Refrigerator-Freezer Energy Testing with Alternative Refrigerants

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ABSTRACT

As a result of the Montreal Protocol (UNEP 1987) that limits the production of ozone-depleting refrigerants, manufacturers are searching for alternatives to replace the R12 that is presently used in residential refrigerator-freezers. Before an alternative can be selected, several issues must be resolved. Among these are energy impacts, system compatibility, cost, and availability. In an effort to determine the energy impacts of some of the alternatives, energy consumption tests were performed in accordance with section 8 of the Association of Home Appliance Manufacturers (AHAM) standard for household refrigerators and household freezers (AHAM 1985). The results are presented for an 18 ft³ (0.51 m³), top-mount refrigerator-freezer with a static condenser using the following refrigerants: R12, R500, R12/dimethylether (DME), R22/R142b, and R134a. Conclusions from the AHAM test are that R500 and R12/DME have a reduced energy consumption relative to R12 when replaced in the test unit with no modifications to the refrigeration system. Run times were slightly lower than R12 for both refrigerants, indicating a higher capacity. While the R134a and R22/R142b results were less promising (7.8% and 8.6% higher energy consumption, respectively), changes to the refrigeration system, such as a different capillary tube or compressor, may improve their performance. It is noted that the test results are only an initial step in determining a replacement for R12. Further analysis should be performed to determine long-term effects on compressor life and operation over a wide range of ambient temperatures.

INTRODUCTION

In 1974, scientists presented the theory that chlorofluorocarbons (CFCs) slowly migrate into the stratosphere where they decompose by action of sunlight and split off free chlorine molecules that react with ozone, thus reducing the concentration of ozone in the upper atmosphere (Molina and Rowland 1974). This theory, along with other findings, led the United States, along with 23 other countries, to sign a landmark agreement (Montreal Protocol) to protect the stratospheric ozone layer from emissions of chlorinated and brominated compounds (UNEP 1987). The impact of the Montreal Protocol in the US was that the Environmental Protection Agency (EPA) issued a proposed rule to freeze production of R11, R12, R113, and R115 at 1986 levels by their relative ozone depletion potentials. This will be followed by a 20% reduction in mid-1993 and a 50% reduction by mid-1998 (Federal Register 1987).

In 1987, the National Appliance Energy Conservation Act (NAECA) was enacted, which established energy-efficiency standards for several consumer appliances including refrigerator-freezers (NAECA 1987). The NAECA requires the Department of Energy (DOE) to determine the acceptability of the standard for refrigerator-freezers, which goes into effect on January 1, 1990. Should the standard fail to be accepted, several states, notably California, have standards of their own that require minimum energy efficiencies for residential refrigerator-freezers.

The impending standards, along with the reductions in the production of R12 brought on by the Montreal Protocol, have created a major problem for refrigerator-freezer manufacturers. They are faced with trying to reduce energy consumption in the same time period in which they must begin using replacement refrigerants that may increase energy consumption. Adding to this dilemma, most changes in refrigeration system design require long lead times to implement in production. Thus, to meet efficiencies imposed by the 1990 standard, decisions will have to be made quickly as to which refrigerant will be used.

Requirements for replacement refrigerants will cause many candidates to be eliminated in the early going. Some of the requirements are that the refrigerant must be nontoxic, stable, nonflammable, compatible with lubricating oils, similar in thermodynamic performance, and available at low cost. Compromises will probably be made in some of these criteria in order to ensure that the energy efficiency targets are met. An outside influence on the choice of replacements involves the refrigerant selected for automotive air-conditioning systems. Automobile air-conditioning requires approximately 20 times more R12 than refrigerator-freezers, thus giving the automobile manufacturers a larger voice in the replacement refrigerants produced (Statt 1988). However, automobile manufacturers are not concerned with energy efficiency, since the energy efficiency of the air-conditioning system has little effect on the gas mileage. For this reason, a replacement for R12 may be produced that does not meet the energy-efficiency needs of refrigerator-freezer manufacturers.

TEST PROCEDURE

Testing of several alternative refrigerants to determine

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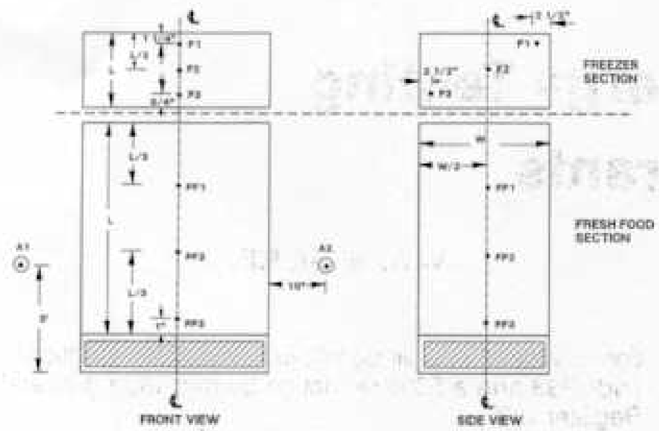

Figure 1 *Refrigerator thermocouple locations*

the estimated annual energy consumption was performed in an 18 ft³ (0.51 m³) refrigerator-freezer in accordance with section 8 of the AHAM standard for household refrigerators and household freezers (AHAM 1985). The standard calls for thermocouple hookups, as shown in Figure 1. A total of four test points are performed. These consist of running the refrigerator at two different control settings with the anti-sweat heater switch in both the "on" and "off" positions. The resultant test points are then used to calculate the energy consumption based on a 5°F (-15.00°C) freezer reference temperature. Other requirements for the test are that the compressor must have a break-in period of 24 hours prior to testing and the power supply to the refrigerator-freezer must be 115 volts ± 1 volt at 60 Hz. Test room conditions are that the ambient temperature must be 90°F ± 1°F (32.22°C ± 0.56°C), air circulation around the cabinet is less than 50 ft/min (15.24 m/min), and radiation shielding must be provided for surfaces greater than 10°F (5.56°C) above the ambient temperature.

Since the refrigerants used in the testing had different densities, it was necessary to optimize the charge for each alternative tested. The procedure was to first calculate the charge based on the liquid density of the alternative refrigerant relative to that of R12 at 70°F (21.11°C), a normal ambient temperature at which the refrigerant is charged. For example, R500 has a liquid density of 72.995 lbm/ft³ (1169.23 kg/m³). Based on a charge of 170 gm and a liquid density of 82.704 lbm/ft³ (1324.75 kg/m³) for R12, the charge for R500 is calculated as (72.995/82.704) · 170 gm or 150 gm. The calculated amount was charged into the refrigerator and tests were performed to determine the energy consumption. The calculated charge was then varied in 10 gm increments to determine the optimum charge that yielded the lowest energy consumption.

The procedure for loading the charge was to first evacuate the system to a minimum vacuum of 10 microns of mercury (1.33 E-06 Pa). The refrigerant was then weighed into the refrigerator-freezer as a vapor on the low side using a laboratory balance. If a refrigerant mixture was used, the high boiler was charged first. If a premixed mixture was being tested (such as 55% R22/45% R142b), the refrigerant was charged as a liquid rather than a vapor. For most of the high boiling refrigerants it was necessary to heat the charging cylinders to raise the pressure to a point where the refrigerant would flow into the refrigerator-freezer.

Since some of the refrigerants used in the testing were immiscible with mineral oil, it was necessary to change the oil in the compressor. Following the recommendations of a refrigerator-freezer manufacturer, the compressor was removed and heat was applied to make the oil less viscous. The used oil was discharged into a graduated cylinder to determine the quantity removed. The same quantity of new oil was then poured into the compressor and the compressor was bench-run for approximately one minute to warm the oil and mix it with any remaining used oil in the system. This oil was then drained and another oil charge added to the system in the same manner as previously described.

RESULTS

A total of five refrigerants, including R12, were tested. The four alternative refrigerants were R12/DME, R500, R134a, and R22/R142b. Refrigerants were selected on the basis of their potential for requiring minimal changes in the refrigeration system. Four oils were used according to refrigerant supplier recommendations. The recommendations were based on available solubility and miscibility data for the refrigerant/oil combinations. Pure refrigerants and mixtures were supplied by chemical companies in experimental quantities. In the case of R22/R142b, the two refrigerants were supplied separately.

R134a Tests

R134a is one of the alternative refrigerants mentioned most often as a substitute for R12. From thermodynamic data (Wilson and Basu 1988), it can be estimated that R134a has a lower capacity and operates at lower suction and higher discharge pressures than R12 for the same evaporating and condensing temperatures. Based on this information, a larger compressor would be necessary to achieve capacities equivalent to those obtained with R12. Drawbacks with R134a are that it has not completed toxicity testing and a compatible oil has not been found which ensures trouble-free operation over the expected life of the compressor. At the present time, R134a is undergoing toxicity testing. Assuming it passes all the tests, it should be available for commercial use by 1990 (ACHR News 1988).

Test results are presented in Table 1 for R134a and a polyglycol oil with a viscosity similar to that of the mineral oil used with R12. The results show an increased energy consumption of 7.8% relative to R12. Compressor run times were higher than those for R12, indicating that the capacity of R134a is lower, as previously estimated from the thermodynamic data. An additional test with R134a in a high-viscosity oil (Table 1) resulted in an increased energy consumption of 45.3%. The information from the additional test is quite useful for two reasons. First, the oil is the same as was used in testing where the refrigerator ran for 8.7 years using R134a (Wells, n.d.). Secondly, results of lubricity and wear testing have not been reported for R134a/polyglycol oil combinations, so the viscosity of the oil may have to be adjusted to maintain hydrodynamic film thicknesses or lubricating conditions similar to those obtained with the R12/mineral oil previously used.

TABLE 1
Refrigerator Test Results for R134a vs R12

Refrigerant	Oil	Charge (oz)	Charge (gm)	Energy Consumption (kWh/day)	% Increase	% Run Time
R-12	Mineral-150	6.0	170.0	2.43	—	43.9
R-134a	Polyglycol-165	5.5	155.0	2.62	7.8	49.0
R-134a	Polyglycol-525	5.5	155.0	3.53	45.3	53.6

TABLE 2
Refrigerator Test Results for R22/R142a vs R12

Refrigerant	Oil	Charge (oz)	Charge (gm)	Energy Consumption (kWh/day)	% Increase	% Run Time
R-12	Mineral-150	6.0	170.0	2.43	—	43.9
R-22/R142b (60/40)	Mineral-150	5.4	133.0	2.64	8.6	46.9
R-22/R142b (60/40)	Synthetic-150	5.4	133.0	2.64	8.6	47.4

TABLE 3
Refrigerator Test Results for R12/DME and R500 vs R12

Refrigerant	Oil	Charge (oz)	Charge (gm)	Energy Consumption (kWh/day)	% Increase	% Run Time
R-12	Mineral-150	5.0	170.0	2.43	—	43.9
R-12/DME (86/14)	Mineral-150	4.8	136.0	2.27	6.6	41.9
R-22/DME (90/10)	Mineral-150	4.8	136.0	2.34	3.7	43.6
R-500*	Mineral-150	5.3	150.0	2.29	5.8	38.4

*-73.8% R-12 / 26.2% R-152a

Three differences in the refrigerant/oil combinations can be highlighted. First, R134a is quite soluble in polyglycol oils. This increased refrigerant solubility effectively lowers the viscosity of the resulting refrigerant/oil solution, thus lowering the hydrodynamic film thickness. Next, the viscosity index of polyglycol oils is much greater than mineral oils, which means that they show a much smaller decrease in viscosity as the compressor warms to its operating temperature. Thus, the hydrodynamic film thickness tends to increase as a result of the greater viscosity index of polyglycol oils. Finally, R12 is known to make a significant contribution to the lubricity in compressors due to the chlorine atoms (Huttenlocher 1969). Since R134a contains no chlorine, it is not clear if this added lubricity effect will be seen with fully fluorinated refrigerants. As the result of the three differences, some increase in lubricant viscosity or oil additives may be required if present system longevity is to be maintained.

R22/R142b and R22/R124 Tests

R22/R142b has been mentioned as a possible replacement for R12 on the basis of its low ozone depletion potential (less than 0.05) and its similar boiling point (Radermacher and Lavelle, n.d.). An important consideration in the use of this mixture is the potential for flammability. Mixtures of R22 and R142b are nonflammable below compositions of 68 wt% R142b. While a mixture can be selected that is nonflammable as charged, the possibility exists for a portion of the mixture to leak out, resulting in the remaining mixture becoming flammable. However, the remaining portion of flammable mixture may be so small that it would not pose a large risk to the homeowner.

The results for a mixture of 60 wt% R22 and 40 wt% R142b are shown in Table 2. Tests with the mixture were originally performed using mineral oil identical to that used with R12. Following discussions with the refrigerant supplier, it was recommended that an alkylbenzene oil be used to improve the miscibility of the refrigerant/oil combination at low temperatures (Lavelle, n.d.). Both tests showed an energy consumption increase of 8.6%, which suggests that there is no heat exchanger fouling as a result of a miscibility problem. Longer run times accounted for part of the increased energy consumption. However, the increased power draw resulting from the larger pressure differential probably had the most effect on the energy consumption.

R500 and R12/DME Tests

Both R500 and R12/DME are azeotropic mixtures, which means that they behave as pure refrigerants. R500 is comprised of 73.8 wt% R12 and 26.2 wt% R152a, while R12/DME is 86 wt% R12 and 14 wt% DME. R500 and R12/DME are viewed as interim solutions to the problem of finding a suitable replacement for R12 since both contain a large amount of R12. Therefore, they both have a high ozone depletion potential. The R12/DME mixture, like the R22/R142b, contains a flammable component (DME). It is speculated that the R12/DME mixture would not become flammable should a leak occur due to both refrigerants leaking in a nonpreferential manner that would leave the composition unchanged.

As seen from the energy consumption results in Table

3, both R500 and R12/DME use less energy than R12. R500 had a decrease of 5.8% while R12/DME used 6.6% less energy. These decreases were mainly the result of shorter compressor run times. The amount of R12 could be reduced by 30% to 35% as a result of the reduction in charge and the lower amount of R12 in each mixture. This would effectively reduce the ozone depletion potential of the refrigerant by the same amount. Both refrigerants were run in the same oil as was used with R12. This is a desirable characteristic because synthetic lubricants like the polyglycol oil required for R134a are usually more expensive than mineral oil. The appliance industry is very concerned with trying to hold costs down as it is a very competitive industry. Therefore, the industry would prefer to continue using the same oil.

FUTURE WORK

Much additional work is needed before it can be determined which alternative refrigerant is the best for refrigerator-freezer applications. The work can be categorized into two main areas: 1) information on new refrigerants and oils such as chemical stability, toxicity, ozone depletion potential, flammability limits, thermodynamic property data, and refrigerant/oil solubility curves; and 2) product testing of the refrigerator-freezer and calorimeter data and accelerated life tests for rotary and reciprocating compressors.

Planned work includes energy consumption testing for mixtures of R134a/R152a, R134, and experimental mixtures from refrigerant suppliers. Additionally, testing of R134a in different oils is planned. These tests will be conducted on a refrigerator-freezer that is more fully instrumented than the one used in the tests reported in this work. The additional instrumentation will include pressure readings taken at the suction and discharge side of the compressor along with temperature measurements at the entrance and exit to the condenser, evaporator, and compressor. The additional instrumentation will allow a more accurate determination of the results.

Hardware changes to the refrigeration system will be investigated to determine the correct capillary tube and compressor size for each refrigerant. As shown in Figure 2, the capillary tube is sized to optimize the unit run time for a given system. Using a different refrigerant in the system can cause the capillary tube to be undersized or oversized as the result of changes in the refrigerant properties that affect the amount of refrigerant flow that is necessary. The compressor is sized for a particular refrigerant to deliver the required mass flow rate. By using a refrigerant whose density is different, the mass flow rate will be changed, which would affect the capacity of the unit.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations apply only to residential refrigerator-freezers and more specifically to the particular unit tested. Other refrigeration systems, such as heat pumps, operate at different conditions that could affect the refrigerant performance and thus alter the results. In addition, the conclusions are based on only one test series for determining energy consumption and are not sufficient to adequately predict the overall performance of the system under other conditions such as

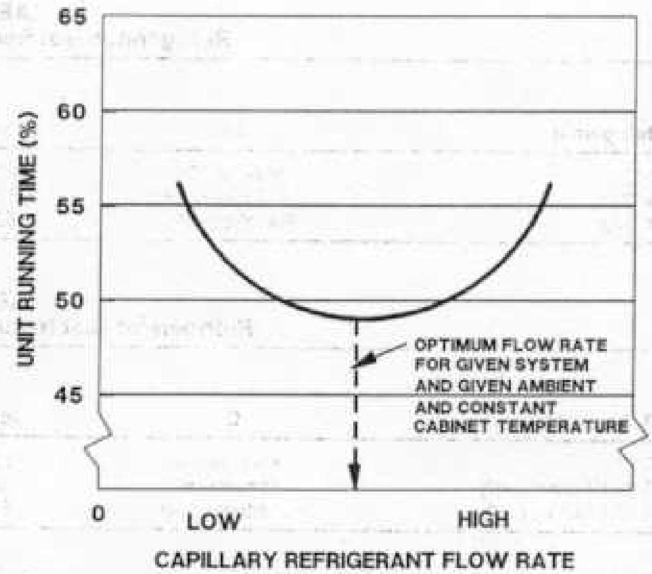

Figure 2 *Effect of capillary tube on run time*

pulldown and elevated ambient temperatures. Therefore, further tests, such as system reliability and accelerated life, are in order before a final decision can be made as to the adequacy of the alternative refrigerants.

— R12/DME and R500 are possible short-term alternatives on the basis of reduced energy consumption. The reason they are only short-term alternatives is that they still contain R12, which is in the process of being phased out of production. However, the test results reveal that a reduction of approximately 30% to 35% in the ozone depletion potential could be realized from their use.

— The use of R134a as an alternative refrigerant resulted in a 7.8% increase in energy consumption compared to R12 using a similiar viscosity oil as is used for R12.

— Using a much higher viscosity oil than is normally used for R12, the energy consumption for R134a increased dramatically to 45.3% higher than the results for R12.

— The mixture of 60 wt% R22/40 wt% R142b has an 8.6% higher energy consumption than R12 when run in a system with either a mineral oil or an alkylbenzene oil to improve solubility characteristics.

The preceding results were for an unmodified refrigeration system. The possibility exists that some of the results could be altered by changing the system design, either by using a different compressor or optimizing the capillary tube size. Additionally, results could be affected by testing in another manufacturer's product.

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