



**Air-Conditioning, Heating, and Refrigeration  
Institute (AHRI) Low-GWP Alternative Refrigerants  
Evaluation Program (Low-GWP AREP)**

## **LITERATURE REVIEW**

### **Reference List for low GWP Refrigerants Testing**

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**This document provides a reference list of existing literature on testing of low-GWP refrigerants conducted other than through AHRI's Low-GWP AREP. It was prepared by AHRI's Low-GWP AREP Technical Committee to inform the public of the existing research in the area of low-GWP alternative refrigerants.**



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## Reference List for Low GWP AREP “Natural and New Refrigerants” Literature Review

A team was formed as part of the Low-GWP Alternative Refrigerants Evaluation Program (Low-GWP AREP) to select and compile "existing works of good quality" that provide performance test information on "natural refrigerants" and low-GWP fluorinated refrigerants with comparison to the performance of an HCFC or HFC refrigerant as a "baseline". The test information can take the form of compressor calorimeter tests, drop-in system tests, or soft-optimized system tests for air-conditioners, heat pumps, dehumidifiers, chillers, water heaters, ice makers, and refrigeration equipment. Including this information with the Low GWP AREP results is intended to provide a convenience for users. A second purpose is to identify any gaps in the data for "natural refrigerants" or low-GWP fluorinated refrigerants that may warrant testing.

What follows is a list of papers that provide test results for many refrigerants of interest for the Low GWP AREP program. Short descriptions of the tests and tested refrigerants are given for most papers.

As the literature review progressed, categories were added for heat transfer data for the “natural refrigerants” and for the new refrigerants being evaluated in the Low GWP AREP Program. Reports on system and compressor tests with the new refrigerants are included as well.

Some papers included here provide test results and heat transfer measurements obtained with R-744 (CO<sub>2</sub>) as the refrigerant. This refrigerant has been studied extensively in recent years. Just a few of the R-744 papers that are available are included here.

### Systems Tests

#### Air Conditioning

[aki10] Akira, F., Tsutomu, S., Shigehiro, S., and Yoshikazu, K., “Application of Low Global Warming Potential Refrigerants for Room Air Conditioner”, 2010 International Symposium on Next-Generation Air Conditioning and Refrigeration Technology, Japan

[apr09] Aprea, C. and Maiorino, A., “Heat Rejection Pressure Optimization for a Carbon Dioxide Split System: An Experimental Study”, Applied Energy, Vol. 86, 2009, p.2373-2380. A split system air conditioning prototype operating with CO<sub>2</sub> refrigerant, two compressor stages, and an internal heat exchanger (IHX) was used in this project. At an evaporating temperature of 5° C and gas cooler outlet temperature of 30° C with 80 bar operating pressure, the cooling capacity is approximately 3 kW. Air was the heat transfer fluid for both the evaporator and the gas cooler. An EEV connected in series with a back pressure valve was used as the throttling device to improve evaporator operation when load changes. Optimum pressure level for the gas cooler vs. external ambient temperature was determined for ambient temperatures of 25°, 30°, and 35° C.

[cav05] Cavallini, A., Cecchinato, L., Corradi, M., Formasieri, E., and Zilio, C., “Two Stage Transcritical Carbon Dioxide Cycle Optimization: A Theoretical and Experimental Analysis”, International Journal of Refrigeration, Vol. 28, 2005, p.1274-1283. Tests were run with a reciprocating two-stage compressor

using CO<sub>2</sub> as the refrigerant. The system was equipped with external gas intercooling between the two compressor stages and a back-pressure valve as the throttling device. The test conditions were chosen in the range of air-conditioning applications: evaporator saturation temperature 2.7° C, evaporator outlet temperature 8 to 10° C, and gas cooler outlet temperature 33° C. The evaporator and gas intercooler were fin-tube coils with air as the external fluid. The results confirmed that an optimum gas cooler pressure gave maximum COP in the transcritical cycle. The effect of temperature of the secondary fluid in the intercooler was evaluated as well.

[cho00] Cho, H., Baek, C., Park, C., and Kim, Y., "Performance Evaluation of a Two-Stage CO<sub>2</sub> Cycle With Gas Injection in the Cooling Mode Operation", *International Journal of Refrigeration*, Vol. 32, 2000, p.40-46. This study investigated the performance of two-stage CO<sub>2</sub> cycles with and without gas injection and with optimal control of the EEV opening in a two-stage cycle with gas injection. The test conditions were for a comfort cooling application. The refrigerant charge amount, compressor drive frequencies, and EEV openings were varied to determine the optimum conditions for COP and cooling capacity.

[cho07a] Cho, H., Ryu, C., and Kim, Y., "Cooling Performance of a Variable Speed CO<sub>2</sub> Cycle with an Electronic Expansion Valve and Internal Heat Exchanger", *International Journal of Refrigeration*, Vol. 30, 2007, p.664-671. This study measured the performance of a CO<sub>2</sub> air conditioning system equipped with a variable-speed scroll compressor, finned tube gas cooler and evaporator, an electronic expansion valve and an internal heat exchanger (IHX) with varying length. Cooling performance was measured at standard indoor test conditions of 27° C DB/19.5° C WB and outdoor conditions of 35° C DB/24° C WB. First, the optimum charge was determined for the system. Then tests were conducted by varying the compressor speed, EEV opening, and IHX length at the optimum charge condition.

[dev05] Devotta, S., Padalkar, A.S., and Sane, N.K., "Performance Assessment of HC-290 as a Drop-In Substitute for HCFC-22 in a Window Air Conditioner", *International Journal of Refrigeration*, Vol. 28, Issue 4, June 2005, p. 594-604. Capacity and COP data are provided for a window air conditioner using R-22, the design refrigerant, and for R-290 as a drop-in refrigerant.

[elb08] Elbel, S., and Hrnjak, P., "Experimental Validation of a Prototype Ejector Designed to Reduce Throttling Losses Encountered in Transcritical R744 System Operation", *International Journal of Refrigeration*, Vol. 31, 2008 p. 411-422. An ejector improved the COP and cooling capacity by up to 7% and 8% respectively in a transcritical CO<sub>2</sub> system. The ejector performed with a higher efficiency when the high-side pressure was relatively low. Despite lower ejector efficiencies the COP increased as the high side pressure increased as a result of reducing the motive nozzle throat area in the variable-geometry ejector.

[end10] Endoh, K., Matsushima, H., and Takaku, S., "Evaluation of Cycle Performance of Room Air Conditioner Using HFO-1234yf as Refrigerant", *International Refrigeration and Air Conditioning Conference*, Purdue University, 2010. An R-410A room air conditioner/heat pump with a rated cooling capacity of 4 kW was used for the tests. Baseline tests were run with R-410A. Then drop-in and optimized system tests were conducted with R-1234yf. Cooling mode test conditions were 27° C dry

bulb, 19° C wet bulb, and 35° C outdoor air. Heating mode test conditions were 20° C dry bulb, 15° C wet bulb (indoors), and 7° C outdoor air.

[fuj10] Fujitaka, A., Shimizu, T., Satao, S., and Kawabe, T., “Application of Low Global Warming Potential Refrigerants for Room Air Conditioner”, 2010 International Symposium on Next-Generation Air Conditioning and Refrigeration Technology, Tokyo, February 2010. A 4 kW room air conditioner/heat pump was tested in cooling mode and heating mode with R-410A as the baseline refrigerant and R-1234yf as the low GWP alternative. Drop-in tests with R-1234yf employed increased compressor speed to make up in part for the lower volumetric cooling capacity of the refrigerant. Tests also were performed with R-32/R-1234yf mixtures ranging from 10% R-32 to 50% R-32.

[har10] Hara, H., Oono, M., and Iwata, I., “Experimental Study of Low GWP Refrigerants for Room Air Conditioners”, 2010 International Symposium on Next-Generation Air Conditioning and Refrigeration Technology, Japan

[hic12] Hickman, K., “Alternatives to High GWP HFC Refrigerants: Chiller Applications”, ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, October 29-30, 2012. This paper includes several test results for low-GWP refrigerants in chillers. A drop-in test was conducted on a 70 ton production air-cooled chiller with three scroll compressors in each of two circuits. Performance with R-32 was compared to performance with the design refrigerant, R-410A. An R-134a water-cooled centrifugal chiller with a rated capacity of 560 tons was tested with XP10 as indicated in the following reference [kon12]. In a test for the Low-GWP AREP program, an air-cooled water chiller/heat pump with a design cooling capacity of 4.8 tons (16.9 kW) was used to test a number of low-GWP refrigerant alternatives. The unit originally was designed to use R-22 or R-407C but it was refitted with a compressor and expansion valve designed for R-410A. Refrigerants tested include R-410A, R-32, DR-5, ARM-70, L-41a, L-41b, and HPR1D. The results can be found in Report SDO13 included with the Low-GWP AREP Program Test Reports from AHRI.

[kon12] Kontomaris, K., Kauffman, J.P, and Kulankara, S., “A Reduced GWP Replacement for HFC-134a in Centrifugal Chillers: XP10 Measured Performance and Projected Climate Impact”, International Refrigeration and Air Conditioning Conference, Purdue University, July 16-19 2012. The performance of XP-10, a lower-GWP refrigerant (GWP of 600-650), was measured at full and part-load conditions in a centrifugal chiller designed for R-134a. Energy efficiencies with XP-10 were close to those of R-134a, resulting in an 0.6% higher energy consumption for XP-10 when integrated over a representative load profile as described by AHRI Standard 550-590. It is concluded that XP-10 can be considered a near drop-in replacement for R-134a in centrifugal chillers.

[koy08a] Koyama, S., Xue, J., Takata, N., and Kuwahara, K., “An Experimental Study on the Cooling Performance of a CO<sub>2</sub> Cycle with an Internal Heat Exchanger”, Eighth IIR Gustav Lorentzen Conference on Natural Working Fluids, Copenhagen DK, 2008. An experimental facility with a 2 kW cooling capacity was operated at full capacity with gas cooler inlet temperature of 30° C and outlet temperature of 45° C. Two sets of evaporator conditions were tested: 20° C inlet temperature and 10° or 4.5° C outlet

temperatures. Tests were run with and without an internal heat exchanger. Results showed that the cooling performance of the CO<sub>2</sub> cycle depends greatly on the heat rejection pressure and there exists an optimum value where COP is maximized. The internal heat exchanger was found to be an important contributor to achieve higher COP and reduced optimal pressure level for comfort cooling applications.

[oka10] Okazaki, T., Maeyama, H., Saito, M., and Yamamoto, T., “Performance and Reliability Evaluation of a Room Air Conditioner with Low GWP Refrigerant”, 2010 International Symposium on Next-Generation Air Conditioning and Refrigeration Technology, Tokyo, February 2010. A 4 kW room air conditioner was tested with R-410A as the baseline refrigerant and R-1234yf as the low GWP alternative. Both drop-in and modified unit tests were conducted. Tests also were performed with R-32/R-1234yf mixtures ranging from 10% R-32 to 60% R-32.

[pot12] Pottger, G., and Hrnjak, P., “Effect of Subcooling on the Performance of Vapor Compression Systems: Experimental and Numerical Investigation”, International Refrigeration and Air Conditioning Conference, Purdue University, July 16-19 2012. A simulation model was used to determine the effect of condenser subcooling in a 3.5 kW residential air conditioning split system with an air-to-refrigerant multipass cross-flow multichannel condenser and evaporator. The results indicated that R-1234yf would benefit more from subcooling than R-410A, R-134a, and R-717 due to its smaller heat of vaporization. COP was found to undergo a maximum as subcooling is varied. Experimental results from a vehicular AC system confirmed the model predictions. For a given operating condition COP increased up to 18% for R-1234yf and only 9% for R-134a.

[shi01] Shigeharu, Y., Ryuzaburo, K., and Shigeru, K., “The Performance Evaluation of Room Air Conditioner Using R-32 in the Case of Cooling and Heating Mode”, Trans. JSRAE, Vol. 18, No. 3, 2001.

[ued12] Ueda, K., Wajima, K., Yokoyama, A., and Shimizu, A., “Study of Application Low GWP Refrigerant HFO-1234ze(E) for the Centrifugal Heat Pump”, JRAIA International Symposium on New Refrigerants and Environmental Technology, Kobe Japan, November 8-9, 2012. Drop-in tests with R-1234ze(E) were conducted on a two-stage 400 Ton (1407 kW) inverter-driven centrifugal chiller designed for R-134a. Cooling tests were conducted over a range of part-load capacities and reduced cooling water temperatures.

### **Air-Heating Heat Pump and Laboratory Heat Pump Test Rig Results**

[bar12] Barve, A. and Cremaschi, L., “Drop-In Performance of Low-GWP Refrigerants in a Heat Pump System for Residential Application”, International Refrigeration and Air Conditioning Conference, Purdue University, July 16-19, 2012. Drop-in performance tests were conducted with R-32 and R-1234yf in an R-410A 5 Ton (17.6 kW) heat pump split system. Both cooling and heating modes were tested, and additional tests were run at high (simulated) outdoor temperatures of 110° F (43° C) and 115° F (46° C).

[bis12] Biswas, A. and Cremaschi, L., “Performance and Capacity Comparison of Two New LGWP Refrigerant Alternatives to R-410A in Residential Air Conditioning Applications”, International Refrigeration and Air Conditioning Conference, Purdue University, July 16-19, 2012. Performance tests

were conducted with developmental refrigerants DR-4 and DR-5 in an R-410A 5 Ton (17.6 kW) heat pump split system. Both cooling and heating modes were tested, and additional tests were run at high (simulated) outdoor temperatures of 110° F (43° C) and 115° F (46° C). DR-5 had up to 4% higher capacity and up to 22% higher COP than R-410A while DR-4 had up to 16% higher COP but 30% lower capacity than R-410A.

[cha00] Chang, Y.S., Kim, M.S., and Ro, S.T., "Performance and Heat Transfer Characteristics of Hydrocarbon Refrigerants in a Heat Pump System", *International Journal of Refrigeration*, Vol. 23, Issue 3, May 2000, p. 232-242. Tests were run on a heat pump system using propane, isobutene, butane, propylene, and binary mixtures of propane/isobutene and propane/butane. Performance of each refrigerant is compared at several compressor speeds and temperature levels. COP and heating/cooling capacity results are presented. Results are compared to R-22. Condensation and evaporation heat transfer coefficients of selected refrigerants are obtained and compared to those of R-22.

[fuk12] Fukuda, S., Takaya, N., and Koyama, S., "The Circulation Composition of the Zeotropic Mixture R-1234ze(E)/R-32 in a Heat Pump Cycle", *International Refrigeration and Air Conditioning Conference*, Purdue University, July 16-19, 2012. The circulation composition of several zeotropic blends was measured in a laboratory heat pump test facility using an R-410A compressor. The blend compositions were R-1234ze(E)/R-32 : 20/80 mass %, 50/50 mass %, and 80/20 mass %. COPs and heating/cooling capacities are compared for the blends with those of R-410A and R-32. The circulation composition was found to vary with the velocity ratio of vapor and liquid, the operating pressure of the heat pump cycle, and the degree of subcooling at the condenser outlet.

[har10] Hara, H., Oono, M., and Iwata, I., "Experimental Study of Low GWP Refrigerants for Room Air-Conditioners", *2010 International Symposium on Next-Generation Air Conditioning and Refrigeration Technology*, Tokyo, February 2010. A 4 kW room air conditioner/heat pump was tested in cooling mode and heating mode with R-410A as the baseline refrigerant and R-1234yf as the low GWP alternative. Drop-in tests were conducted and then R-1234yf tests were performed with a larger compressor and with heat exchangers/lines modified to reduce pressure drop. Tests also were performed with R-32/R-1234yf mixtures ranging from 10% R-32 to 50% R-32.

[hwa03b] Hwang, Y., Gado, A., and Radermacher, R., "Performance of Propane in a Unitary Heat Pump", *Twenty-First International Congress of Refrigeration*, Washington D.C. USA, 2003

[jak04] Jakobsen, Arne et al, "Development of a Reversible CO<sub>2</sub> Residential Air Conditioning System Compared to a State-of-the Art R-410A Unit", *6<sup>th</sup> Gustav Lorentzen Conference*, Glasgow, 2004. A reversible CO<sub>2</sub> prototype RAC split unit was built and tested in calorimetric test chambers. A state-of-the art inverter-driven R-410A split unit was tested to serve as a baseline. CO<sub>2</sub> system testing was continuing at the time the paper was written. Some test results are presented.

[kon11] Kontomaris, K., and Leck, T., "Low GWP Working Fluids for Domestic, Commercial, and Industrial Heat Pumps: DR-5 and DR-2", *IEA Heat Pump Newsletter*, Vol. 29 (4), 2011 p.30-33. DR-5 is a near azeotropic blend of R-1234yf and R-32 which was tested as an alternative to R-410A in several types of

air conditioning and heat pump equipment. Tests were run in 4.5 kW, 7.2 kW, and 10 kW residential heat pumps, each from a different manufacturer. The 4.5 kW and 7.2 kW systems were equipped with variable speed inverter drives which allowed capacity matches to the R-410A baseline tests. The measured COP with DR-5 was higher than for R-410A whether tests were drop-in or capacity matched. In drop-in tests the capacity with DR-5 was 8% lower for the 7.2 kW unit and 1.5% lower for the 10 kW unit. Theoretical performance predictions also are offered in this paper for another refrigerant, DR-2, which is a potential working fluid for commercial and industrial high-temperature heat pumps. DR-2 is a relatively low pressure fluid which also has been evaluated as a replacement for R-123 in centrifugal chillers.

[koy10a] Koyama, S., Takata, N., and Fukuda, S., "Drop-in Experiments on Heat Pump Cycle Using HFO-1234ze(E) and Its Mixtures With HFC-32", International Refrigeration and Air Conditioning Conference, Purdue University, 2010. Drop-in experiments were conducted in a laboratory apparatus simulating a residential heat pump system. An inverter-driven compressor designed for a heating capacity of 2.8 kW on R-410A was used in the facility. All tests were in the heating mode. Refrigerants tested were R-410A, R-1234ze(E) and a 50/50 mixture of R-1234ze(E) and R-32.

[koy10b] Koyama, S., Takada, N., Matsuo, Y., Yoshitake, D., and Fukuda, S., "Possibility to Introduce HFO-1234ze(E) and Its Mixture with HFC-32 as Low-GWP Alternatives for Heat Pump Refrigeration Systems", 2010 International Symposium on Next-Generation Air Conditioning and Refrigeration Technology, Tokyo, February 2010. An experimental heat pump facility was used for drop-in tests of R-410A, R-1234ze(E), and a 50/50 mixture of R-1234ze(E) and R-32. The heating mode capacity on R-410A was 2.8 kW. All tests were for the heating mode.

[koy12] Koyama, S., Fukuda, S., Osafune, K., and Akasaka, R., "Development of Low GWP Refrigerants Suitable for Heat Pump Systems", JRAIA International Symposium on New Refrigerants and Environmental Technology, Kobe Japan, November 8-9, 2012. Tests of R-1234ze(E) and R-1234ze(Z) were conducted on a laboratory heat pump test rig at high temperature heat pump conditions; water heat sink temperatures at condenser inlet was 50° C and outlet was 75° C. Water heat source temperatures were 45° C at inlet and 39° C at outlet. Tests also were conducted at conditions appropriate for air conditioning heat pumps. Refrigerants tested were R-410A, R-32, R-1234ze(E)/R-32 (20/80 mass %), R-1234ze(E)/R-32 (50/50 mass %), and R-1234ze(E). The authors concluded that the mixture R-1234ze(E)/R-32 (50/50 mass %) could be used as an alternative to R-410A.

[lec10] Leck, T., "New High Performance, Low GWP Refrigerants for Stationary AC and Refrigeration", International Refrigeration and Air Conditioning Conference, Purdue University, 2010. Cooling and heating performance tests were run on an instrumented mini-split heat pump of nominal 3 kW capacity. Refrigerants tested were R-410A as the baseline, R-1234yf, and proposed new DuPont fluids DR-4 and DR-5.

[lec11a] Leck, T., "Environmental and Performance Results for Low GWP AC Fluid Candidates", ASHRAE Transactions, Vol. 117 Pt. 2, 2011 p. 132-140. R-1234yf has been proposed for use as a replacement for

R-134a for many air conditioning and refrigeration applications. Other new refrigerant compositions are being developed. Measured cooling and heating performance results for some of the new candidate refrigerants are presented in this paper. Trade-offs affecting the environmental impact of the developmental refrigerants – GWP and energy efficiency – are discussed.

[lec11b] Leck, T., “Property and Performance Measurements of Low GWP Fluids for AC and Heat Pump Applications”, International Congress of Refrigeration, Prague, Czech Republic, August 21-26 2011. Tests were conducted on minisplit heat pumps of four different capacities (2.8, 4.0, 7.1, and 7.2 kW) and two 10.6 kW ducted split heat pumps. R-410A is the baseline refrigerant. Tests were conducted in minisplits with R-1234yf as a drop-in refrigerant and also with larger compressors and optimized heat exchangers. Other higher-capacity blends DR-4 and DR-5 (DuPont) also were tested as drop-ins in R-410A systems. DR-4 also was tested with modified heat exchangers to account for glide effects.

[lee12a] Lee, H-S., Kim, H-J., Kang, D-G, and Jung, D., “Thermodynamic Performance of R-32/152a Mixture For Water Source Heat Pumps”, International Journal – Energy, Issue 1, April 2012 p. 100-106. Air conditioning and heat pump performance of R-32/R-152a mixtures in the range of 20% R-32 to 50% R-32 in 10% increments was measured for comparison with R-22 in a water source heat pump bench tester. Evaporation and condensation temperatures were 7°/45° C and -7°/41° C for summer and winter conditions respectively. The authors conclude that R-32/152a mixtures can be a long-term solution to replace R-22 from the viewpoint of energy efficiency and global warming in residential air conditioners and heat pumps.

[lee12b] Lee, H-S., Kang, D-G, and Jung, D., “Performance of Non-Flammable Azeotropic HFO1234yf/HFC134a Mixture for HFC-134a Applications”, submitted to the International Journal of Refrigeration. Drop-in performance of R-134a, R-1234yf, and mixtures of R-1234yf/R-134a at concentrations of 95/5, 90/10, and 85/15% by mass were measured in a heat pump bench tester under summer and winter conditions. Test results showed that COP, capacity, and discharge temperatures of R-1234yf and R-1234yf/R-134a mixtures are similar to those of R-134a. Compositions with more than 10% of R-134a are considered nonflammable and are azeotropic. The authors believe that an R-1234yf/R-134a mixture with 10-11% R-134a is a low-GWP alternative to R-134a in applications such as air conditioners and mobile systems with minor modifications.

[miy10] Miyara, A., Onaka, Y., and Koyama, S., “Ways of Next Generation Refrigerants and Heat Pump/Refrigeration Systems”, International Journal of Air-Conditioning and Refrigeration, Vol. 18, No. 1 (2010) p 1-5. Results are reported for drop-in tests of R-1234ze(E)/R-32 mixtures (20%/80%), (50%/50%), and (80%/20%), R-1234ze(E) by itself, and R-410A for reference.

[pan96] Pande, M., Hwang, Y.H., Judge, J., and Radermacher, R., “An Experimental Evaluation of Flammable and Non-Flammable High Pressure HFC Replacements for R-22”, International Refrigeration and Air Conditioning Conference, Purdue University, 1996, p 21-26. A residential heat pump with a nominal capacity of 7.0 kW was used to test HFC-32, R-410A, and R-410B with R-22 as the baseline

refrigerant. Tests were run according to ASHRAE Standard 116-1983 in both the cooling and heating modes.

[par07a] Park, K-J., and Jung, D., “Thermodynamic Performance of HCFC-22 Alternative Refrigerants for Residential Air-Conditioning Applications”, *Energy and Buildings*, Vol. 39, Issue 6, June 2007, p 675-680. This paper reports on tests in a breadboard laboratory heat pump/air conditioner with evaporation and condensing temperatures of 7° and 45° C respectively. Fluids tested were HCFC-22 (baseline), two pure HCs (R-290 and R-1270), and seven mixtures of R1270, R290, R-152a, and DME.

[par07b] Park, K-J., Seo, T., and Jung, D., “Performance of Alternative Refrigerants for Residential Air-Conditioning Applications”, *Applied Energy*, Vol. 84, Issue 10, October 2007, p 985-991. Similar to the paper cited above.

[pha12a] Pham, H., and Rajendran, R., “R32 and HFOs as Low-GWP Refrigerants for Air Conditioning”, *International Refrigeration and Air Conditioning Conference*, Purdue University, July 16-19, 2012, System drop-in tests were conducted on a 3-ton heat pump with a scroll compressor designed for R-410A. Both heating and cooling tests were conducted using AHRI 210/240 test standards. Performance with R-32 was compared to baseline R-410A tests. Only TXV setting changes and charge optimization was carried out for the comparison tests. Similar drop-in tests in the same system were carried out with three HFO blends with GWP around 500. Another set of cooling-only tests were performed with a 3-ton condensing unit having a compact microchannel heat exchanger which enabled 30% to 40% charge reduction. LCCP implications for the tested refrigerants are discussed in the paper.

[pia12] Piao, C-C., Taira, S., and Moriwaki, M., “Alternatives to High GWP HFC Refrigerants: Residential and Small Commercial Unitary Equipment”. *ASHRAE/NIST Refrigerants Conference*, Gaithersburg, MD, October 29-30, 2012. Drop-in tests were performed on an R-410A residential unitary heat pump with a rated capacity of 4 kW in cooling and 5 kW in heating. R-32/R-1234yf mixtures were tested over the full composition range from 0/100% to 100/0% by mass in 10% increments. Tests were conducted at 100% and 50% of rated capacity. The compressor had a variable speed drive. A second set of tests were conducted using R-32 in an R-410A residential heat pump of 3.5 kW/4.2 kW cooling/heating capacity. A variable speed drive and EEV were used with R-32 to match the capacity of the system with R-410A and to maximize efficiency. A third set of tests was carried out on an R-410A residential unitary heat pump to explore effects of high ambient temperature in the cooling mode. This heat pump had capacities of 6 kW/7 kW cooling/ heating. Tests were run at ambient temperatures from 35° C to 52° C. In addition to the test data for R-410A and R-32, simulation results are presented for R-22 . A fourth series of drop-in tests were conducted with R-32 on a commercial R-410A unitary heat pump system with a 12.5 kW/14 kW cooling/heating capacity. Tests were conducted at 100% and 50% of rated capacity.

[rit03] Ritcher, M.R., Song, S.M., Yin, J.M., Kim, M.H., Bullard, C.W., and Hrnjak, P.S., “ Experimental Results of Transcritical CO<sub>2</sub> Heat Pump for Residential Application”, *Energy*, Vol. 28, No. 10, 2003, p. 1005-1019. Experiments compared a commercially available R-410A heat pump and a prototype CO<sub>2</sub> system in heating mode. The CO<sub>2</sub> system used aluminum microchannel heat exchangers and a

prototype semi-hermetic compressor. System performance is compared for two configurations: first, when the CO<sub>2</sub> compressor speed is set to match the R-410A system's heating capacity at 8.2° C outdoors and 21.1° C indoors, and second, when the air conditioning capacity is matched at 35° C outdoors and 26.5° C indoors. The CO<sub>2</sub> system operated with a slightly lower heating COP but its higher capacity at lower outdoor temperatures reduces the need for less efficient supplemental heat.

[spa11] Spatz, M., Yana Motta, S., and Achaichia, N., "Low Global Warming Refrigerants for Stationary Air Conditioning Applications", International Congress of Refrigeration, Prague, Czech Republic, August 21-26 2011. An R-410A DC inverter ductless split reversible heat pump with a nominal cooling capacity of 4 kW was tested over a range of cooling and heating conditions with the compressor running at rated and half-speed. Performance also was measured with HFO blend L-41 (Honeywell) and R-32. Capacity, efficiency, discharge temperature, and mass flow rate results are reported. A ducted reversible 13 SEER heat pump with a 10.5 kW cooling capacity was tested in cooling mode and heating mode using R-407C as the baseline refrigerant. Tests were run in this system with L-20, L-20+, and N-20 refrigerants (Honeywell). Capacity, efficiency, discharge temperature, pressure ratio, and mass flow rate results are reported. Also see Yana Motta, S., and Spatz, M., "Latest Developments in Low Global Warming Refrigerants for Heat Pump Applications", IEA Heat Pump Centre Newsletter, Vol. 29 (4) 2011 p. 34-37.

[spa12] Spatz, M., Yana Motta, S., "Recent Developments in Low GWP Refrigerants for Stationary Air Conditioning Applications", JRAIA International Symposium on New Refrigerants and Environmental Technology, Kobe Japan, November 8-9, 2012. Tests in both cooling and heating modes were conducted on a 3 ton (10.5 kW) ducted split reversible heat pump designed for R-410A. Low-GWP refrigerants tested were L-41 and R-32 with the results compared to those for R-410A. The capacity with L-41 was slightly lower than for R-410A so additional tests were run with a larger compressor. The efficiency with L41 was equivalent or slightly higher with both compressors than with R-410A. The efficiency with L-41 also slightly exceeded that with R-32 but at lower discharge temperatures than R-32.

[su12] Su, X. "R32 Performance in Low Ambient Heating – Economizer Cycle", JRAIA International Symposium on New Refrigerants and Environmental Technology, Kobe Japan, November 8-9, 2012. Tests were conducted in a laboratory test rig including a variable-speed scroll compressor. The test rig included an economizer that could be switched in and out of the cycle. The focus of the tests was to explore heat pump system operation at low ambient source temperatures down to -20° C. Vapor injection was used to improve low ambient capacity and COP. The author concluded that low ambient operation with R-32 was demonstrated with only minor limitations compared with R-410A in an economizer cycle.

[wu12] Wu, Y., Liang, X., Tu, X., and Zhuang, R., "Study of R-161 Refrigerant for Residential Air-Conditioning Applications", International Refrigeration and Air Conditioning Conference, Purdue University, July 16-19, 2012. Tests of R-161 and R-22 were performed on a 3.5 kW heat pump in both cooling and heating modes. The refrigerant charge with R-161 was 57% of that of R-22. With R-161 the rating point cooling capacity was reduced by 7.6% and the EER increased by 6.1%. In the heating mode the capacity was reduced by 6.8% and the COP increased 4.7%.

[xu11] Xu, B., Chen, J., Qi, Z., and Li, F., “Experimental Study of R-290 Enhanced System Performance in Residential Air-Conditioners and Heat Pumps”, International Congress of Refrigeration, Prague, Czech Republic, August 21-26 2011. A 3.5 kW residential split system air conditioner and heat pump designed for R-22 was tested with R-290 in drop-in mode and with a suction line heat exchanger (SLHX). Tests were conducted according to Chinese Standard GB/T7725-2004. Cooling capacity in drop-in mode was 7.6% lower than for R-22 but the COP was 6.8% higher. When the SLHX was added the capacity with R-290 increased only 1.3% and the COP increased 1%. For heating, the capacity in drop-in mode was 11.1% less than for R-22 but the COP was 2.6% higher. With the SLHX the heating capacity increased 0.8% and the COP was the same as for R-290 in the drop-in mode.

[xu12] Xu, X., Hwang, Y., and Radermacher, R., “Performance Measurement of R-32 in Vapor Injection Heat Pump System”, International Refrigeration and Air Conditioning Conference, Purdue University, July 16-19, 2012. The performance of R-410A and R-32 was measured in a vapor-injected heat pump system designed for R-410A. Both cooling and heating conditions were tested. For a single-stage cycle without vapor injection the capacity improvement with R-32 was between 3.4% and 9.7% and the COP improvement was between 2% and 9%. For the vapor injection mode the capacity improvement with R-32 was 1.8% to 7.4% and the COP improvement was between 1.2% to 5.7%.

[yaj00] Yajima, R., Kita, K., Taira, S., and Domyo, N., “R32 As A Solution for Energy Conservation and Low Emission”, International Refrigeration and Air Conditioning Conference, Purdue University, 2000, p 407-414. A 16 kW split heat pump air conditioner with a scroll compressor and inverter drive was tested with R-410A and HFC-32 at several operating conditions in both cooling and heating.

### **Water-Heating Heat Pumps and Heat Pump Chillers**

[aga08] Agrawal, N. and Bhattacharyya, S., “Optimized Transcritical CO<sub>2</sub> Heat Pumps: Performance Comparison of Capillary Tubes Against Expansion Valves”, International Journal of Refrigeration, Vol. 31, Issue 3, May 2008, p. 388-395. The performance of a capillary tube based transcritical CO<sub>2</sub> heat pump for simultaneous heating and cooling at 73° C and 4° C respectively was measured and compared to performance with an expansion valve. The capillary tube system was found to be quite flexible in response to changes in ambient temperature. A mathematical model of the heat pump system also is discussed in the paper.

[cav10a] Cavalini, A., Da Riva, E., and Del Col, D., “Performance of a Large Capacity Propane Heat Pump with Low Charge Heat Exchangers”, International Journal of Refrigeration, Vol. 33, Issue2, March 2010, p. 242-250. A 100kW heat pump was tested with propane as a refrigerant. A microchannel condenser and a brazed plate condenser were each tested in the unit to minimize the refrigerant charge and to compare energy efficiency. The influence on performance of a microchannel internal heat exchanger also was determined.

[cho96] Choi, D.K., Domanski, P.A., and Didion, D.A., “Evaluation of Flammable Refrigerants for Use in a Water-to-Water Residential Heat Pump”, IIF-IIR Commissions B1, B2, E1 and E2 – Aarhus, Denmark 1996. The performance of R-290 and zeotropic mixtures of R-290/R-600a (70/30) and R-32/R-152a

(50/50) is compared to that of R-22 in a test apparatus that simulates a residential ground-source water-to-water heat pump. Counterflow was used in the heat exchangers to effectively employ the temperature glide in the mixtures. One set of tests were “drop-in” tests and a second set was run to achieve the same heating or cooling capacity for all refrigerants using a variable-speed compressor. Test conditions were specified on the heat transfer fluid side of the heat exchangers, not the refrigerant side. For cooling the evaporator conditions were 13° C inlet and 7° C outlet with condenser conditions of 29° C inlet and 35° C outlet. For heating the evaporator conditions were 5° C inlet and 1° C outlet with condenser conditions of 39° C inlet and 45° C outlet.

[deb00] De Blas, J., “Propane as a Refrigerant for Heat Pump Applications in Southern Europe”, IEA Heat Pump Center Newsletter, Vol. 18, No. 4, 2000. This article reports on the development of an improved air-to-water heat pump for the southern European market in a collaborative project involving universities, manufacturers, and government laboratories. The starting point was an existing commercially-available 21 kW R-22 heat pump. This heat pump was then optimized for R-290 with improved heat exchangers and compressor. The goals of the project, which were achieved, were to increase COP by 10% and reduce refrigerant charge by 40%.

[guo12] Guo, W., Ji, G., Zhan, H. and Wang, D. “R32 Compressor Development for Air Conditioning Applications in China”, International Refrigeration and Air Conditioning Conference, Purdue University, July 16-19, 2012. R-32 compressor drop-in tests were conducted on R-410A scroll compressors with capacities of 6.5 kW, 12.7 kW, and 35.1 kW with results reported in this paper. System tests were conducted on a 65 kW air-to-water heat pump with dual 10 HP compressors. The R-410A compressors were replaced with R32 compressors fitted for enhanced vapor injection (EVI). An economizer was added to the system. Data is compared in rated and maximum cooling and heating conditions with the vapor injection on and off. Capacities increased by 11% with EVI on in the cooling condition and 16-19% in the heating condition. EER was reduced slightly in the cooling condition with EVI on, but increased by 2.5% – 7.5% in the heating condition with EVI on.

[hua11] Huang, Y., Yin, Q., Yu, J. and Wang, J, “Comparative Experimental Researches of Air-Water Heat Pump with R-32 and R-410A for Household, 2011 International Congress of Refrigeration

[kim05] Kim, S., Kim, Y., Lee, G., and Kim, M., “The Performance of a Transcritical CO<sub>2</sub> Cycle with an Internal Heat Exchanger”, International Journal of Refrigeration, Vol. 28, Issue 7., November 2005, p. 1064-1072. The performance of a transcritical CO<sub>2</sub> cycle with an internal heat exchanger was investigated for hot water heating. Secondary heat transfer fluid temperatures were varied in the evaporator and gas cooler inlets. Discharge pressure also was varied. Refrigerant mass flow rate, compressor power, heating capacity, and COP are presented with respect to the length of the internal heat exchanger over a range of operating conditions.

[nek02] Neksa, P., “CO<sub>2</sub> Heat Pump Systems”, International Journal of Refrigeration, Vol. 25, Issue 4., June 2002, p. 421-427. An overview is provided of activities in the CO<sub>2</sub> heat pump field. Characteristics

of the transcritical process in heat pumps are discussed. Theoretical and experimental results are presented for several heat pump applications.

[pal08a] Palm, B., "Ammonia as Refrigerant in Small-Capacity Systems", IEA Heat Pump Centre Newsletter, Vol. 26 (4) 2008 p.23-31. A 9 kW water-heating heat pump with ammonia as a refrigerant and miscible PAG lubricant was designed and tested. The heat pump produced hot water at close to 60° C while having a condensing temperature below 50° C. A desuperheater was included in the system and provided a portion of the heating. Microchannel heat exchangers allowed the ammonia charge to be kept to 100 g. The charge with plate heat exchangers was 120 g. COPs over a range of evaporating temperatures (-8 to 4° C) were 3.6 to 4.3 if a motor efficiency of 90% can be achieved.

[pay98] Payne, W.V., Domanski, P.A., and Muller, J. "A Study of a Water-to-Water Heat Pump Using Flammable Refrigerants", IIR Commission B2 Report, Oslo, Norway – 1998. The performance of R-290 and zeotropic mixtures of R-32/R-290 (50/50) and R-32/R-152a (50/50) is compared to that of R-22 in a test apparatus that simulates a residential ground-source water-to-water heat pump. Counterflow brazed plate heat exchangers were used to effectively employ the temperature glide in the mixtures. The tests were run to achieve the same heating or cooling capacity for all refrigerants using a variable-speed compressor. Test conditions for the heat pump were according to ARI Standard 330-93.

[pet12] Petersen, M., Bowers, C.D., Elbel, S. and Hrnjak, P., "Development of High Efficiency Carbon Dioxide Commercial Heat Pump Water Heater", International Refrigeration and Air Conditioning Conference, Purdue University, July 16-19 2012. This work focused on the development of a high efficiency R-744 heat pump water heater for commercial applications with effective utilization of the cooling capability for air conditioning or refrigeration. Performance results are presented for four R-744 packages of approximately 35 kW capacity. These results are compared to those for a baseline commercial R-134a heat pump with the same capacity and footprint. Influences of an internal heat exchanger and an enhanced evaporator in the R-744 system are described.

[ued12] Ueda, K., Wajima, K., Yokoyama, A., and Shimizu, A., "Study of Application Low GWP Refrigerant HFO-1234ze(E) for the Centrifugal Heat Pump", JRAIA International Symposium on New Refrigerants and Environmental Technology, Kobe Japan, November 8-9, 2012. Drop-in tests with R-1234ze(E) were conducted on a centrifugal chiller as reported in the first section of this literature survey. Heat pumping tests were performed on a two-stage 547 kW inverter-driven centrifugal heat pump designed for R-134a. Heat pumping tests were conducted with a heat source water temperature range of 45° C at outlet to 50° C at inlet and hot water output temperatures of 80° C in and 90° C out. Tests were also run at lower temperature heat pumping conditions.

**Medium-Temperature Refrigeration** (some papers include low temperature refrigeration as well)

[aga98] Agarwal, R.S., "Hydrocarbon Blends and Blends of HFC-134a-HC600a as Drop-In Refrigerants for Small Capacity Commercial Refrigeration Appliance – An Experimental Study", International Refrigeration and Air Conditioning Conference, Purdue University, 1998, p 51-56. Experimental work is reported for horizontal bottle coolers with R-12 as a baseline and mixtures of R-134a and R-600a. The R-

600a proportions were 6%, 8%, 10%, and 12%. “Rated energy consumption” tests were conducted with 32° C ambient temperature and 2° C average cabinet temperature. Pull-down tests were conducted at 43° C ambient temperature and 2° C cabinet temperature after pull-down.

[bae05] Baek, J., Groll, E., and Lawless, P., “Piston-Cylinder Work Producing Expansion Device in a Transcritical Carbon Dioxide Cycle – Part I: Experimental Investigation, and Part II: Theoretical Model”, *International Journal of Refrigeration*, Vol. 28, Issue 2, March 2005, p. 141-164. A piston-cylinder work output expansion device was designed, constructed, and tested to replace the expansion valve in a transcritical CO<sub>2</sub> system to recover energy from the expansion process and improve the COP of the system.

[cab08] Cabello, R., Sanchez, D., Llopis, R., and Torella, E., “Experimental Evaluation of the Energy Efficiency of a CO<sub>2</sub> Plant Working in Transcritical Conditions”, *Applied Thermal Energy*, Vol. 28, 2008, p. 1596-1604. The performance of a CO<sub>2</sub> refrigeration system was measured at three evaporating temperatures, (-1°, -10°, and -18° C) for three gas cooler outlet temperatures (31°, 33.6°, and 40°C) over a range of gas cooler pressures from 74 to 105 bar. The system had a 4 kW single-stage semi-hermetic compressor, a back-pressure expansion valve in series with an electronic expansion valve, and no internal heat exchanger. The test results were used to determine the gas cooler pressures associated with peak COPs and compare them with the optimum gas cooler pressures predicted by existing models. Also, the energy efficiency penalty for operation at non-optimum pressures was determined.

[cab11] Cabello, R., Sanchez, D., Llopis, R., Torrella, E., and Patino, J., “Experimental Comparison of Two CO<sub>2</sub> Transcritical Cycles: Single and Double-Stage Expansion”, *International Congress of Refrigeration*, Prague, Czech Republic, August 21-26 2011. Two different CO<sub>2</sub> transcritical cycles are used in commercial CO<sub>2</sub> refrigerating plants. One cycle has a double expansion stage (back-pressure plus thermostatic valve) which can control both the gas-cooler pressure and the degree of superheat at the evaporator. The other cycle uses a single expansion system (back-pressure) which is only able to regulate the gas cooler pressure. This paper shows the behavior and performance of both cycles working in the same experimental plant under similar operating conditions in the evaporator and gas cooler.

[dea05] DeAngelis, J.M. and Hrnayak, P., “Experimental Study of System Performance Improvements in Transcritical R744 Systems with Applications in Bottle Coolers”, ACRC report CR-57, University of Illinois, 2005

[hal03] Halimic, E., Ross, D., Agnew, B., Anderson, A., and Potts, I., “A Comparison of the Operating Performance of Alternative Refrigerants”, *Applied Thermal Engineering*, Vol. 23, Issue 12, August 2003, p. 1441-1451. The refrigerating capacity and COP of R-410A, R-290, and R-134a were compared with those of R-12 when used in a proprietary vapor compression refrigeration unit initially designed to operate with R-12.

[hwa03a] Hwang, Y., Jin, D-H, and Radermacher, R., “Comparison of Hydrocarbon R-290 and Two HFCs R-404A and R-410A for Commercial Refrigeration System Applications”, Report for the ARI Green Project, Air-Conditioning and Refrigeration Institute, Arlington VA, December 23, 2003. Tests were run

on a medium temperature commercial refrigeration system consisting of a unit cooler and a condensing unit having a capacity of 11 kW. The design refrigerant was R-404A. Refrigerants tested were R-404A, R-410A, and R-290. Compressor capacity was adjusted by changing compressor size and by variable speed to achieve the same cooling capacity for each refrigerant. The evaporator inlet air temperature was 1.7° C while the condenser inlet air temperature was 35° C for full load tests and 18.3° C for part load tests.

[hwa04] Hwang, Y., Celik, A., and Radermacher, R., "Performance of CO<sub>2</sub> Cycles with a Two-Stage Compressor", International Refrigeration and Air Conditioning Conference, Purdue University, July 12-15, 2004. The performance of four CO<sub>2</sub> cycle options was measured for three different evaporating temperatures; 7.2°, -6.7°, and -23.3° C under ARI Standard 520 for condensing units. The cycle options included a basic cycle, a cycle with a suction line heat exchanger, a cycle with an intercooler, and a two-stage split cycle. The compressor was a hermetic rotary-type compressor.

[hwa07] Hwang, Y., Jin, D.-H., and Radermacher, R., "Comparison of R-290 and Two HFC Blends for Walk-In Refrigeration Systems", International Journal of Refrigeration, Vol. 30, Issue 4, June 2007, p 633-641. An experimental evaluation of R-290, R-410A, and R-404A was conducted in a walk-in system. The results were used for LCCP comparisons of systems using these refrigerants.

[kre11] Kreiger, T. and Schuster, M., "Natural Refrigerants for Plug-In Refrigeration Cabinets", International Congress of Refrigeration, Prague, Czech Republic, August 21-26 2011. A bottle cooler designed for R-290 was tested and the results were compared to performance of a bottle cooler of similar capacity using R-404A. The comparisons were based on pull-down time, compressor running time, and energy consumption for 24 hour steady state operation. The energy consumption with R-290 was reduced by 10% for the steady state test.

[li04] Li, M., Ma, Y., Guan, H., and Li, L., "Development and Experimental Study of CO<sub>2</sub> Expander in CO<sub>2</sub> Supercritical Refrigeration Cycles", International Journal of Green Energy, Vol. 1 (1) 2004, p. 89-99. This paper discusses the development of a rolling piston expander including seal technology, contact friction control, and suction design. Testing in a transcritical system showed that power recovery depended on the rotational speed of the expander. Efficiency of the prototype was observed to be about 32%.

[mad05] Madsen, K., Poulsen, C., and Wiesenfarth, M., "Study of Capillary Tubes in a Transcritical CO<sub>2</sub> Refrigeration System", International Journal of Refrigeration, Vol. 28, Issue 8, December 2005, p. 1212-1218. Capillary tubes were tested in an experimental CO<sub>2</sub> system with evaporating temperature of -10° C and temperatures after the gas cooler ranging from 20° to 50° C. Theoretical analyses also are included in the paper. The conclusion was that capillary tubes can be a competitive solution to a fixed pressure control or more expensive optimal pressure controls in smaller systems (e.g., bottle coolers) with fixed displacement compressors.

[man08] Mani, K., and Selladurai, V., "Experimental Analysis of a New Refrigerant Mixture as Drop-In Replacement for CFC-12 and HFC-134a", International Journal of Thermal Sciences, Vol. 47, Issue 11, November 2008, p 1490-1495. This paper reports on an experimental performance study in a vapor

compression system of R290/R600a (68%/32% by weight) vs. R-12 and R-134a for high temperature refrigeration.

[mey00] Meyer, J., "Experimental Evaluation of Five Refrigerants as Replacements for R-22", ASHRAE Transactions 2000, American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE), Atlanta, GA, USA, Vol. 106, Pt.2. A comparative analysis of the performance of R-134a, R-290, R-404A, R-407C, R-410A, and R-22 is based on tests in a system with nominal cooling capacity of 4 kW. The evaporator and condenser were tube-in-tube heat exchangers with water in counterflow to the refrigerant. Measurements were taken over a range of evaporating temperatures from  $-20^{\circ}\text{C}$  to  $20^{\circ}\text{C}$  at a condensing temperature of  $55^{\circ}\text{C}$ .

[min10] Minor, B.H., Montoya, C., and Kasa, F.S., "HFO-1234yf Performance in a Beverage Cooler", International Refrigeration and Air Conditioning Conference, Purdue University, 2010. Tests were conducted on standard 19 cubic foot beverage coolers. One cooler provided an R-134a baseline. Another cooler was optimized for R-1234yf, and a third and fourth cooler were optimized for CO<sub>2</sub> using two different compressor types. The ambient test condition was  $40.6^{\circ}\text{C}$ . Pull-down tests with no internal loads and with several percentages of loading were performed. Energy consumption for steady-state operation over 24 hours also was measured. LCCP comparisons are provided for the tested refrigerants.

[mon10a] Montagner, G.P. and Melo, C., "An Experimental Study of CO<sub>2</sub> Thermodynamic Cycles", 9<sup>th</sup> IIR Gustav Lorentzen Conference on Natural Working Fluids, Sydney, Australia, 2010. Tests were conducted on a standard CO<sub>2</sub> thermodynamic cycle using a capillary tube as an expansion device. The test system is the one described in the next reference below. It was shown that for each capillary tube there is a specific refrigerant charge that maximizes system COP. Capillary tube CO<sub>2</sub> systems were shown to be susceptible to variations in operating conditions. Tests also were carried out with a modified cycle with a needle valve in series with the capillary tube. It was shown that the evaporator pressure can be controlled by regulating the refrigerant flow through the expansion device. The discharge pressure can be controlled by adjusting the refrigerant charge in the high pressure side of the system. Typical evaporator temperatures obtained in the tests ranged from  $-10^{\circ}\text{C}$  to  $-20^{\circ}\text{C}$ . gas cooler exit temperatures varied from  $33^{\circ}\text{C}$  to  $45^{\circ}\text{C}$ .

[mon10b] Montagner, G.P. and Melo, C., "Exploring the Performance Characteristics of CO<sub>2</sub> Cycles in a Breadboard-Type Test facility", International Refrigeration and Air Conditioning Conference, Purdue University, 2010. A breadboard CO<sub>2</sub> test system was used for performance tests under light commercial refrigeration conditions. The system provided a nominal 600 W of cooling capacity at an evaporating temperature of  $-7.5^{\circ}\text{C}$  with the refrigerant temperature at the exit of the gas cooler at  $38^{\circ}\text{C}$ . Tests were run with gas cooler exit temperatures ranging from  $34^{\circ}$  to  $45^{\circ}\text{C}$ . A needle valve in series with a capillary tube was shown to be an effective means for controlling evaporating pressure and reducing the effect of operating conditions. In some of the experiments the discharge pressure was controlled by varying the refrigerant charge. This had some effect on evaporator superheating.

[mon11] Montagner, G.P. and Melo, C., "Experimental Evaluation of CO<sub>2</sub> Cycles Under Different Expansion Strategies", International Congress of Refrigeration, Prague, Czech Republic, August 21-26 2011. An experimental study was carried out to evaluate CO<sub>2</sub> cycles for light commercial refrigeration systems. The effects of refrigerant charge, ambient temperatures, and thermal load were investigated in a system having a capillary tube and a thermostatic expansion valve as alternative expansion devices.

[oki10] Okishi, K., Ishida, S., Leck, T.J., and Minor, B.H., "HFO-1234yf Performance in a Vending Machine", Proceedings of the JRAIA International Symposium, Kobe, Japan, December 2-3, 2010. Beverage vending machines in Japan can store both hot and cold beverages at suitable temperatures. During part of the year the vending machines may operate in cooling-only mode and in another part of the year a heat pump mode can be used to obtain the simultaneous heating and cooling. The condensing temperature of a vending machine can reach 70° C for maintaining beverages at 55° C. The desired temperature for the cold beverages is 3° C. Tests were run at steady-state conditions with R-134a as the baseline refrigerant and R-1234yf as the alternative. Cooling capacity and COP in the cooling mode, and heating capacity and COP in the heat pump mode, were measured and compared for the two refrigerants.

[rac10] Rached, W., Komornicki, J., and Maldeme, C., "Safe and Environment Friendly Refrigeration and Refrigerants", 2010 International Symposium on Next-Generation Air Conditioning and Refrigeration Technology, Tokyo, February 2010. A test facility with an R-404A scroll compressor was used to compare the performance of R-404A and a new refrigerant, ARM01 (Arkema) at evaporator temperature of -7°C and two condensing temperatures, 43°C and 32°C. Capacity and COP were the parameters evaluated.

[rig05] Rigola, J., Rausch, G., Perez-Segarra, C.D. and Oliva, A., "Numerical Simulation and Experimental Validation of Vapour Compression Refrigeration Systems. Special Emphasis on CO<sub>2</sub> Transcritical Cycles", International Journal of Refrigeration, Vol. 28, Issue 8, December 2005, p 1225-1237. Compressor and cycle performance of a small capacity refrigeration system with an evaporation temperature around 0° C; transcritical performance vs. sub-critical conventional cycle. The abstract does not indicate what refrigerant was used for the conventional cycle.

[rig10] Rigola, J., Ablanque, N., Perez-Sagarra, C.D., and Oliva, A. "Numerical Simulation and Experimental Validation of Internal Heat Exchanger Influence on CO<sub>2</sub> Transcritical Cycle Performance", International Journal of Refrigeration, Vol. 33, 2010, p.664-674. Experimental results are presented for a transcritical CO<sub>2</sub> system with and without an internal heat exchanger (IHx). Tests were run in conditions applicable to small commercial refrigeration systems; about 600 W capacity, -5° C evaporating temperature, and three ambient temperatures, 25°, 35°, and 43°C. The effect of gas cooler pressure on COP and capacity was explored.

[rin11] Rinne, F., Minor, B., and Salem, K., "Hybrid Supermarket System using Low GWP Refrigerants", International Congress of Refrigeration, Prague, Czech Republic, August 21-26 2011. Refrigerant XP10 was retrofitted in a supermarket medium temperature refrigeration system replacing R-134a. Test

results are shown for compressor calorimeter tests at three operating conditions;  $-23^{\circ}\text{C}/41^{\circ}\text{C}$ ,  $-21^{\circ}\text{C}/41^{\circ}\text{C}$ , and  $-12^{\circ}\text{C}/41^{\circ}\text{C}$ . XP10 relative to R-134a exhibited capacity increases of 7% to 10% and COP increases from 0 to 2%. A rack refrigeration unit in a supermarket was converted to XP10 from R-134a. Only the TXV setting was changed. Integrated electric power to the rack unit over a 24 hour period with similar weather conditions showed a reduction of 3.3% with XP10. Also see the paper by the same authors, "Experimental Study of R-134a Alternative in a Supermarket Refrigeration System", ASHRAE Transactions, Vol. 117, part 2, 2011 p. 124-131.

[sek05] Sekhar, S.J. and Lai, D.M., "HFC134a/HC600a/HC290 Mixture A Retrofit for CFC-12 Systems", International Journal of Refrigeration, Vol. 28, Issue 5, August 2005, p 735-743. An R-134a/HC blend with 9% HC by weight was tested in two low-temperature systems (a domestic refrigerator and a deep freezer) and two medium-temperature systems (a bottle cooler and a 3.5 kW walk-in cooler).

[sha12] Shapiro, D., "Drop-in Testing of Next-Generation R-134a Alternates in a Commercial Bottle Cooler/Freezer", International Refrigeration and Air Conditioning Conference, Purdue University, July 16-19, 2012. Drop-in tests were conducted with R-134a as a baseline and the following alternative refrigerants: R-1234yf, XP10, R-1234ze(E), and N13. Tests were conducted in accordance with ASHRAE Standard 72 at  $-5.6^{\circ}\text{C}$  and  $3.3^{\circ}\text{C}$  bottle cooler temperature setpoints. Two ambient conditions were tested:  $23.9^{\circ}\text{C}/55\% \text{rh}$  and  $26.7^{\circ}\text{C}/55\% \text{rh}$ . In addition to the ASHRAE test conditions, full pull-down tests and half pull-down tests were conducted. With the exception of R-1234ze(E) all the alternative refrigerants had similar performance to R-134a. R-1234ze(E) had lower density at compressor suction conditions so had longer compressor run times. A larger displacement compressor would likely bring this refrigerant to roughly the same performance as the other refrigerants.

[spa10] Spatz, M.W., Motta, S.Y., and Becerra, E.V., "Low Global Warming Alternative Refrigerants for Stationary AC&R Applications", 2010 International Symposium on Next-Generation Air Conditioning and Refrigeration Technology, Tokyo, February 2010. A vending machine was tested with R-134a, R-1234yf, and R-1234ze(E). Efficiency and capacity were measured inside environmental chambers. Tests also were performed on a typical North American air conditioning system. The cooling capacity with R-410A is 10.6 kW and the unit has a SEER of 13. The unit was tested using low GWP refrigerants HDR-06 and HDR-11 (Honeywell) using the same compressor as for R-410A. Tests also were run using refrigerant HDR-01 (Honeywell) which has properties closer to those of R-22. An R-22 compressor was used for the HDR-01 testing. Capacity and COP results are compared to R-410A for these new low GWP refrigerants.

[yan10] Yana Motta, S., Becerra, E.V., and Spatz, M.W., "Analysis of LGWP Alternatives for Small Refrigeration (Plugin) Applications", International Refrigeration and Air Conditioning Conference, Purdue University, 2010. An experimental study was conducted for R-134a, R-1234yf, and R-1234ze(E) using a representative vending machine. A larger compressor was substituted for the R-1234ze(E) tests. Tests were conducted with  $32.2^{\circ}\text{C}$  ambient temperature and  $2^{\circ}\text{C}$  interior temperature.

[yan11a] Yana Motta, S., Spatz, M., and Becerra, E.V., "Analysis of LGWP Alternatives for Small Refrigeration (Plug-In) Applications", International Congress of Refrigeration, Prague, Czech Republic,

August 21-26 2011. Pull-down and cycling tests were conducted on a 360-bottle/glass door vending machine equipped with a 0.56 kW hermetic reciprocating compressor. R-134a was the baseline refrigerant. Drop-in pull-down tests were performed with R-1234yf with the cabinet fully loaded. Test results included time to pull down to the desired temperature, integrated energy consumption during pull down, and standard cycling energy evaluation. Another series of tests were performed on a cassette-type vending machine split between an indoor evaporator/fan and an outdoor condenser/fan/compressor unit. Both air-side and refrigerant-side parameters were measured with R-134a as the baseline refrigerant and R-1234yf and R-1234ze(E) as alternatives. A larger compressor was used with R-1234ze(E). Capacity, COP, and heat exchanger conditions were reported for the tests.

[yan11b] Yana Motta, S., and Spatz, M., “Latest Developments in Low Global Warming Refrigerants for Commercial Supermarket Refrigeration”, International Congress of Refrigeration, Prague, Czech Republic, August 21-26 2011. Tests were performed using a commercially-available condensing unit and evaporator for a walk-in freezer/cooler. Three ambient temperatures were used: 13°C, 24° C, and 35° C. Test conditions for the freezer side were: medium temperature refrigeration 10° C and 2° C; Low temperature refrigeration -18° C and -26° C. R-404A was the baseline refrigerant. Capacity, efficiency, mass flow, and discharge temperature data are presented for R-407A, R-407F, N-40 and N-20 (Honeywell).

[yan12a] Yana Motta, S., Spatz, M., and Vera Becerra, E., “Low Global Warming Refrigerants for Commercial Refrigeration Systems”, International Refrigeration and Air Conditioning Conference, Purdue University, July 16-19, 2012. Tests were conducted on a commercial condensing unit and an evaporator for a walk-in freezer/cooler. Three outdoor ambient temperatures were used: 13, 24, and 35° C. Two application ranges were evaluated for the evaporator: -18° and -26° C for freezers and 10° and 2° C for coolers. Capacity, efficiency, and mass flow data are presented for R-407A, R-407F, N-40, and N-20 for low and medium temperatures. Additional data is provided for lower GWP A2L refrigerant L-40. Glide effects on performance are discussed. Compressor calorimeter data were taken and compared to actual system performance. It was found that typical compressor calorimeter tests impose unrealistic penalties on blends with glide. Fractionation due to leaks in real systems also was studied.

[yan12b] Yana Motta, S., Spatz, M., “Low-GWP Replacements for R-404A in Commercial Refrigeration Applications”, JRAIA International Symposium on New Refrigerants and Environmental Technology, Kobe Japan, November 8-9, 2012. Tests were performed on a commercially-available condensing unit and an evaporator for a walk-in freezer/cooler for three outdoor ambient temperatures; 13° C, 24° C, and 35° C. Two ranges of applications were tested; -18° C and – 26° C for low temperature refrigeration and 10° C and 2° C for medium temperature. Baseline tests were run with R-404A. Lower GWP refrigerants tested were R-407F, N-41, and N-20. The results of compressor calorimeter testing of a 3.2 ton semi-hermetic reciprocating compressor designed for R-22 and tested on R-404A and N-40 also are reported.

### **Low-Temperature Refrigeration**

[eng95] Engler, T., Mobner, F. and Oellrich L.R., “Experimental Results and Theoretical Investigations with Alternative Refrigerants”, 19<sup>th</sup> International Congress of Refrigeration 1995, Proceedings, Vol. IVb. A semihermetic reciprocating compressor with a swept volume of 22.4 m<sup>3</sup>/hr was used for tests with a double pipe counter-current condenser and a double pipe counter-current evaporator. The evaporator temperature was varied from -45° C to -10° C. The condensing temperature was varied between 30° C and 40° C. Refrigerants tested were R-22, R-502, R-507, R-290, R-32/134a (38/62), R-290/R-600a (70/30), R-32/125/134a (30/20/50) and R-125/143a/134a (45/45/10).

[hwa05] Hwang, Y., Jin, D-H, and Radermacher, R., “Comparison of Hydrocarbon R-290 and Two HFCs R-404A and R-410A for Low-Temperature Refrigeration Applications – Final Report”, Report for the International Council of Air-Conditioning and Refrigeration Manufacturer’s Association and the Air-Conditioning and Refrigeration Institute, Arlington VA, November 17, 2005. This study is similar to the one reported under [hwa07], but for low-temperature refrigeration conditions. The evaporator inlet air temperature was -23.3° C while the condenser inlet air temperature was 35° C for full load tests and 18.3° C for part load tests.

[kru00] Kruse, H., “Refrigerant Use in Europe”, ASHRAE Journal, American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE), Atlanta, GA, USA, September 2000. Summaries of energy consumption measured in calorimeter tests are presented for substitutes for R-22 and R-502 operating in refrigeration systems with temperatures from -10° C to -40° C. The substitutes tested include R-404A, R-407A, R-407B, R-407C, R-507, R-410A, and R-290.

[par07c] Park, K-J. and Jung, D., “Thermodynamic Performance of R-502 Alternative Refrigerant Mixtures for Low Temperature and Transport Applications”, Energy Conversion and Management, Vol. 48, Issue 12, December 2007, p 3084-3089. R-1270 and R-290 were tested and compared to R-502 in a refrigerating bench tester with a scroll compressor with 3 – 3.5 kW capacity. Average saturation temperatures were -28° and 45° C in the evaporator and condenser respectively.

[pei00] Peixoto, R.A., Epof, S., and Parra, D., “Experimental Investigation of the Performance of Commercial Freezers Using Refrigerant HC-600a”, Purdue University, 2000, IIF-IIR Commission B1, B2, E1, and E2. A 170 liter chest freezer was tested with R-600a and R-134a. Pull down and energy consumption tests were performed with each refrigerant.

[pha12b] Pham, H., and Rajendran, R., “Lower-GWP Refrigerants in Refrigeration”, ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, October 29-30, 2012. Compressor drop-in tests were conducted on low-GWP refrigerants DR-7 and L-40 with R-404A as a baseline. A 6-hp scroll compressor was tested at conditions representing low temperature and medium temperature refrigeration conditions; -32°/21° C, -32°/42° C, -18°/21° C, -18°/38° C, -7°/21° C, and -7°/49° C. Also, two low temperature systems were tested with these refrigerants as drop-ins. One was a 0.5-hp critically charged reach-in freezer and the other was a 3-hp walk-in freezer with a receiver. The reach-in freezer was tested at 23.9° C room temperature and -17.8° C box temperature. The walk-in was tested at 35° C and 15° C ambients and -23.3° C box temperature.

[sek05] Sekhar, S.J. and Lai, D.M., “HFC134a/HC600a/HC290 Mixture A Retrofit for CFC-12 Systems”, International Journal of Refrigeration, Vol. 28, Issue 5, August 2005, p 735-743. An R-134a/HC blend with 9% HC by weight was tested in two low-temperature systems (a domestic refrigerator and a deep freezer) and two medium-temperature systems (a bottle cooler and a 3.5 kW walk-in cooler).

[yan11b] Yana Motta, S., and Spatz, M., “Latest Developments in Low Global Warming Refrigerants for Commercial Supermarket Refrigeration”, International Congress of Refrigeration, Prague, Czech Republic, August 21-26 2011. Tests were performed using a commercially-available condensing unit and evaporator for a walk-in freezer/cooler. Three ambient temperatures were used: 13°C, 24° C, and 35° C. Test conditions for the freezer side were: medium temperature refrigeration 10° C and 2° C; Low temperature refrigeration -18° C and -26° C. R-404A was the baseline refrigerant. Capacity, efficiency, mass flow, and discharge temperature data are presented for R-407A, R-407F, N-40 and N-20 (Honeywell).

[yan12b] Yana Motta, S., Spatz, M., “Low-GWP Replacements for R-404A in Commercial Refrigeration Applications”, JRAIA International Symposium on New Refrigerants and Environmental Technology, Kobe Japan, November 8-9, 2012. See the citation under “Medium Temperature Refrigeration” above. Low temperature refrigeration tests also are reported in this paper.

### **Review and Overview Papers**

[bea12] Beattie, R.J. and Karnaz, J.A., “investigation of Low GWP refrigerant Interaction with Various Lubricant Candidates”, International Compressor Engineering Conference, Purdue University, July 16-19, 2012. The paper presents an assessment of current and future needs for lubricants for various refrigerants to help manufacturers of HVAC&R equipment to evaluate the choices needed to maintain required system performance. The paper includes results from calorimeter performance testing of R-600a compressors using a number of synthetic lubricants with mineral oil as a baseline.

[bul12] Bullard, C. , “Outlook for Natural Refrigerants”, ASHRAE/NIST Refrigerants Conference, October 29-30, 2012, Gaithersburg MD. USA . The issues associated with transition to lower-GWP refrigerants for vapor compression systems are presented. The paper includes performance of recently-developed prototype systems using natural refrigerants (CO<sub>2</sub>, hydrocarbons, NH<sub>3</sub>) and low GWP synthetic refrigerants R-32 and isomers of R-1234. Outlooks are offered for several types of refrigeration and air-conditioning applications.

[cal12] Calm, J. “Refrigerant Transitions... Again”, ASHRAE/NIST Refrigerants Conference, October 29-30, 2012, Gaithersburg MD. USA . This paper reviews the progression of refrigerants from the inception of mechanical refrigeration to the present (2012). The paper presents factors challenging or likely to challenge the new generation of refrigerants being proposed to achieve zero ODP and reduced GWP.

[cav12] Cavallini, A., Brown, S., and Zilio, C., “Thermophysical Properties, Heat Transfer, and Pressure Drop of HFOs”, ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, October 29-30, 2012. This paper considers heat transfer and pressure drop performance of five propene isomers, R-1233xf, R-

1233zd(E), R-1234yf, R-1234ze(E) and R-1234zf relative to R-134a, R-245fa, and R-123. Both in-tube condensation and in-tube flow boiling are examined. Also, heat transfer and pressure drop performance of five R-32/R-1234yf blends are considered. The detailed information in the paper is based on data and correlations in the literature applied to these fluids. A literature review of relevant articles for condensing and boiling heat transfer and pressure drop of the propene isomers is included.

[col00] Colbourne, D. and Suen, K.O., "Assessment of Performance of Hydrocarbon Refrigerants", Purdue University, IIF-IIR Commission B1, B2, E1, and E2, 2000. A review is provided of 54 papers and reports detailing experimental performance comparisons of various hydrocarbon and non-hydrocarbon refrigerants. Single phase and two-phase heat transfer and pressure drop information also is evaluated.

[mcl12] McLinden, M., Domanski, P., Kazakov, A., Heo, J. and Brown, J., "Possibilities, Limits, and Tradeoffs for Refrigerants in the Vapor Compression Cycle", ASHRAE/NIST Refrigerants Conference, October 29-30, 2012, Gaithersburg MD. USA. This paper explores the possibilities for refrigerants having low GWP by using two complementary approaches. The first approach considers the effect of a refrigerant's fundamental thermodynamic parameters on performance in the simple vapor compression cycle and variations on the cycle. The second approach examined more than 56,000 chemical compounds from a database of chemical structures.

[moh09] Mohanraj, M, Jayaraj, S. and Muraleedharan, C., "Environment Friendly Alternatives to Halogenated Refrigerants, a Review", International Journal of Greenhouse Gas Control, Vol. 3, Issue 1, January 2009, p 108-119. This paper reviews various experimental and theoretical studies carried out around the globe with alternatives such as HCs, HFCs, and their mixtures.

### **Compressor Tests**

[cam94] Camporese, R., Bobbo, S., and Rozza, F., "Hydrocarbons as Substitutes for Halogenated Refrigerants in Refrigerating Systems", International Refrigeration and Air Conditioning Conference, Purdue University, 1994, p 231-236. Several domestic hermetic refrigeration compressors with different displacements were tested in a secondary refrigerant calorimeter. Tests were performed with R-12, R-134a, R-290/R-600a (50%/50%) and R-600a.

[dar11] Da Riva, E. and Del Col, D., "Performance of a Semi-Hermetic Reciprocating Compressor With Propane and Mineral Oil", International Journal of Refrigeration, Vol. 34, Issue 3, May 2011, p 752-763. Experimental results are presented for a semi-hermetic compressor tested with R-290 with and without an internal heat exchanger between the suction line and discharge line.

[jov06] Jover, J., Jornet, M., Pons, J., and Serra, J.M., "Feasibility of a R-744 Compressor for Light Commercial Appliances", International Compressor Engineering Conference, Purdue University, July 17-20, 2006. Performance data (capacity and COP) is presented for R-134a and CO<sub>2</sub> compressors tested at evaporator temperatures of -10°, 0°, and 7.2° C. Compressor inlet temperature was 35° C and condenser temperature was 55° C for R-134a. For CO<sub>2</sub> the gas cooler pressure was 85 bar. Data also is presented for R-404A and CO<sub>2</sub> compressors tested at evaporator temperatures of -10°, -23.3°, and -35° C.

Compressor inlet temperature was 32° C and condenser temperature was 55° C for R-134a. For CO<sub>2</sub> the gas cooler pressure was 85 bar.

[khn04] Khmelnjuk, M., Vozny, V., and Mazur, V., “Experimental Characterization of Small Reciprocating Compressor Working With Azeotropic Blends of Alternative and Natural Refrigerants”, International Refrigeration and Air Conditioning Conference, Purdue University, 2004. A 0.1 kW hermetic reciprocating compressor from Zanussi was tested using the ISO 917 standard with pure R-134a, R-152a, and R-600a. Suction temperature was 32° C and condensing temperature was 55° C. In addition to the three “pure” refrigerants, mixtures of R-152a/R-600a in proportions of 50/50, 60/40, and 75/25 were tested. Mixtures of R-134a/R-600a in proportions of 80/20, 70/30, 60/40, and 50/50 also were tested.

[nav05] Navarro, E., Urchueguia, J.F., Gonálvez, J., and Corberán, J.M., “Test Results of Performance and Oil Circulation Rate of Commercial Reciprocating Compressors of Different Capacities Working with Propane (R-290) as Refrigerant”, International Journal of Refrigeration, Vol. 28, Issue 6, September 2005, p. 881-888. Five R-407C hermetic compressors covering different capacities, stroke-to-bore ratios, and number of cylinders were tested with propane as a refrigerant and the results are compared to performance with R-407C. Volumetric efficiency and isentropic efficiency, as well as other parameters, were measured.

[pha12] Pham, H., and Rajendran, R., “R32 and HFOs as Low-GWP Refrigerants for Air Conditioning”, International Refrigeration and Air Conditioning Conference, Purdue University, July 16-19, 2012. This paper, discussed previously in the Air-Heating Heat Pump Section above, also includes test results for a 3-ton scroll compressor tested with R-410A and R-32 at three air conditioning and two heat pump test conditions.

[rig06] Rigola, J., Rausch, G., Perez-Segarra, C., and Oliva, A., “Numerical Study and Experimental Comparison of CO<sub>2</sub> Reciprocating Compressors for Small Cooling and/or Freezing Capacity Applications”, International Compressor Engineering Conference, Purdue University, July 17-20, 2006. Performance of hermetic and semi-hermetic CO<sub>2</sub> compressors working in a transcritical cycle is compared to the performance of a commercial hermetic reciprocating compressor operating with R-134a. Evaporator temperatures for the tests were -10°, 0°, and 7.2° C. Compressor inlet temperature was 35° C and condenser temperature was 55° C for R-134a.

[rov06] Rovira, J., Rigola, J., Oliva, A., and Perez-Segarra, C.D., “Numerical Simulation and Experimental Comparison of Refrigeration and Air-Conditioning Scroll Compressors Application to Trans-Critical Carbon Dioxide Cycles”, International Compressor Engineering Conference, Purdue University, July 17-20, 2006. This paper uses experimental data from previous papers (cited) on CO<sub>2</sub> scroll compressor tests to evaluate numerical simulation models. The data encompasses evaporator temperatures of -10°, 0°, and 10° C, condensing temperatures of 25°, 35°, and 45° C and also different driving frequencies. The paper mentions using R-22 data for reference but that data does not seem to be shown.

[tie96] Tiedemann, T., Burke, M., and Kruse, H., “Recent Developments to Extend the Use of Ammonia”, International Refrigeration and Air Conditioning Conference, Purdue University, 1996, p 389-395. Test

data are reported on volumetric efficiency and COP of ammonia and R-22 tests using a “small” (under 30 kW) open type ammonia compressor.

## Heat Transfer Papers

### Evaporating

[bab12] Baba, D., Nakagawa, T., and Koyama, S., “Flow Boiling Heat Transfer and Pressure Drop of R-1234ze(E) and R-32 in Horizontal Micro-Fin Tube”, International Refrigeration and Air Conditioning Conference, Purdue University, July 16-19, 2012. The flow boiling heat transfer of R-1234ze(E), R-32, and R-1234ze(E)/R32 (50/50 mass %) was measured in a horizontal micro-fin copper tube with a 6 mm outside diameter, 5.21 mm mean inside diameter, 0.26 mm fin height, and 20 degree spiral angle. The mass velocity range was 150 to 400 kg m<sup>-2</sup> s<sup>-1</sup> at a constant inlet temperature 10° C. The heat transfer and pressure drop of the pure refrigerants are compared to some correlations.

[cho12] Choi, K., Oh, J-T., Nguyen, C., and Kim, K., “Boiling Heat Transfer of R-1234yf in Horizontal Circular Small Tubes”, International Refrigeration and Air Conditioning Conference, Purdue University, July 16-19, 2012. Heat transfer and pressure drop were measured in horizontal tubes with inner tube diameters of 1.5 mm and 3 mm. Local heat transfer coefficients were obtained for heat fluxes from 5 to 40 kW m<sup>-2</sup>, mass fluxes from 50 to 600 kg m<sup>-2</sup> s<sup>-1</sup>, saturation temperatures of 0°, 5°, and 10° C, and quality up to 1.0. A new boiling heat transfer correlation for R-1234yf was developed.

[dan10] Dang, C., Saitoh, S., Nakamura, Y., Minxia, K., and Hihara, E., “Boiling Heat Transfer of HFO-1234yf Flowing in Smooth Small-Diameter Horizontal Tube”, 2010 International Symposium on Next-Generation Air Conditioning and Refrigeration Technology, Tokyo, February 2010. The tube inner diameter was 2 mm. Local heat transfer coefficients were measured over a range of heat flux, mass flux, and inlet vapor quality (from 0 to 0.25). Results were compared to several heat transfer correlations.

[dom04] Domanski, P., “Performance of HC and HFC Refrigerants in a Finned-Tube Evaporator and Its Effect on System Efficiency”, 6<sup>th</sup> IIR Gustav Lorentzen Natural Working Fluids Conference, Glasgow, 2004

[ham10] Hamdar, M., Zoughalb, A., and Clodic, D., “Flow Boiling Heat Transfer and Pressure Drop of Pure HFC-152a in a Horizontal Mini-Channel”, International Journal of Refrigeration, Vol. 33, Issue 3, May 2010, p 566-577.

[jun05] Jung, Dongsoo, Lee, Heungseok, Bae, Dongsoo, and Ha, Jongchui, “Nucleate Boiling Heat Transfer Coefficients of Flammable Refrigerants on Various Tubes”, International Journal of Refrigeration, Vol. 28, Issue 3, May, 2005, p. 451-455. Nucleate boiling coefficients were measured for R-1270, R-290, R-600a, R-600, and RE-170. Tubes used were a low-fin with 1023 fins per meter, Turbo-B, and Thermoexcel-E.

[kim12] Kim, S. and Hrnjak, P., “Effect of Oil on Flow Boiling Heat Transfer and Flow Patterns of CO<sub>2</sub> in 11.2 mm Horizontal and Enhanced Tubes”, International Refrigeration and Air Conditioning Conference, Purdue University, July 16-19, 2012. Tests were run with pure CO<sub>2</sub> and also with miscible POE oil at an

oil circulation rate between 0.5% and 2%. The experimental conditions include an evaporation temperature of  $-15^{\circ}\text{C}$ , mass fluxes from 40 to  $200\text{ kg m}^{-2}\text{ s}^{-1}$  with heat fluxes from 0.5 to  $10\text{ kW m}^{-2}$ , and vapor qualities from 0.1 to 0.8. Oil reduced the heat transfer coefficient of  $\text{CO}_2$  at low qualities (e.g., 0.1 to 0.4) and low mass fluxes ( $100\text{-}200\text{ kg/m}^2$ ) because of the suppression of nucleate boiling. At vapor qualities above 0.5 where the convective contribution is dominant, oil increases heat transfer coefficients.

[kot08] Kotthoff, S. and Gorenflo, D., "Pool Boiling Heat Transfer to Hydrocarbons and Ammonia: A State-of-the-Art Review", *International Journal of Refrigeration*, Vol. 31, Issue 4, June 2008, p. 573-602. Data is analyzed for 12 hydrocarbons showing the influence of heat flux and reduced saturation pressure. Correlations are provided. The review closes with short discussions for mixtures of hydrocarbons, for the bundle effect, and for the behavior of advanced tubes.

[li12a] Li, M., Dang, C., and Hihara, E., "Investigation of Flow Boiling Heat Transfer of Binary Mixtures (HFO1234yf/R32) at Two Concentrations in a Smooth Horizontal Tube", *International Refrigeration and Air Conditioning Conference*, Purdue University, July 16-19, 2012. Two mixtures of R-1234yf/R-32, 80/20 and 50/50 mass %, were used for flow boiling heat transfer measurements in a smooth horizontal tube at a saturation temperature of  $15^{\circ}\text{C}$ . The inner diameter of the tube was 4 mm. Mass fluxes ranged from 100 to  $300\text{ kg m}^{-2}\text{ s}^{-1}$  and the heat flux ranged from 6 to  $24\text{ kW/m}^2$ . Heat transfer coefficients of the mixtures were compared to those of pure R-1234yf. A theoretical heat transfer prediction model was proposed for the mixtures.

[llo07] Llopis, R., Cabello, R., Navarro-Esbri, J. and Torrella, E. "A Dynamic Mathematical Model of a Shell-and-Tube Evaporator. Validation with Pure and Blend Refrigerants", *International Journal of Energy Research*, Vol. 31, Issue 3, March 2007, p. 232-244. A mathematical model of a shell-and-tube evaporator is based upon continuity, energy conservation, and heat transfer fundamentals. The model is formulated as a control volume combination that represents different refrigerant states along the evaporator. The strategy of working with physical fundamentals allows the steady-state and dynamic-state analysis of any of its performance variables. A steady state validation was made with R-22, R-134a, and the zeotropic blend R-407C. A dynamic validation with transient experimental tests was conducted with R-22.

[mor12] Mortada, S., Zoughaib, A., Arzano-Daurelle, C., and Clodic, D., "Boiling Heat Transfer and Pressure Drop of R-134a and R-1234yf in Minichannels for Low Mass Fluxes", *International Journal of Refrigeration*, Vol. 35, Issue 4, June 2012, p. 962-973. Tests were conducted in a six-channel tube with rectangular channels of 1.1 mm hydraulic diameter. Mass fluxes were in the range 20 to  $100\text{ kg m}^{-2}\text{ s}^{-1}$  with heat fluxes from 2 to  $15\text{ kW m}^{-2}$  and vapor quality 0-1. Four different intervals of mass and heat fluxes were detected and heat transfer correlations were proposed for each.

[oh12] Oh, J., Choi, K., Saito, K., et al. "Comparison of Heat Transfer Coefficient During Evaporation of Natural Refrigerants and R-1234yf in Horizontal Small Tubes", *10<sup>th</sup> IIR Gustav Lorentzen Conference on Natural Working Fluids 2012 Proceedings*, Delft, The Netherlands, June 25-27, 2012. Evaporation heat

transfer of R-744, R-717, R-290, and R-1234yf was measured in horizontal small tubes with inner diameters of 1.5 and 3 mm. Mass fluxes were in the range 50 to 600 kg m<sup>-2</sup> s<sup>-1</sup> with heat fluxes from 5 to 70 kW m<sup>-2</sup> and vapor quality 0-1. Evaporative heat transfer coefficient correlations are proposed.

[pam10] Pamitran, A. S., Choi, K.-I., Oh, J.-T., and Hrnjak, P., "Evaluation of Heat Transfer Coefficient Correlations Based on Flow Pattern for Two-Phase Flow Boiling of C<sub>3</sub>H<sub>8</sub> and CO<sub>2</sub> in Horizontal Small Tubes", 2010 International Symposium on Next-Generation Air Conditioning and Refrigeration Technology, Tokyo, February 2010. The tube inner diameters were 1.5 mm and 3 mm. Heat transfer coefficients were measured over a range of heat flux, mass flux, and inlet vapor quality (up to 1.0). Measured heat transfer coefficients were compared with some existing correlations based on the flow pattern. A new correlation is presented.

[par10a] Park, C.Y. and Hrnjak, P.S., "Pure NH<sub>3</sub> and CO<sub>2</sub> Heat Transfer and Pressure Drop in Horizontal Smooth Tubes for NH<sub>3</sub> Two-Stage and NH<sub>3</sub>/CO<sub>2</sub> Cascade Refrigeration Systems: A Review", International Journal of Air-Conditioning and Refrigeration, Vol. 18, Issue 2, 2010, p 85-100

[par10b] Park, Ki-Jung and Jung, Dongsoo, "Nucleate Boiling Heat Transfer Coefficients of R-1234yf on Plain and Low Fin Surfaces", International Journal of Refrigeration, Vol. 33, Issue 3, May 2010, p 553-557.

[pen12] Peng, L., Wang, X., Han, X., and Chen, G., "Experimental Investigation of Evaporation Heat Transfer and Pressure Drop Characteristics of HFC-161 in a Horizontal Smooth Tube", International Refrigeration and Air Conditioning Conference, Purdue University, July 16-19, 2012. Local evaporating heat transfer coefficients and total pressure drops were measured in a horizontal smooth tube with an inner diameter of 9 mm. Mass fluxes were in the range 100 to 200 kg m<sup>-2</sup> s<sup>-1</sup> with heat fluxes from 15 to 25 kW m<sup>-2</sup> and evaporation temperatures of 5° and 10° C. The measured heat transfer coefficient of R-161 is higher than that of R-22.

[rig04] Rigola, J., "Numerical Model of In-Tube Ammonia Evaporation, Analysis of Available Heat Transfer Correlations", 6<sup>th</sup> IIR Gustav Lorentzen Natural Working Fluids Conference, Glasgow, 2004

[tho08] Thome, J.R., Cheng, L., Ribatski, G., and Vales, L.F., "Flow Boiling of Ammonia and Hydrocarbons: A State-of-the-Art Review", International Journal of Refrigeration, Vol. 31, Issue 4, June 2008, p. 603-620. A comprehensive review of flow boiling heat transfer, two-phase pressure drops, and flow patterns of ammonia and hydrocarbons applied in HVAC&R is presented. Further research needs are identified at the conclusion of the paper.

[tib12] Tibirica, C., Ribatski, C., and Thome, J., "Flow Boiling Characteristics for R-1234ze(E) in 1.0 and 2.2 mm Circular Channels", ASME Transactions – Journal of Heat Transfer Vol. 134 (2), 2012

[zha12] Zhao, Y., Liang, Y., Sun, Y., and Chen, J., "Development of a Mini-Channel Evaporator Model Using R-1234yf as Working Fluid". International Journal of Refrigeration, Vol. 35, Issue 8, December 2012, p. 2166-2178. R-1234yf test data from six different evaporator samples were compared to model

predictions under typical conditions for an automotive air conditioning system. The model using Kandikar's correlation to calculate two-phase heat transfer provided the best results. Under the same conditions R-1234yf has a lower two-phase heat transfer coefficient than R-134a.

### Condensing

[cav10a] Cavallini, J.S., Del Col, C., and Zilio, C., "In Tube Condensing Performance of Refrigerants Considering Penalization Terms (Exergy Losses) for Heat Transfer and Pressure Drop", *International Journal of Heat Transfer*, 2010, p.2885-2896.

[del10] Del Col, D., Torresin, D., and Cavallini, A., "Heat Transfer and Pressure Drop During Condensation of the Low GWP Refrigerant R-1234yf", *International Journal of Refrigeration*, Vol. 33, Issue 7, November 2010, p 1307-1318.

[del12] Del Col, D., Bortolin, S., Bortolato, M., and Rossetto, L., "Condensation Heat Transfer and Pressure Drop with Propane in a Minichannel", *International Refrigeration and Air Conditioning Conference*, Purdue University, July 16-19, 2012. The local heat transfer coefficient was measured during condensation of propane in a 0.96 mm diameter circular minichannel. Tests were carried out at mass fluxes ranging from 100 to 800 kg m<sup>-2</sup> s<sup>-1</sup>. The test data was compared to available correlations.

[fer12] Fernandez-Seara, J., and Uhia, F., "Heat Transfer and Friction Characteristics of Spirally Corrugated Tubes for Outer Ammonia Condensation". *International Journal of Refrigeration*, Vol. 35, Issue 7, November 2012, p. 2022-2032. Experiments evaluated the heat transfer and friction characteristics of spirally corrugated tubes for the outer condensation of ammonia. The tubes were stainless steel with 18/20 mm nominal diameters. Tests were run at a saturation temperature of 40° C and wall subcooling from 1 to 7.5° C. Heat transfer coefficients on both sides of the tubes and friction factors inside the tubes were measured. The condensation coefficients were close to those of a smooth tube. The inner heat transfer enhancement factors ranged from 2.11 to 2.53.

[hos12] Hossain, A., Onaka, Y., and Miyara, A., "Experimental Study on Condensation Heat Transfer and Pressure Drop in Horizontal Smooth Tubes for R-1234ze(E), R-32, and R-410A", *International Journal of Refrigeration*, Vol. 35, Issue 4, June 2012, p. 927-938. Heat transfer and pressure drop measurements were made in a horizontal smooth copper tube with a diameter of 4.35 mm and length of 3.6 m. Tests were conducted for mass fluxes varying from 150 to 400 kg m<sup>-2</sup> s<sup>-1</sup> and saturation temperatures ranging between 35° and 45° C over the vapor quality range from 0.0 to 1.0. The heat transfer of R-1234ze(E) was about 20%-40% lower than for R-32 but 10%-30% higher than for R-410A at a saturation temperature of 40° C. Results were compared with existing prediction methods for condensing refrigerants.

[hrn12] Hrnjak, P. "Low Refrigerant Charge – With a Focus on Microchannel Heat Exchangers", *ASHRAE/NIST Refrigerants Conference*, October 29-30, 2012, Gaithersburg MD. USA . This paper presents strategies for charge reduction in components of air conditioning and refrigeration systems. A

particular focus is on condensing heat exchangers, particularly microchannel condensers. Comparisons of refrigerants based on their potential for low condenser charge are included.

[iqb12] Iqbal, I. and Bansal, P., "In-tube Condensation Heat Transfer of CO<sub>2</sub> at Low Temperatures in a Horizontal Smooth Tube", *International Journal of Refrigeration*, Vol. 35, Issue 2, March 2012, p. 270-277. CO<sub>2</sub> condensation heat transfer was measured in a horizontal smooth tube of 6.52 mm internal diameter at saturation temperatures between 0° and -15° C with mass fluxes from 50 to 200 kg m<sup>-2</sup> s<sup>-1</sup> and for various vapor qualities. A new empirical correlation was developed to improve the prediction of CO<sub>2</sub> heat transfer coefficients.

[jun04] Jung, D., Chae, S., Bae, D., and Oho, S., "Condensation Heat Transfer Coefficients of Flammable Refrigerants", *International Journal of Refrigeration*, Vol. 27, Issue 3, May 2004, p. 314-317. Condensation heat transfer coefficients were measured for R-1270, R-290, R-600a, R-600, RE-170, and R-32 on a plain tube.

[koy11] Koyama, S., Baba, D., and Nakahata, H., "Experimental Study on Heat Transfer and Pressure Drop Characteristics of Pure Refrigerant R-1234ze(E) Condensing on a Horizontal Micro-Fin Tube", *International Congress of Refrigeration*, Prague, Czech Republic, August 21-26 2011. Condensation heat transfer inside a 6 mm copper tube with 0.26 mm fin height and 20 degree helix angle was studied over a range of mass velocities. Effects of mass velocity on heat transfer and pressure drop were determined and compared with previous correlations.

[li12b] Li, M., Dang, C., and Hihara, E., "Experimental and Theoretical Study on Condensation Heat Transfer of Nonazeotropic Refrigerant Mixture R-1234yf/R-32 Inside a Horizontal Smooth Tube", *International Refrigeration and Air Conditioning Conference*, Purdue University, July 16-19, 2012. Two mixtures of R-1234yf/R-32, 52/48 and 77/23 mass %, were used for condensing heat transfer measurements in a smooth horizontal tube with an inner diameter of 4 mm. Mass fluxes ranged from 100 to 300 kg m<sup>-2</sup> s<sup>-1</sup>. Heat transfer coefficients of the mixtures were evaluated by combining correlations of heat transfer and mass transfer at both the vapor side and the liquid side.

[lon12] Longo, G. and Zilio, C., "HFO1234yf Condensation Inside a Brazed Plate Heat Exchanger", *International Refrigeration and Air Conditioning Conference*, Purdue University, July 16-19, 2012. Heat transfer coefficients and pressure drops were measured for condensation inside a brazed plate heat exchanger. The effects of saturation temperature, mass flux, and superheating were investigated. R-1234yf exhibits heat transfer coefficients lower by 10-12% and frictional pressure drops lower by 10-20% than R-134a under the same operating conditions.

[man12] Mancin, S., Del Col, D., and Rossetto, L., "R-32 Partial Condensation Inside a Brazed Plate Heat Exchanger", *International Refrigeration and Air Conditioning Conference*, Purdue University, July 16-19, 2012. Experimental measurements were made during partial condensation of superheated R-32 in a commercial brazed plate heat exchanger prototype. The effects of 5, 10, 15, and 25 K superheat were explored. Measurements were carried out at mass fluxes of 15-40 kg m<sup>-2</sup> s<sup>-1</sup> and outlet vapor quality from 0.0 to 0.65. The data were collected at around 36.5° C saturation temperature. The data was used

to validate a step-by-step model for calculating heat transfer coefficient taking superheating into account.

[miy08] Miyara, A., "Condensation of Hydrocarbons – A Review", *International Journal of Refrigeration*, Vol. 31, Issue 4, June 2008, p. 621-632. Recent studies of condensation are reviewed. For in-tube condensation, heat transfer coefficients of smooth tubes correlate well with a previously proposed equation developed for fluorocarbons. Little data is available for enhanced tubes. In the case of condensation on a horizontal tube, heat transfer on a smooth tube is explained well by the Nusselt theory. Different heat transfer coefficients appear for enhanced tubes. Since blended hydrocarbons may be used, models of mixed vapor condensation also are reviewed.

[par08] Park, K-J. Jung, D., and Seo, T., "Flow Condensation Heat Transfer Characteristics of Hydrocarbon Refrigerants and Dimethyl Ether Inside a Horizontal Plain Tube", *International Journal of Multiphase Flow*, Vol. 34, Issue 7, July 2008, p. 628-635. Flow condensation heat transfer coefficients are measured for R-22, propylene, propane, DME, and isobutene in a horizontal plain tube. Heat transfer and pressure drop data are obtained in the vapor quality range 10-90%.

[par11] Park, K-J., Kang, D., and Jung, D., "Condensation Heat Transfer Coefficients of R-1234yf On Plain Low Fin, and Turbo-C Tubes", *International Journal of Refrigeration*, Vol. 34, Issue 1, January 2011, p 317-321

[son12] Son, C-H. and Oh, H-K., "Condensation Heat Transfer Characteristics of CO<sub>2</sub> in a Horizontal Smooth-and Microfin-Tube at High Saturation Temperatures", *Applied Thermal Engineering*, Vol. 36, No. 1, April 2012, p. 51-62. The heat transfer characteristics of CO<sub>2</sub> at high saturation temperatures in a horizontal smooth- and microfin-tube were measured over a range of temperatures (20°-30°C) and mass flux. Data was compared against previous heat transfer correlations. Relatively good agreement was found with a different existing correlation for each type of tube.

[wan12] Wang, L., Dang, C., and Hihara, E., "Experimental Study on Condensation Heat Transfer and Pressure Drop of Low GWP Refrigerant R-1234yf in a Horizontal Tube", *International Journal of Refrigeration*, Vol. 35, Issue 5, August 2012, p. 1418-1429. Condensation heat transfer of R-1234yf was measured in a horizontal tube with an inner diameter of 4 mm. The mass flux range was 100-400 kg m<sup>-2</sup> s<sup>-1</sup> and saturation temperatures were 40°, 45°, and 50° C. Results were compared to those with R-134a and R-32. The researchers also observed the two-phase flow patterns in the tube. The Haraguchi correlation agreed fairly well with the experimental data.

### **Evaporating and Condensing Heat Transfer**

[cav12] Cavallini, A., Brown, j., and Zilio, C., "Thermophysical Properties, Heat Transfer, and Pressure Drop of HFOs", *ASHRAE/NIST Refrigerants Conference*, October 29-30, 2012, Gaithersburg MD. USA . Heat transfer and pressure drop performance of halogenated propene isomers are presented for in-tube condensation and in-tube flow boiling. The paper presents information for R-1233xf, R-1233zd(E), R-1234yf, R-1234ze(E), and R-1234zf. In addition to these pure fluids, heat transfer and pressure drop

information is presented for five R-32/R-1234yf blends. The paper also presents thermophysical property estimations for the five pure fluids relative to R-134a, R-245fa, and R-123.

[kaj12] Kaji, R., Yoshioka, R., and Fujino, H., "The Effect of Inner Grooved Tubes on the Heat Transfer Performance of Air-Cooled Heat Exchangers for CO<sub>2</sub> Heat Pump System", International Refrigeration and Air Conditioning Conference, Purdue University, July 16-19, 2012. Tests were carried out to investigate the heat transfer performance of finned tube heat exchangers using CO<sub>2</sub> as the refrigerant and immiscible PAG oil. Three types of air-cooled heat exchangers with smooth and inner grooved tubes were used. The deterioration of performance with oil was different depending upon the inner surface geometry of the grooved tubes. Flow visualization studies were conducted. It was found that heat transfer performance can be improved by using inner grooved tubes with an optimal pattern to remove oil away from the inner surface.

[koy08b] Koyama, S., and Kuwahara, K., "Heat Transfer Characteristics of CO<sub>2</sub> as Refrigerant for Heat Pump Water Heaters", IEA Heat Pump Centre Newsletter, Vol. 26, (4), 2008 p.32-40. Cooling heat transfer characteristics of CO<sub>2</sub> are reported for three types of spiral-grooved tubes and a smooth tube. Tests were run at pressures of 8 MPa and 10 MPa. Mass velocities ranged from 360 to 690 kg/(m<sup>2</sup>-s). Boiling and evaporating heat transfer characteristics of CO<sub>2</sub> were measured in five types of spiral groove tubes and a smooth tube.

[lee06] Lee, H-S., Yoon, J-I., Kim, J., and Bansal, P.K., "Characteristics of Condensing and Evaporating Heat Transfer Using Hydrocarbon Refrigerants", Applied Thermal Engineering, Vol. 26, Issue 10, July 2006, p 1054-1062. Hydrocarbons included are R-290, R-600a, and R-1270. R-22 was tested for reference.