ALTERNATIVE REFRIGERANTS FOR BUILDING AIR CONDITIONING

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ABSTRACT

The majority of building air conditioning has traditionally been achieved with vapor compression technology using CFC-11 or HCFC-22 as refrigerant fluids. CFC-11 is being successfully replaced by HCFC-123 (retrofit or new equipment) or by HFC-134a (new equipment), but HCFC-123 is scheduled for phase-out longer term by provisions of the Montreal Protocol and the United States Clean Air Act. . Performance and environmental properties are presented for CFC-11 alternatives HCFC-123, HFC-134a, and HFC-245ca.

HCFC-22 is also scheduled for phase-out, and three alternatives for HCFC-22 have been identified: HFC-134a, a near-azeotropic mixture of R32/R125, and a zeotropic mixture of R32/R125/R134a. Performance test results, future potential energy efficiencies, and environmental properties are presented for these alternative refrigerants.

MONTREAL PROTOCOL AND UNITED STATES CLEAN AIR ACT REQUIREMENTS

International cooperation for protection of the stratospheric ozone layer resulted in an agreement known as the Montreal Protocol on Substances that Deplete the Ozone Layer. It was signed in 1987, and developed provisions for controlling CFCs and Halons, beginning in mid-1989. Subsequent Protocol amendments established and accelerated phase-out schedules. In the developed countries, phase-out of production and consumption of CFCs for new equipment was January 1, 1996. For HCFCs, there is a schedule of consumption reductions, to a virtual elimination (99.5% reduction) by 2020.

The United States Clean Air Act Amendment also requires CFC phase-out by January 1, 1996. HCFC-22 production and consumption for new equipment is not permitted after January 1, 2010, and HCFC-22 production must be completely phased out by 2020. For HCFC-123, the phase-out date for use in new air conditioning equipment is January 1, 2020, with complete phase-out by January 1, 2030.

CFC-11 ALTERNATIVE REFRIGERANTS

Three potential alternatives for CFC-11 (CCL3F) are HCFC-123 (CHCL2CF3), HFC-134a (CH2FCF3), and HFC-245ca (CHF2CF2CH2F). A listing of environmental, safety, and performance parameters is in Table 1.

TABLE 1 CFC-11 ALTERNATIVES

	CFC-11	R-123	R-134a	R245ca
ODP	1.0	0.016	0	0
GWP(100 yr)	4000	93	1300	610
AEL	1000	30	1000	?
COP	7.55	7.42	6.94	7.30
PSIG(100F)	8.7	6.1	124.3	8.7

Note: COP calculated at 100 F condenser, 40 F evaporator

HCFC-123

Although HCFC-123 has an ozone depletion value of 0.016, it has the lowest global warming potential of the alternatives (GWP = 93). The calculated thermodynamic energy efficiency of HCFC-123 (COP: coefficient of performance) is very close to that of CFC-11. The AEL (DuPont Company designation of allowable exposure level for an 8 or 12 hour/day work environment) for HCFC-123 is 30 ppm, and questions have been raised about the safe use of this compound. The AEL value is a chronic toxicity measure, which refers to impacts of sustained exposures over long periods, such as that experienced in a lifetime of work. Most chronic concentrations can be monitored, and safety measures taken to control exposure to acceptable levels. The use of HCFC-123 has been investigated by the U.S. Environmental Protection Agency (EPA). EPA has stated that evaluations of industrial chiller installations have shown average emissions are below 1 ppm, and by following monitoring and safe handling procedures, HCFC-123 can be safely used in centrifugal chillers (5). As reported by Calm (4), HCFC-123 has the same short term exposure level as CFC-11 (1000 ppm). In Calm's article, he states that one manufacturer suggests a 60 minute exposure limit of 1000 ppm with a 1 minute ceiling of 2500 ppm.

The world's most efficient centrifugal chillers are operating at slightly below 0.50 kw/ton (ARI standard rating conditions) using HCFC-123 (9). At the present time, HCFC-123 offers the lowest global warming potential and highest thermodynamic efficiency of all the alternative refrigerants.

HFC-134a

HFC-134a has zero ozone depletion potential, but a higher value of GWP than the other CFC-11 alternatives, plus lower calculated thermodynamic energy efficiency. HFC-134a has a higher vapor pressure than the other alternatives, and must be used in equipment meeting requirements of the A.S.M.E. Boiler and Pressure Vessel Code (pressure above 15 psig).

HFC-245ca

HFC-245ca has zero ozone depletion potential, an intermediate value of global warming potential, a calculated energy efficiency near those values for CFC-11 and HCFC-123, and would seem to be a logical replacement for HCFC-123. Glamm and Keuper (7) have reported that HFC-245ca will not perform satisfactorily when substituted for CFC-11 or HCFC-123 in existing chillers with no hardware changes; however, chillers designed for use with HFC-245ca can provide performance similar to that of HCFC-123 chillers. There are several hurdles to be overcome before HFC-245ca can be used commercially. According to the current Underwriter's Laboratory flammability test procedure 2182, HFC-245ca is classified as a flammable refrigerant, even though it is "marginally" flammable. This is a significant obstacle to use of HFC-245ca in the United States. There has been industry discussion of building and safety code requirements for using such marginally flammable fluids, but changes to building codes are not easily made. Other factors representing uncertainty, time, and expense are the lack of data on the toxicity of HFC-245ca, and no commercial manufacturing facility. There is obviously more work required to resolve the long term alternative for CFC-11.

HCFC-22 ALTERNATIVES

Three potential alternatives for HCFC-22 have been identified: HFC-134a, a near-azeotropic mixture of R32/R125, and a zeotropic mixture of R32/R125/R134a. There are two R32/R125 mixtures: R410A has the composition of 50/50 wt.% R32/R125, and R410B has the composition of 45/55wt.% R32/R125. According to UL 2182 test procedure, both mixtures are classified as practically nonflammable. The zeotropic mixture has the composition of 23/25/52 wt.% R32/R125/R134a. It has the ASHRAE designation of R407C, and is also classified as practically nonflammable. A listing of environmental, safety, and performance parameters is in Table 2.

TABLE 2 HCFC-22 ALTERNATIVES

	R-22	R134a	R410B	R410A	R407C
ODP	0.05	0	0	0	0
GWP	1700	1300	2000	1900	1600
AEL	1000	1000	1000	1000	1000
COP	4.83	4.90	4.39	4.43	4.67
Capacity	1.0	0.65	1.40	1.43	1.0
PSIA(110F)	241	161	377	380	258

Note: COP calculated at 110 F condenser, 45 F evaporator
Cooling capacity is relative to HCFC-22

General Comments on HCFC-22 Alternatives Applications and Properties

HFC-134a. HFC-134a is typically considered to be the long term replacement for CFC-12 due to the close match of boiling points and performance; however, HFC-134a is being considered in some HCFC-22 applications. HFC-134a is not a direct replacement for HCFC-22 because it has about 35% lower capacity and requires a larger compressor displacement for the same capacity equipment. HFC-134a is being offered by chiller manufacturers in equipment ranging in capacity from 100 to 6000 tons. In addition, one equipment manufacturer is offering a line of air conditioning equipment from 2 to 4 tons based on HFC-134a. Both applications have traditionally used HCFC-22.

R407C Applications. R407C was designed to have similar pressure and operating performance as HCFC-22 in existing equipment, thereby being a candidate for use in new equipment or as a service refrigerant for existing equipment. This objective has been met with R407C in systems with positive displacement compressors and direct expansion evaporators, with performance variations due to specific system design, particularly heat exchanger sizing. Performance of R407C in systems with refrigerant on the shell side of evaporators (flooded evaporators) and condensers has been very poor (35 - 40% reduction in capacity and energy efficiency) due to low refrigerant side heat transfer coefficients (1).

R407C is not an azeotropic mixture, as the vapor composition is different from the liquid composition of 23/25/52 wt.% R32/R125/R134a. At 40 degrees F, the vapor composition is 35/33/32 wt.% R32/R125/R134a. Temperature glide is often used to characterize zeotropic mixtures such as R407C, and this mixture has a temperature glide of 9 degrees F.

R407C Heat Transfer. Heat transfer behavior of R407C has been described in other published articles (2). The heat transfer coefficients versus HCFC-22 are very different in two types of evaporation systems as shown in Figure 1. If the mixture had no temperature glide, the heat transfer coefficients would be about the same as HCFC-22. But with the zeotropic mixture indicated by the temperature glide of 9 degrees F, there is degradation of heat transfer coefficients due to increased mass transfer resistance.

The effect is 10 - 20% reduction when the mixture is evaporating inside heat exchanger tubes (DX evaporator) at the flow conditions normally experienced with split system air conditioners and heat pumps. Since the air side heat transfer coefficient is controlling in these systems, the 10 - 20% reduction doesn't have much effect on overall system heat transfer.

There is a dramatic reduction of 75% in refrigerant side heat transfer coefficient for R407C in systems with pool boiling evaporators: refrigerant boiling on the outside of heat exchanger tubes, water flowing inside the tubes. There is no air-side control of heat transfer in this situation, resulting in overall poor heat transfer and the reductions in performance described above.

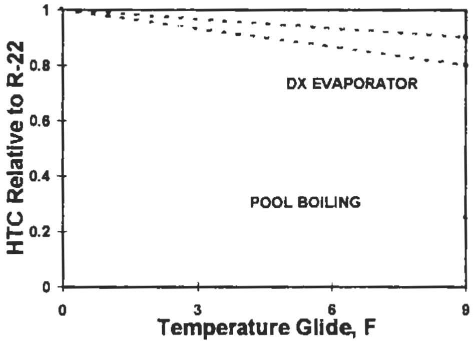

Figure 1 Refrigerant Heat Transfer

R410A/R410B Applications. R410A and R410B operate at pressures about 50% higher than HCFC22, and must be used in new equipment designed for the higher pressure rating. These refrigerants offer the opportunity to achieve higher energy efficiency than indicated by the thermodynamic cycle calculations due to improved compressor efficiencies and heat exchanger design changes. The differences in performance of R410A and R410B are very small, within the experimental error of most test facilities, and this paper will only have test data for R410B.

The R410 mixtures are considered to be near-azeotropic as the temperature glide is small (0.2 F) and the liquid and vapor compositions are closer than for R407C. For the 45/55 wt.% liquid mixture of R32/R125, the vapor composition is 48/52 wt.% R32/R125.

Since there are differences in the vapor and liquid compositions of both R407C and R410 mixtures, the refrigerants must be liquid charged into systems to maintain desired compositions.

R410A/R410B Heat Transfer. The heat transfer coefficients for the R410 mixtures do not have the reductions versus HCFC-22 as described for R407C. The pool boiling heat transfer coefficients for R410A are similar to HCFC-22 (10), and the inside-tube evaporation heat transfer coefficients for R410A are approximately 35% higher than for HCFC-22 (2). These differences are due to the near-azeotropic behavior (no increase in mass transfer resistance) of the R32/R125 mixtures, and the higher concentration of HFC-32 which has high thermal conductivity.

Performance Tests of HCFC-22 Alternatives - Heat Pump Description

To better understand the performance of the HCFC-22 alternatives, tests were performed in a commercial split system residential heat pump. The heat pump used for the tests was designed to operate with HCFC-22 and had a rated capacity of 30,000 Btu/hr (2 1/2 tons). The unit was equipped with a reciprocating compressor, a fixed orifice for cooling, an expansion valve for heating, a fin and tube evaporator with four circuits, and a spined fin condenser with five circuits and one subcooling circuit. The heat pump did not have an accumulator.

The heat pump was set up in two independently controlled environmental chambers so the dry and wet bulb temperatures for the outdoor and indoor coils could be maintained at standard ARI conditions. The 95 F and 82 F cooling and 47 F and 17 F heating tests were selected in order to verify steady state performance over a wide range of operating conditions. Instrumentation for the test system was described in an earlier paper (3).

The original fixed orifice tubes and expansion valve were used for testing both HCFC-22 and R407C. Each was replaced with a needle valve during tests with R410B. The original two piston reciprocating compressor was used during the HCFC-22 and R407C tests. A modified one piston compressor with 33% less displacement and the same motor as the original compressor was used for the R410B tests. A high pressure cutoff switch was installed for the R410B tests as an added safety precaution. A polyolester lubricant was used with all three refrigerants.

Performance Tests of HCFC-22 Alternatives - Test Results

Charge Size Determination. The first set of experiments were conducted at the 95 F cooling test condition to determine the optimum charge size for HCFC-22, R407C, and R410B. The charge sizes for HCFC-22 and R407C were selected based on maintaining 10 F superheat. The charge size for R410B was selected based on maintaining 10 F superheat and determining the needle valve setting to provide maximum energy efficiency. The charge sizes selected for HCFC-22, R407C, and R410B were 9.8, 9.2, and 7.5 lbs, respectively. The same charge size for each refrigerant was used for the remaining steady state tests.

Capacity Data and Potential. The capacity measurements for each refrigerant at the four test conditions are in Figure 2. R407C provided essentially the same cooling capacity as HCFC-22 with no equipment changes. During heating the R407C mixture capacity decreased 2 - 4% versus HCFC-22 because the expansion valve used for heating was not optimized for the mixture. Additional work has shown that R407C will provide the same heating capacity as HCFC-22, with minor adjustments to the expansion valve (EV). R410B provided a close match in both cooling and heating capacity using the modified compressor and expansion devices.

System modifications for improving the heating capacity for the ternary mixture were considered. Based on experimental data, the addition of a suction line accumulator (AC) allows mixture composition shifting during the heating cycle. HFC-32 and HFC-125 concentrations increase depending on the operating conditions and amount of refrigerant stored in the accumulator. The net result is that heating capacity can be increased by 3 - 6% during the heating cycles. Tests in other equipment have shown even greater capacity increases of 6 - 10% during the heating cycles (1). The additional capacity will reduce the amount of supplemental heat required during the heating season. The use of a suction line accumulator with R410B will not significantly change the circulating composition or improve heating capacity.

Energy Efficiency Data and Potential. Energy efficiency data for each refrigerant at the four test conditions are in Figure 3. The energy efficiency ratio for R407C versus HCFC-22 during cooling and heating ranged from 0.95 to 0.97. The energy efficiency ratio for R410B versus HCFC-22 during cooling ranged from 1.01 to 1.04 and for heating was about 0.98. System modifications for improving cooling cycle energy efficiency for both mixtures were considered. The benefits of counterflow evaporators and condensers (XC) and liquid line/suction line heat exchange (LSHX) were investigated using a computer model (8). Results from the computer model calculations are in Figure 3.

Computer model calculations indicate that utilizing a counter flow evaporator and condenser can increase R407C energy efficiency by 5 - 7%. This has been verified as reported in a recent presentation (6). Calculations indicate the use of a LSHX could increase R407C energy efficiency by an additional 2%, and this has been confirmed in experiments in our laboratory. These data indicate that improvements of 2 - 5% in energy efficiency versus HCFC-22 may be obtainable for cooling with the R407C mixture.

To increase the energy efficiency of R410B, heat exchanger recircuiting changes were investigated by modeling. The number of circuits could be reduced to increase the rate of heat transfer, reducing the temperature lift across the cooling cycle and increasing energy efficiency. Based on calculations with R410B, recircuiting the heat pump indoor coil from 4 circuits to 3 circuits and the outdoor coil from 5 circuits feeding one subcooling circuit to 3 could increase R410B energy efficiency by 2% during cooling operation, resulting in R410B having 3 - 6% higher energy efficiency than HCFC-22. Additional benefits may be possible by applying the LSHX with R410B.

Compressor Discharge Temperatures and Pressures. R407C had 9 - 12 F lower compressor discharge temperatures and R410B had 14 - 34 F lower discharge temperatures compared with HCFC-22 depending on operating condition (see Figure 4). The lower temperatures should provide a positive effect on life expectancy of the compressor and lubricant.

Compressor discharge pressures are in Figure 5. R407C had 4 - 14% higher pressure and R410B had 42 - 49% higher pressure than HCFC-22, depending on operating condition. System modifications such as smaller diameter tubes or increased tube wall and compressor shell thickness will be required to use R410B in air conditioning and heat pump systems.

CONCLUSIONS

CFC-11 Alternative Refrigerants

HCFC-123 offers the lowest global warming potential and highest thermodynamic efficiency of all the alternative refrigerants. However, the United States Clean Air Act Amendment requires phase-out of HCFC-123 for new air conditioning equipment by January 1, 2020, with complete phase-out by January 1, 2030. HFC-245ca has similar properties as HCFC-123, but testing has shown that HFC-245ca cannot be used satisfactorily in chillers designed for CFC-11 or HCFC-123 without hardware changes. Chillers designed for use with HFC-245ca can provide performance similar to that of HCFC-123 chillers. Additional concerns with the use of HFC-245ca are its rating of marginally flammable, lack of toxicity data, and no commercial manufacturing facility.

HCFC-22 Alternatives

Three HCFC-22 alternatives have been identified: HFC-134a is a low pressure alternative for use in commercial chillers and redesigned air conditioners. R407C is a ternary zeotropic mixture having similar pressure and capacity as HCFC-22 for use in new equipment or as a service refrigerant for existing equipment. R410A and R410B are near-azeotropic mixtures having pressure 50% higher than that of HCFC-22, having application in new equipment designs.

Performance data for HCFC-22, R407C, and R410B were obtained from tests in a split system heat pump. It was shown that it is possible to exceed the energy efficiency of HCFC-22 with either R407C or R410B if appropriate equipment design changes are made. The future choice of these alternatives will be based on economics and difficulty of design changes for specific equipment.

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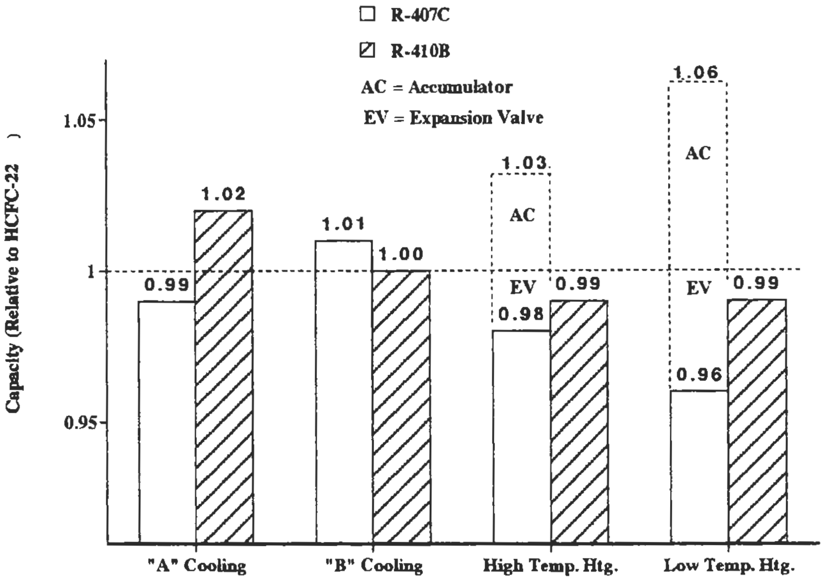

Figure 2 Capacity Comparisons and Potentials

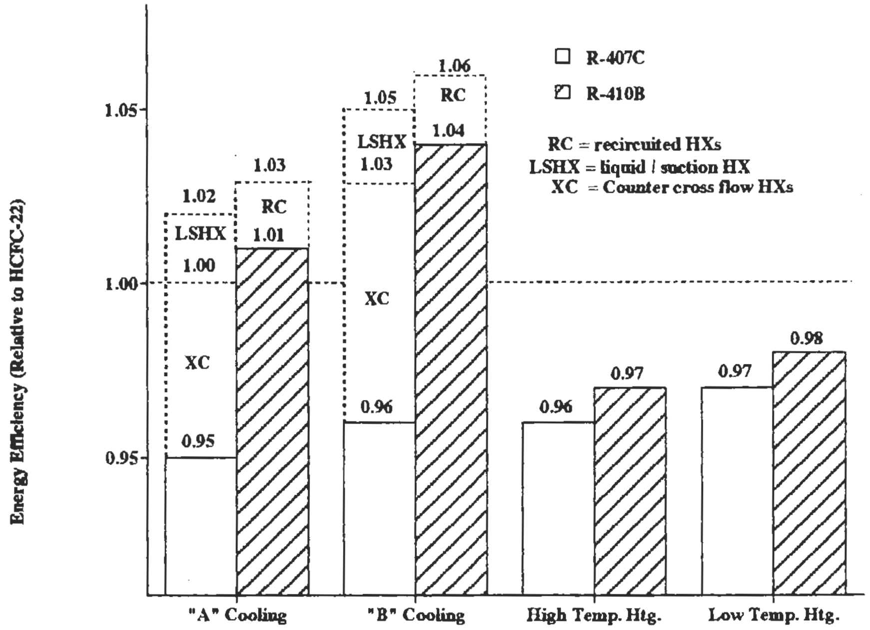

Figure 3 Energy Efficiency Comparisons and Potentials

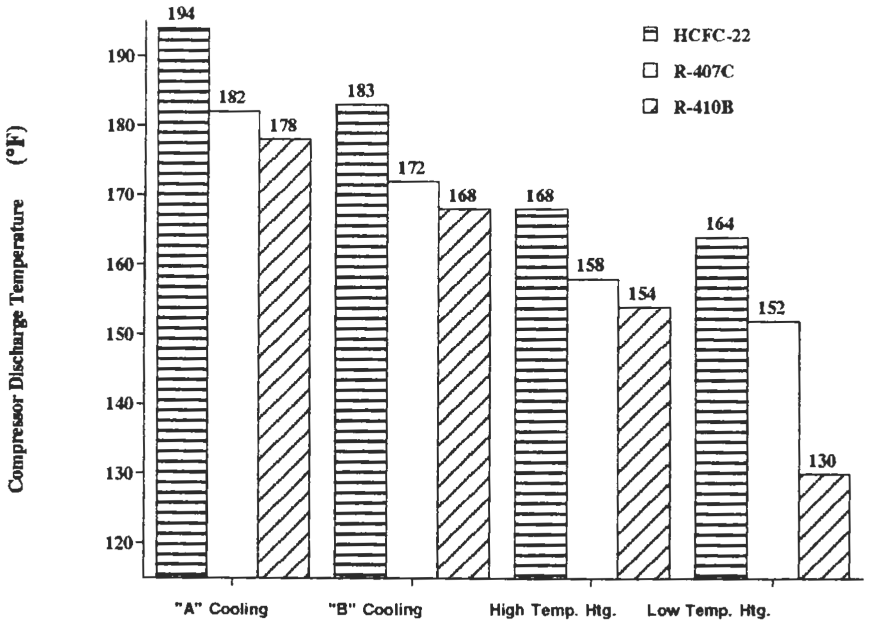

Figure 4 Compressor Discharge Temperatures

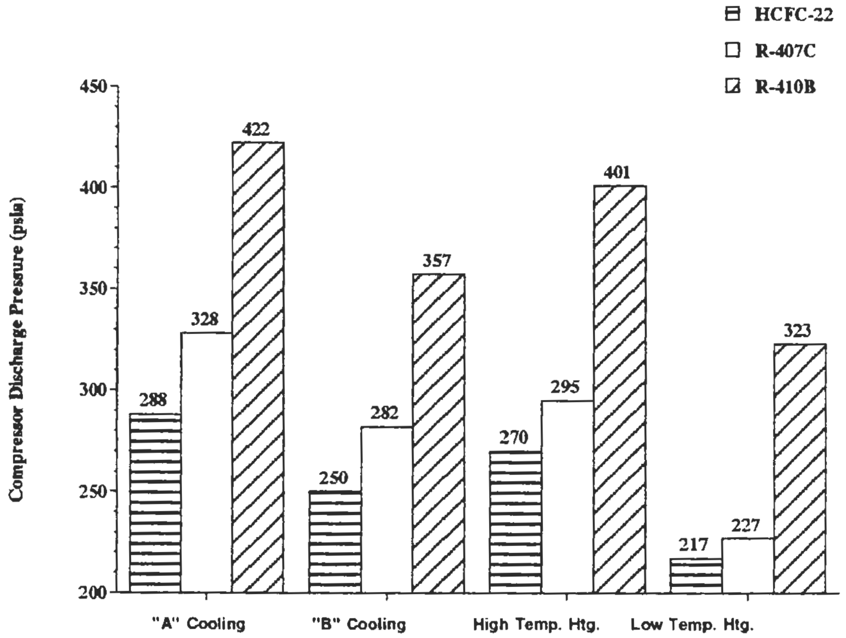

Figure 5 Compressor Discharge Pressures