvement of the WAC. Based on the test data, the heat pump design model (HPDM) [Rice et al. (1981)] was modified to include specific features of a WAC (e.g., the sling effect and the sub-merged sub-cooler). The model has the unique capability of analyzing a heat exchanger using the segment-by-segment approach. This model was calibrated against the baseline experimental data and was then used to perform parametric analyses to assess the performance of the WAC with alternative refrigerants including R32, R600a, R290, R1234yf and R1234ze. The paper discusses the relative merits of each refrigerant on the system performance.

2. SYSTEM CONFIGURATION AND DESIGN DETAILS

A high efficiency WAC having a nominal cooling capacity of 10,000 Btu/hr was extensively tested in an environmental chamber and modelled. The WAC has a single-speed rotary compressor, a fin-&-tube evaporator and condenser, a capillary tube and a motor mounted on a single axis shaft to drive both the evaporator blower and the condenser fan. In addition to these basic components, the WAC has a fin-&-tube sub-cooler, submerged in a water collection pan, which gathers water condensate from the evaporator. The submerged sub-cooler is downstream of the air-to-refrigerant condenser to further subcool the liquid refrigerant. The schematic diagram of the WAC and its P-h diagram are shown in Figures 1 and 2 respectively. The condenser fan blade is specially configured, to pick up water from the water collection pan and to spray it in the air stream flowing over the condenser coil surface. The water droplets evaporate and enhance the condenser heat transfer. This feature is called the "sling" effect. Figures 3, 4 and 5 respectively show the single axis fan, the "slinger" and instrumented WAC. Some of the basic parameters of the evaporator and condenser are given in Table 1.

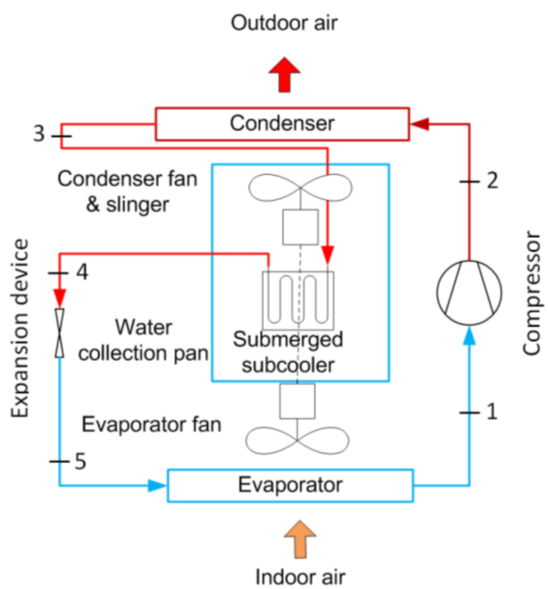

Figure 1: Schematics of Window Air Conditioner

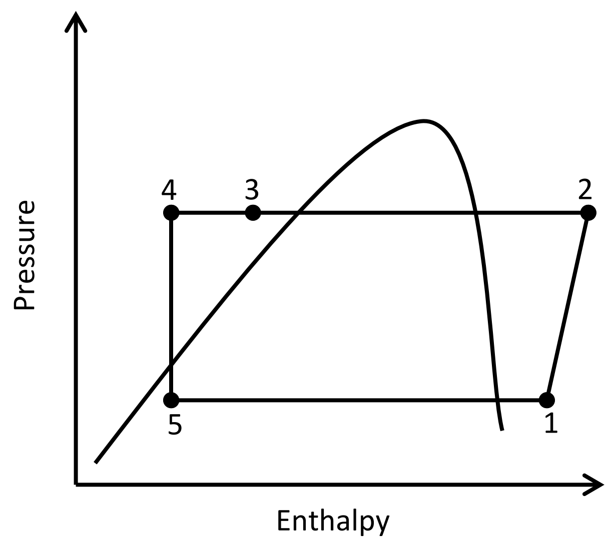

Figure 2: P-h diagram of Window Air Conditioner

Figure 3: Single axis blower/fan

Figure 4: Slinger on condenser fan

Figure 5: Instrumented WAC

Table 1: Condenser and Evaporator of WAC

Parameters	Fin-&-Tube Condenser Coil	Fin-&-Tube Evaporator Coil
Face area [ft^2]	1.356	0.797
Total Tube Number	48	48
Number of rows	3 (cross counter-flow)	4 (cross counter-flow)
Number of parallel circuits	4	3

At the standard rating conditions [DOE(2011), e-CFR(2014)], i.e. ambient temperature of 95ºF and indoor dry bulb/wet bulb temperatures of 80ºF/67ºF, the corresponding compressor isentropic and volumetric efficiencies are taken as 66% and 86% respectively, from the manufacturer's manual. The compressor shell heat loss ratio, relative to the compressor power, is assumed to be 20%. In this study, the high efficiency WAC was extensively tested over a range of operation conditions. The experimental data was used to calibrate the HPDM for the WAC to match the measured performance. Simulations were performed for multiple alternative refrigerants, e.g. R32, R600a, R290, R1234yf, R1234ze, and a mixture of R32/R125 with molar concentrations of 90%/10%. The GWPs of these refrigerants are given in Table 2. All refrigerant properties were calculated using NIST REFPROP 9.0. The comparisons are presented in terms of efficiency, compressor displacement volume, heat exchanger saturation temperature changes, and compressor discharge temperature.

Table 2: GWPs of the Refrigerants

	R410A	R32	R134a	R600a	R290	R1234yf	R1234ze	R32-90%/R125-10%
GWP	2079	675	1430	20	20	4	6	1251

3. HPDM WITH SPECIFIC FEATURES OF WINDOW AIR CONDITIONER AND ITS VALIDATION

The HPDM is a hardware-based steady-state component-based simulation model that uses Newton-Raphson method to solve simultaneous system equations. The component HX models have different levels of complexity, which fall into three categories, i.e. bulk models, phase-to-phase models, and discretized models. These are used to build a heat exchanger having arbitrary circuitry, geometry, and represent any boundary conditions. All phase-to-phase and segment-to-segment heat exchanger models are capable to calculate refrigerant charge inventory. For the system modeling, a component-based modeling framework has been developed that allows connecting steady-state component models in any manner. Details of some of the component models used to model the WAC unit are described below.

Compressor: HPDM provides multiple choices per AHRI standard [ANSI/AHRI (2007)] for modeling a single-speed compressor; however, 10-coefficient compressor map has been used here to model the baseline WAC unit using R410A. It simulates energy balance from inlet to outlet using the calculated power and given heat loss ratio; and it also considers the actual suction state to correct the map mass flow predictions. Since the compressor maps are not available for other alternative refrigerants being considered in this study, constant values of volumetric efficiency, isentropic efficiency, compressor displacement volume and rotational speed (3500 RPM) have been used.

Heat Exchangers: A segment-to-segment modeling approach has been used here where each tube segment has individual air side and refrigerant side entering states, and may have possible phase transition. Within each segment, an ε -NTU approach is used for heat transfer calculations and air-side fin is simplified as an equivalent annular fin. Both refrigerant and air-side heat transfer and pressure drops are considered. The coil model can simulate arbitrary tube and fin geometries and circuitries and any entering and exit states of refrigerant, misdistribution, two-dimensional air side temperature, and local inputs of humidity and velocity. The tube circuitry and 2-D boundary conditions are provided by an input file. The segment-to-segment modeling approach is also capable of simulating the dehumidification process of water condensing on an HX coil (i.e. evaporator) by following Braun et al. (1989) methodology, where the driving potential for heat and mass transfer is the enthalpy difference between the inlet air and the saturated air at the refrigerant temperature. The flow-pattern-dependent heat transfer correlations by Thome et al. (2002, 2003a, 2003b) are used to calculate the tube side evaporation and condensation heat transfer coefficients.

Expansion Device: The degree of superheat at the compressor suction as well as the degree of sub-cooling at condenser outlet is explicitly specified to model the expansion device.

Fans and Blowers: For a given airflow rate, the model uses the fan curve to simulate static head, power consumption, and calculate air-side temperature increment from inlet to outlet.

Submerged sub-cooler: The sub-cooler model considers phase transition in the heat transfer section, i.e. allowing two-phase or liquid refrigerant entrance [LBNL (1997)]. It assumes natural convection at the water side. The water pool temperature is a measured input. Effectiveness-NTU method is used to calculate energy transfer rate between the refrigerant and water.

The "slinger" Effect: The slinger sprays water droplets into the air stream flowing over the condenser coil surface [LBNL (1997)]. Instead of modeling the heat and mass transfer process, a simple approach was adopted here to treat the slinger effect as an air side heat transfer enhancement factor from the experimental data. Figure 6 compares the model predicted air side heat transfer enhancement multipliers due to the sling effect to laboratory data reduced heat transfer multipliers, as a function of the ambient temperature. The laboratory data reduced heat transfer multipliers were obtained by adjusting air side heat transfer coefficient of the condenser model to match the measured performance, assuming no sling effect. Since there is a large dispersion in the laboratory measurements, deviations between the laboratory reduced and model predicted heat transfer multipliers can be up to 30%. However, the average multipliers are close; with laboratory reduced multiplier being 1.33, and the model predicted average multiplier being 1.24.

Figure 7 shows the incremental performance benefits with submerged sub-cooler and the slinger, in comparison to a baseline WAC without the submerged sub-cooler and the slinger.

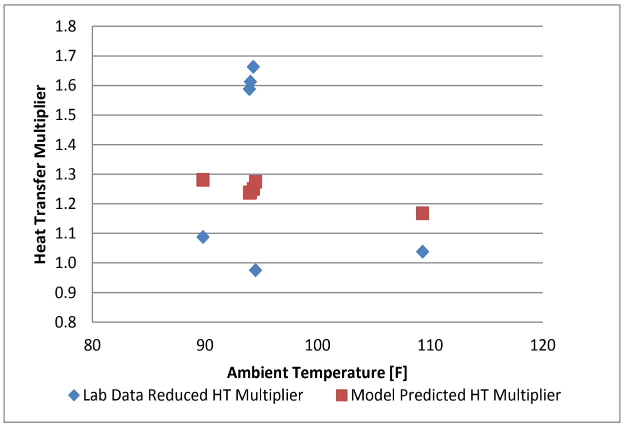

Figure 6: Heat transfer enhancement ratio due to 'sling effect' vs. ambient temperatures

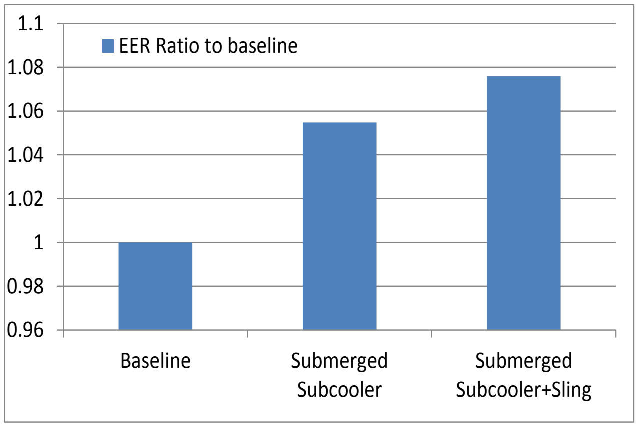

Figure 7: Incremental EER enhancements by using submerged sub-cooler and slinger.

4. COMPARISON OF ORNL MODEL WITH THE TEST DATA

After the model had been calibrated with the experimental data, the model predictions were compared with the test data over a range of ambient conditions. The measured EER is plotted against the simulated EER in Figure 8. The model predictions agree to within -0.5% to +6.5% with a standard deviation being limited to 2.7%.

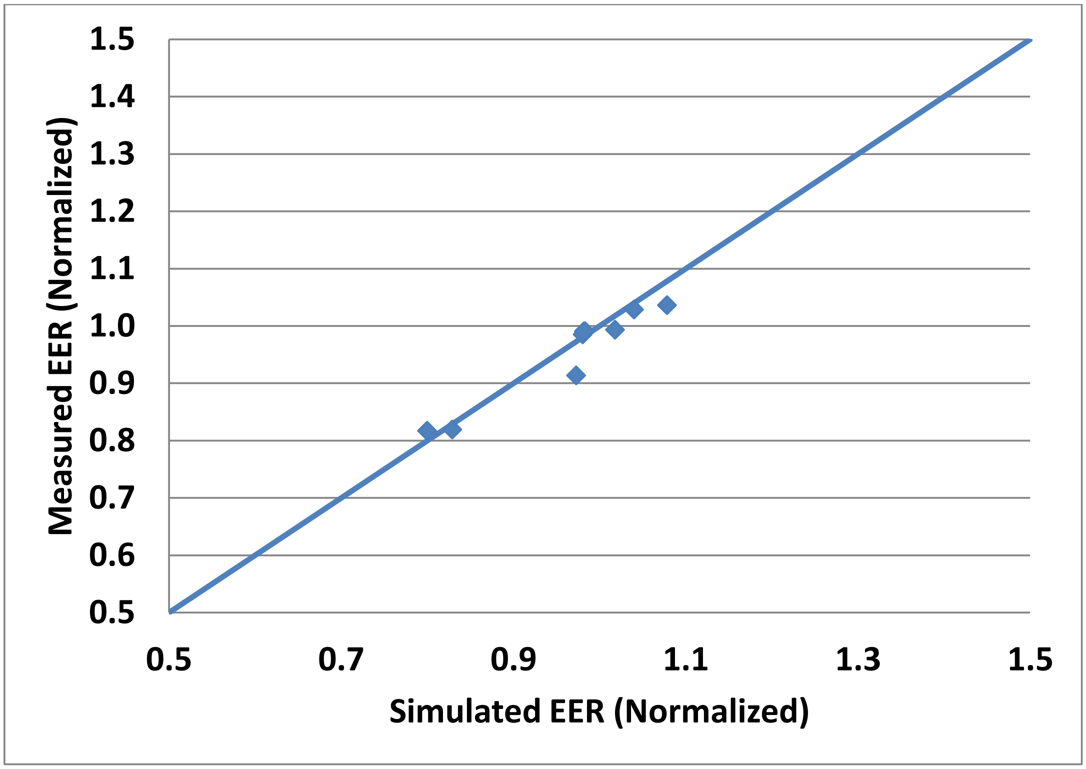

Figure 8: Variation of 'measured EER' with 'simulated EER' at different ambient temperatures

5. RESULTS AND DISCUSSION

In order to identify the best potential replacement for R410A in WACs, simulations were performed at the standard rating condition of 95ºF outdoor dry bulb temperature, and 80ºF/67ºF indoor dry bulb/wet bulb temperature. The compressor displacement volume was automatically adjusted to facilitate the same cooling capacity of 10,000 Btu/h, for various refrigerants, while assuming the same isentropic efficiency of 66% and volumetric efficiency of 86%. The degrees of condenser sub-cooling and the evaporator superheat are held at 10ºR. All the simulations were run with the submerged sub-cooler and slinger.

Required Compressor Displacement Volumes: Figure 9 illustrates the required compressor displacement volumes to achieve the cooling capacity of 10,000 Btu/h for each refrigerant. It can be seen that R410A, R32, and R32-90%/R125-10% require similar displacement volumes. It means that R32, and R32-90%/R125-10% can be suitable "drop-in" replacements for R410A using the same compressor. However, other refrigerants require a noticeably larger displacement volume, which implies that specific compressors will need to be designed if these refrigerants were to be considered for WACs.

Comparison of Heat Exchanger Configurations: Figures 10 and 11 show the variations of saturation temperatures in the evaporator and condenser respectively for various refrigerants. It can be seen that saturation temperature drops are more significant for R134a, R600a, R1234yf, and R1234ze. It indicates that these refrigerants would require different heat exchanger configurations if used for WACs.

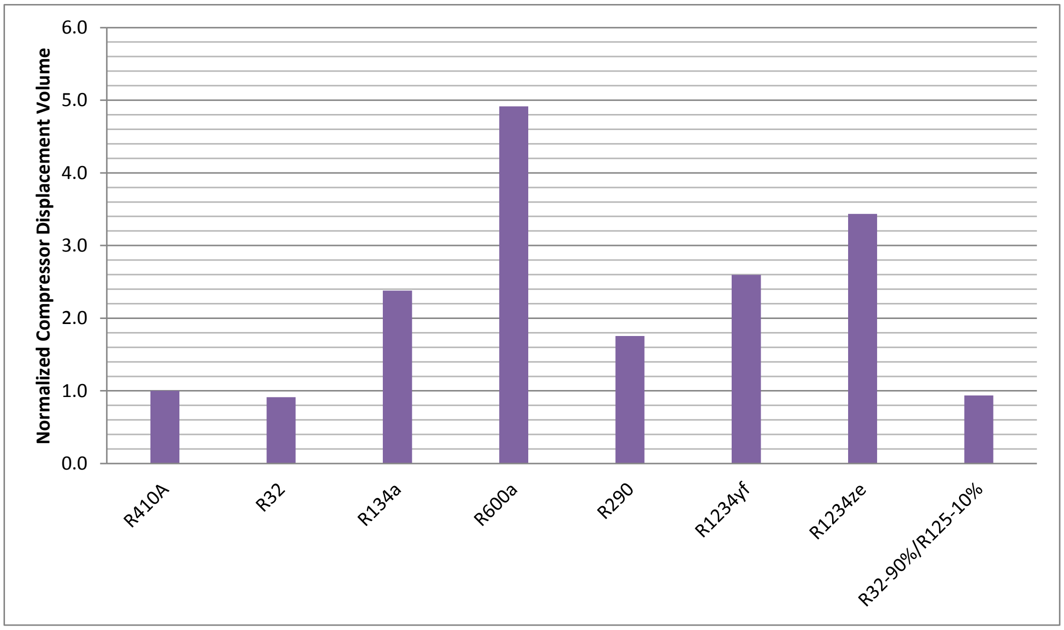

Figure 9: Normalized Compressor Displacement Volumes of Various Refrigerants

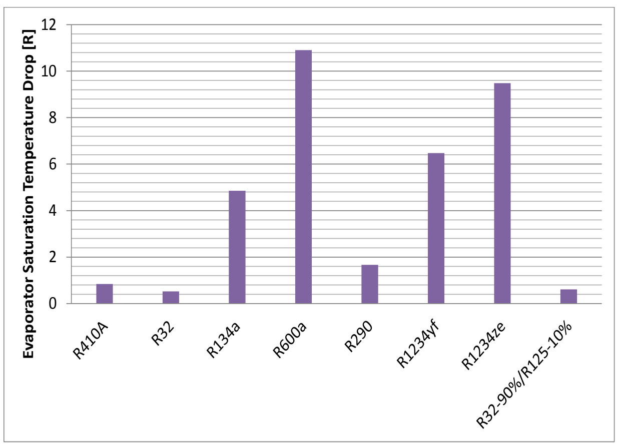

Figure 10: Evaporator Saturation Temperature Changes of Various Refrigerants

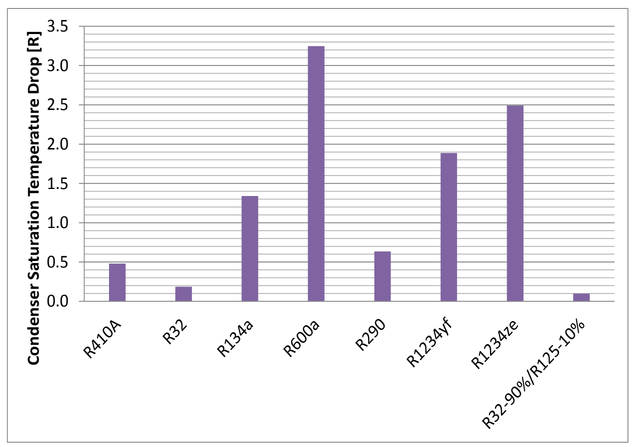

Figure 11: Condenser Saturation Temperature Changes of Various Refrigerants

Comparing Compressor Discharge Temperatures: The variation of discharge temperatures of various refrigerants has been exhibited in Figure 12, where R32 shows the highest discharge temperature, which is about 30ºR higher than R410A. It may be noted here that the "slinger" is effective in a number of ways, including reducing the condenser saturation temperature, and hence reducing the discharge temperature by about 7ºR as compared with not using the slinger.

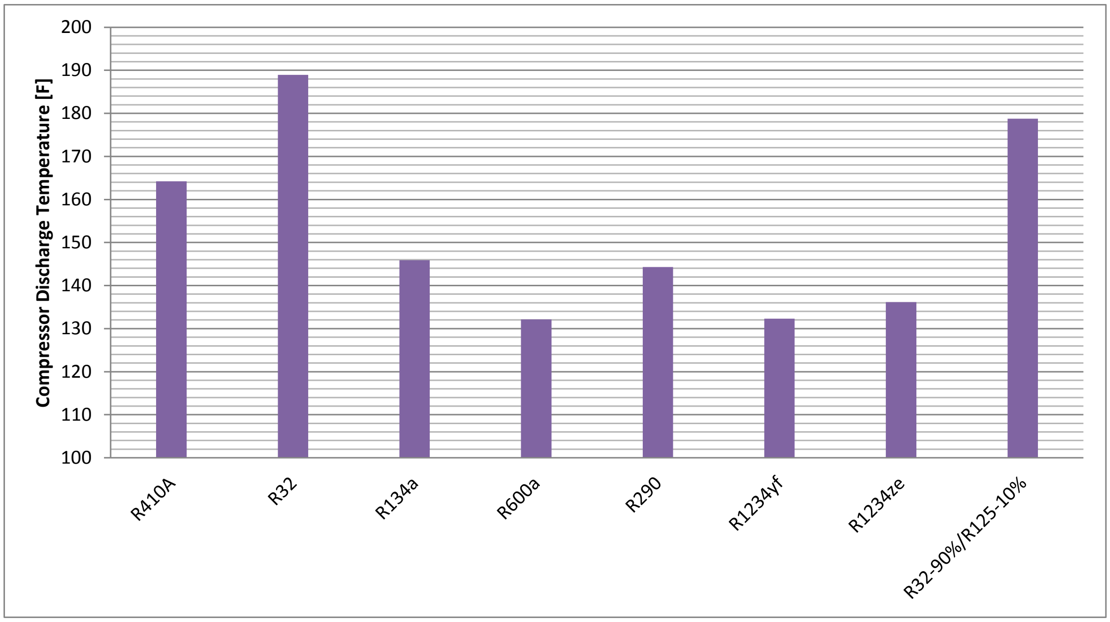

Figure 12: Compressor Discharge Temperatures of Various Refrigerants

Comparing EERs: Figure 13 illustrates the EERs of various refrigerants at the ambient temperature of 95ºF. It can be seen that R32 results in the highest EERs with the same heat exchangers and compressor as that of the base unit. This is followed by R290, the mixture of R32(90%)/R125(10%) and R410A, while all other refrigerants perform worse than R410A.

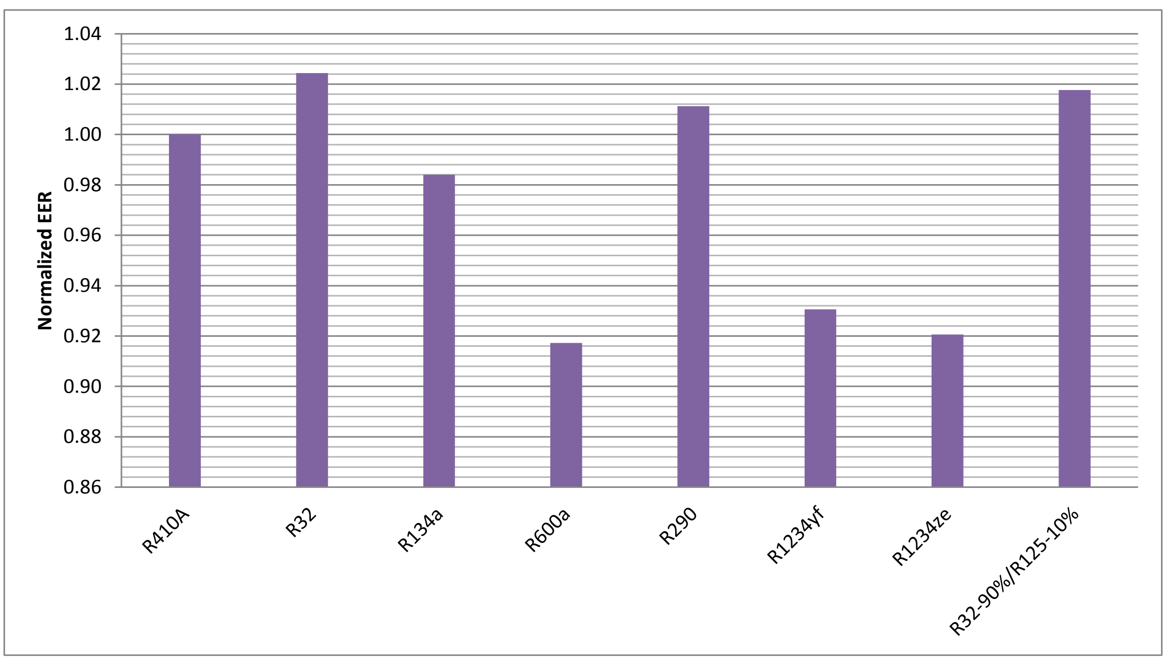

Figure 13: Normalized EERs of Various Refrigerants at 95ºF ambient temperature

6. CONCLUSIONS

A high efficiency WAC, using R-410A, was extensively tested. The experimental data demonstrates that the combination of a submerged subcooling loop and slinger effect boosts the system EER at 95ºF by almost 8% (Figure 7). A calibrated WAC system model was used to assess the lower GWP alternative refrigerants (for R410A) as R32, R600a, R290, R1234yf, R1234ze, and a mixture of R32/R125 with molar concentrations of 90%/10%. From the perspective of efficiency and 'drop in' refrigerant, R32 is clearly the best choice since it results in the highest EER without the need for any modification in components. However, R32 suffers from slight flammability concerns and it also has the highest discharge temperature of up to 200ºF at 95ºF ambient. An alternative option is the mixture of R32/R125 with the respective molar concentration of 90%/10% for balancing between efficiency and flammability. R1234yf and R1234ze, i.e. two HFO refrigerants, offer the worst EERs, and require larger compressor displacement volumes to achieve the same cooling capacity. Clearly, the compressor and heat exchangers have to be re-optimized for any of these HFO refrigerants. Between the two natural refrigerants, R290 can be a potential replacement for R410A, since it leads to a higher EER with the same heat exchanger configurations. However, R290 needs a larger compressor displacement volume than R410A and has significant flammability issues.

ACKNOWLEDGMENTS

The authors also acknowledge the support of Building Technologies Office of the US Department of Energy under contract DE-AC05-00OR22725 with UT-Battelle for their financial support and industry partner for their in-kind and technical support.

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