Test Results of Hydrocarbon Mixtures in Domestic Refrigerators/Freezers

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ABSTRACT

In the first part of the present research, an R290/R600 mixture was tested as a drop-in substitute in a 20-cubic-feet, single-evaporator, auto-defrost, topmount, conventional domestic refrigerator/freezer. All the hardware remained the same, only the capillary tube was lengthened to achieve the optimum performance. The best result with an optimized R290/R600 blend was 6% savings compared to the baseline test with R12. In the second part of the research, an 18.0-cubic-feet, auto-defrost, topmount, domestic refrigerator was used for experiments. Having tested for the single-evaporator baseline performance, the unit was converted to a two-evaporator modified-Lorenz-Meutzner cycle. The optimum performance of the modified unit yielded 14.6% and 16.7% energy savings with binary mixtures R290/n-c5, and R290/R600, respectively. A ternary mixture R290/R600/n-c5 with 17.3% energy savings proved to be better than the binary mixtures. The superior transport properties of the hydrocarbon mixtures are believed to be responsible for their better test performance.

INTRODUCTION

The Montreal Protocol regulates the production and trade of ozone-depleting substances (UNEP 1987). Since the refrigerants used in air conditioning and refrigeration units contain chlorine, which causes the ozone depletion, the industry and research institutes are challenged to find suitable alternates. The Department of Energy's appliance energy standards, designed to contain the global warming effects, is another major challenge facing the refrigeration industry. The long-term reliability of the proposed alternate refrigerants is yet to be resolved.

Naturally occurring substances, e.g., water, carbon dioxide, ammonia, and hydrocarbons are believed to be environmentally safe refrigerants. Now, with the CFC phase-out underway, interest in these environmentally safe refrigerants is growing. The thermodynamic properties of hydrocarbons, for example propane, are similar to that of R12 and R22. Table 1 shows that hydrocarbons have lower viscosity and higher thermal conductivity compared to that of CFCs and HFCs. These superior transport properties are believed to contribute to the higher energy efficiency of hydrocarbons vis-a-vis CFCs and HCFs. Table 2 shows that the global warming potential (GWP) of hydrocarbons such as propane (R290), n-butane (R600), and n-pentane (n-c5) is much lower than that of synthetic refrigerants. It also shows that the ozone depletion potential (ODP) of hydrocarbons is zero. Another advantage of hydrocarbons is their solubility in mineral oil, which is traditionally used as a lubricant in the compressors.

In Germany refrigerators using an R290/R600a blend are already in the market (Meyer 1993). These refrigerators are reported to have 10% energy saving compared to the R12 system. The charge of the blend is only one-thirds of the R12 charge, which reduces the fire hazard. Until now, hydrocarbons are not accepted as substitute refrigerants in the USA because of their flammability. However, studies predict an increase of the risk of kitchen fires by only 0.04%, when using the flammable refrigerant R152a (Report for EPA, Arthur D. Little, Inc., 1991).

Studies have shown energy savings with hydrocarbon refrigerants. Tests with cyclopropane as a drop-in substitute in a U.S. refrigerator/freezer system showed energy savings of 6% (Kim 1993). In addition, propane was tested in a 2.5-ton air conditioning unit (Treadwell 1991). After running the propane system with a larger compressor, 2% savings were achieved compared to the original R22 system.

The present paper describes the tests and results of using hydrocarbon mixtures in two domestic refrigerator systems.

Table 1 Transport properties of select refrigerants

Refrigerants	R12	R22	R123	R290	R600	n_c5
Viscosity						
35°C liquid (μPa/s)	182.0	151.7	386.3	87.19	144.6	200.0
-20°C vapor (μPa/s)	10.45	10.75	8.86	7.07	6.32	5.79
Thermal Conductivity						
35°C liquid (mW/mK)	63.1	82.1	76.1	99.2	108.9	108.7
-20°C vapor (mW/mK)	7.89	8.90	7.33	14.38	12.93	11.67

Table 2 ODP and GWP of the select refrigerants

Refrigerants	R12	R134a	R22	R123	R290	R600	n_c5
ODP	1	0	0.05	0.02	0	0	0
*GWP	4500	420	1600	90	3	3	3

*GWP of CO_2 = 1; time base: 100 years

THEORETICAL BACKGROUND

Single-Evaporator Refrigerator

Drop-in tests with R290/R600 mixture were conducted on a conventional, single-evaporator domestic refrigerator. The refrigerant evaporates at a low pressure in the evaporator acquiring heat from the surrounding air. Usually, the vapor leaves the evaporator superheated. Passing through a suction-line heat exchanger, the vapor gains more heat and then enters a compressor, where it is compressed to the condensing pressure. The refrigerant is then desuperheated, condensed, and subcooled in the condenser, while the heat is rejected to the surroundings. The subcooled liquid exchanges heat with the vapor coming out of the evaporator in the suction-line heat exchanger, and is cooled further. Finally the refrigerant is expanded to the evaporator inlet, and the cycle is completed.

Lorenz-Meutzner Cycle Refrigerator

American standards for domestic refrigerators typically require to keep the freezer and food compartment temperatures around -15°C (5°F) and 3.3°C (38°F), respectively. The existence of two evaporator pressure levels suggests that the food compartment with smaller temperature lift operates with higher coefficient of performance (COP) than that of the freezer. This aspect is not utilized in the single-evaporator domestic refrigerator, discussed in the previous section, where the food compartment is less efficiently cooled by the freezer evaporator. This results in about 20-25% lower COP of the food compartment that accounts for about half the refrigerator cooling load (Bare et al., 1991; Smith and Newell, 1993).

Lorenz and Meutzner (1975) presented a remarkable method of utilizing the smaller temperature lift of the food compartment. They used zeotropic refrigerant mixtures as working fluids. Due to the volatility difference of its pure components, the temperature of a zeotropic mixture changes during the phase change at constant pressure. The temperature difference between the saturated liquid and saturated vapor depends upon the concentration of components and is called the gliding temperature difference (GTD). By choosing a mixture with proper temperature glide, the different lifts of the freezer and food compartment evaporators can be effected by a single compressor. Figure 1 shows a schematic diagram of the Lorenz-Meutzner cycle refrigerator. As compared to a conventional refrigerator, the only additions in the hardware are a high-temperature, i.e., food compartment evaporator and a low-temperature heat exchanger between the two evaporators. Detailed commentary on the working of the Lorenz-Meutzner cycle can be found in Rose et al. (1992) and Zhou et al. (1994). Lorenz and

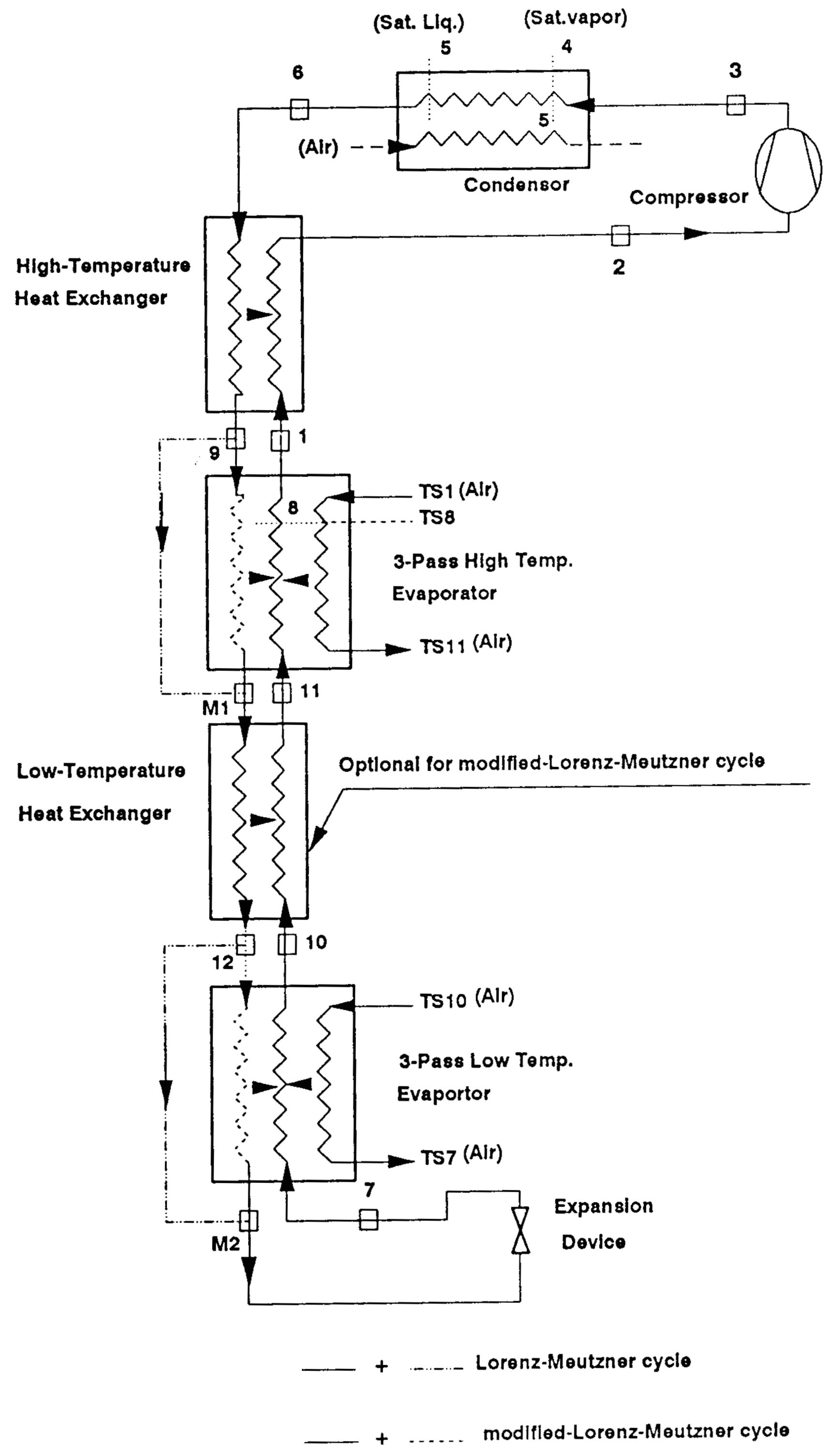

Figure 1: Schematic diagram of a two-evaporator refrigerator

Meutzner reported a 20% energy savings for a mixture of 50% R22/50% R11, compared to a conventional R12 refrigerator. The experimental results of Rose et al. (1992) showed a 9% reduction in energy consumption with zeotrope R22/R123.

Modified-Lorenz-Meutzner Cycle Refrigerator

Radermacher and Jung (1993) presented a modified version of the Lorenz-Meutzner cycle that ran the subcooled liquid line through the freezer and food compartment evaporators, rather than bypassing them as in the Lorenz-Meutzner cycle (Figure 1). The schematic diagram of the modified-Lorenz-Meutzner cycle refrigerator is also shown in Figure 1. It is evident that Lorenz and Meutzner envisioned the freezer and food compartment evaporators as conventional two-way heat exchangers where heat was transferred from compartment air to evaporating refrigerant. The Lorenz-Meutzner cycle required an intermediate low-temperature heat exchanger (intercooler) to help match the refrigerant GTD with that of the air streams in the freezer and food compartment by subcooling the liquid refrigerant. Radermacher and Jung (1993) showed that the performance of the Lorenz-Meutzner cycle can be significantly improved by subcooling the liquid by passing it through the freezer and food compartment evaporators, rather than bypassing them. Thus, the modified-Lorenz-Meutzner cycle makes the LTHX optional. In the modified-Lorenz-Meutzner cycle, the freezer and food compartment evaporators serve as three-way heat exchangers made by a smaller tube (liquid-line) inserted into a larger tube (suction-line). The compartment air surrounding the bigger tube and subcooled liquid in the smaller tube reject heat to the two-phase refrigerant running counterflow through the annulus of the two tubes. Zhou et al. (1994) reported a 16.5% energy savings from the test for a modified-Lorenz-Meutzner cycle refrigerator with a zeotropic mixture.

MIXTURE SELECTION

To select suitable hydrocarbon mixtures as possible test fluids in a single-evaporator refrigerator and a modified-Lorenz-Meutzner cycle refrigerator, the following criteria were set.

(1) Volumetric capacity (VC): Unless major changes in the compressor are made, the volumetric capacity of the mixture should be close to that of R12 in a single-evaporator refrigerator, specially for the drop-in tests. For a given mixture, this requirement suggests that at least one component of the mixture must be more volatile than R12. This means that the normal boiling point (NBP) of the component should be lower than that of R12, and found from the pure refrigerants above R12 in Table 3, which has fluids sorted by their NBPs. Besides, at least one component should be less volatile than R12, and found from the refrigerants below R12 in Table 3.

(2) Gliding temperature difference (GTD): Theoretical and experimental research has shown (Lorenz and Meutzner, 1975, Tiedemann et al., 1991, Jung and Radermacher, 1991a and 1991b, Rose et al., 1992) that the increase in the COP with zeotropic mixtures largely comes from correctly matching the temperature glides of the refrigerant and the air stream. For a single-evaporator refrigerator, the required GTD_E is about 5°C that is roughly equal to the air stream temperature drop in the freezer. However, for a Lorenz-Meutzner cycle refrigerator, the required overall GTD of the refrigerant to match the total temperature drop of the two air streams in both compartments is roughly 20°C to 25°C. Owing to the pressure drop, however, the theoretical GTD in the evaporator would be nearly 30°C.

Using the above criteria, R290/R600 mixture was selected as the test fluid for single-evaporator refrigerator; and R290/n-c5, R290/R600, and R290/R600/n-c5 mixtures were selected as test fluids for the modified-Lorenz-Meutzner cycle refrigerator.

Table 3 NBP and T_{crit} of hydrocarbons and synthetic refrigerants

Hydrocarbon Name	Alternate Name	Refrigerant Number	NBP (°C)	T-crit. (°C)
Methane		R-50	-161.49	-82.00
Ethene	Ethylene	R-1150	-103.70	9.30
Ethane		R-170	-88.63	32.20
Ethyne	Acetylene	C2H2	-84.00	32.15
Carbondioxide		R-744	-78.40	31.10
Propene	Propylene	R-1270	-47.70	91.80
Propane		R-290	-42.07	97.00
Chlorodifluoromethane		R-22	-40.76	96.00
Perfluoropropane		C3F8	-36.65	71.95
Cyclepropene		C3H4 (=CH-CH2-CH=)	-35.00	NA
Propadiene	Allene	C3H4 (CH2=C=CH2)	-34.50	120.00
Cyclepropane		RC-270	-32.80	125.15
Dichlorodifluoromethane		R-12	-29.79	112.00
Propyne	Methaylacetylene	C3H4 (CH3-C≡CH)	-23.22	129.24
2-Methylpropane	Isobutane	R-600a	-11.73	135.00
2-Methylpropene	Isobutylene	C4H8	-6.90	145.00
1-Butene		C4H8	-6.26	146.45
1,3-Butadiene		C4H6	-4.40	151.85
Butane	n-Butane	R-600	-0.50	152.00
trans-2-Butene		C4H8	1.50	155.45
Cyclobutene		C4H6	2.90	NA
cis-2-Butene		C4H8	3.73	162.45
Perfluorobutane		C4F10	3.96	113.25
1-Buten-3-yne		C4H4	5.10	NA
1-Butyne		C4H6	8.10	190.55
2,2-Dimethylpropane	Neopentane	C5H12	9.50	160.65
1,3-Butadiyne		C4H2	10.30	NA
1,2-Butadiene		C4H6	10.85	191.00
Cyclebutane		C4H8	12.50	NA
2-Butyne		C4H6	27.50	NA
2-Methylbutane	Isopentane	C5H12	27.85	190.28
Trifluorodichloroethane		R-123	27.87	183.79
Pentane	n-Pentane	C5H12	36.00	196.66

NA = Not Available

TEST FACILITY AND EXPERIMENTS

Test Conditions and Procedure

The refrigerators were placed in a 32.2±0.5°C (90±1°F) environmental chamber. The test procedure followed closely the section 8 of the AHAM standard (1988). Since the time required for obtaining the four points was too long and various working fluids were to be tested under the same conditions, the thermostat was replaced with an RTD controller to maintain about 5°F freezer and 38°F food compartment temperature. To further simplify the experiments, the defrost circuit was deactivated and the anti-sweat door heater was turned off. However, the defrost circuit was activated manually before a test for a fair comparison. A modified test procedure was instituted throughout the tests. A single-evaporator refrigerator is said to be optimized when the superheat at the outlet of the evaporator and subcooling at the outlet of the condenser is 1°C to 2°C (2°F to 4°F) at the end of the compressor on-time (Rose et al., 1992, and Pannock et al., 1994). The desired 38°F food compartment temperature is reached by adjusting the damper to meter the cold air flowing from the freezer to food compartment. The two-evaporator refrigerator system is said to be optimized when the condenser subcooling is 1.6 to 2.8 °C (3.0 to 5.0 °F) at the end of the compressor on-time, while the average freezer and food compartment temperatures are maintained at -15 °C and 3.3 °C (5.0 °F and 38 °F). Consequently, the optimization process involves the adjustment of refrigerant charge and capillary tube length. To facilitate the capillary tube replacement, two hand valves were added to the refrigeration loop in series between the end of the liquid line and the freezer evaporator inlet. The capillary tube length mounted between the two valves can be changed as needed.

Extensive temperature and pressure measurements were made to study the hydrocarbon mixtures performance in the single-evaporator and the modified-Lorenz-Meutzner cycle refrigerators. Copper-constantan thermocouples were mounted on to obtain the cyclic temperature profile of the refrigerant. The freezer and food compartment air stream temperatures, and the ambient temperature were measured by thermocouples with 25.4 mm diameter and 25.4 mm high (1.0" by 1.0") copper cylinders following the AHAM standard (1988). Pressures were measured at the inlet and outlet of the compressor by 24V DC pressure transducers with accuracy of 0.11% of the full scale (0-250 psia) at constant temperature. The instantaneous power and energy consumption per day were recorded by digital watt transducer and watt-hour meter whose accuracy was within $\pm 0.2\%$ of the reading. Data collection and control of the refrigerator were conducted by a digital computer, 3497A/3498A HP system and data logger. All tests were carried out without door opening.

Drop-in Experimental Tests

The test unit is a 557 l^3 (20 ft^3), automatic defrost, top-mounted domestic refrigerator/freezer. It was equipped with a reciprocating compressor using mineral oil as lubricant. The evaporator is a forced convection and the condenser is a natural convection cross flow heat exchanger. Since the R290/R600 mixture is tested as a drop-in substitute for R12, none of the components were modified. Only the capillary tube length was changed.

After a baseline test was conducted with R12, several tests were conducted to find the optimum conditions for the R290/R600 blend as the drop-in substitute. Capillary tubes of inner diameter of 0.66 mm (0.026 in.) were tested with different lengths. The manner in which the additional capillary tube was installed is described in a previous paper (Pannock 1994). For each capillary tube, different compositions of the blend, each with varying charge, were tested. The first test for a given composition started with a low charge. Then, charge was increased for the next test etc., until a minimum in the energy consumption could be determined. The tests were then repeated with a new composition and finally for a different capillary tube length. The accuracy of the initial composition, which is charged, is $\pm 1\%$.

Modified-Lorenz-Meutzner Refrigerator Tests

A 509.4 l^3 (18.0 ft^3) automatic defrost, topmount refrigerator was modified to run with the modified-Lorenz-Meutzner cycle after completing the baseline tests. The unit was equipped with a reciprocating compressor, charged with a mineral oil, whose capacity and EER were 240.26 W (820 Btu/hr) and 4.91 Btu/hr-W, respectively. After testing the unit for its baseline performance, its hardware was changed to achieve the modified-Lorenz-Meutzner cycle. The original condenser was a natural-convection, cross-counter-flow type, and was installed at the back of the refrigerator. The same condenser was used in the modified refrigerator. The original evaporator was of a forced convection, finned-tube, cross-flow type installed in the freezer. It was made of 68 fins of height 177.8 mm (7.0"), depth 50.8 mm (2.0"), and 16 aluminum tube passes of 609.6 mm (24.0") length and 9.53 mm (3/8") outside diameter (OD). The total internal volume of the original evaporator was 53.79 cm^3 (3.28 in^3). The total heat transfer area was 1.52 m^2 (2356.4 in^3).

The modified-Lorenz-Meutzner refrigerator uses two separate evaporators for the freezer and food compartment. The food compartment evaporator is a natural convection type, 3-way heat exchanger. The food compartment evaporator was made by soldering 9.53 mm (3/8") OD copper tubing (with 3.175 mm (1/8") OD copper tubing insert) on a 584.2 mm (23.0") wide, 635 mm (25.0") high, and 0.40 mm (1/64") thick copper plate. The 3.175 mm (1/8") OD copper tubing served as the subcooled-liquid line of the food compartment evaporator. The arrangement provided seven refrigerant passes along the plate height. The internal volume of the annulus in the food compartment evaporator was 19.33 cm^3 (1.179 in^3). The heat transfer area between the refrigerant and the air stream is 0.864 m^2 (1339.7 in^2). When it was installed, no space was left between the evaporator and the cabinet

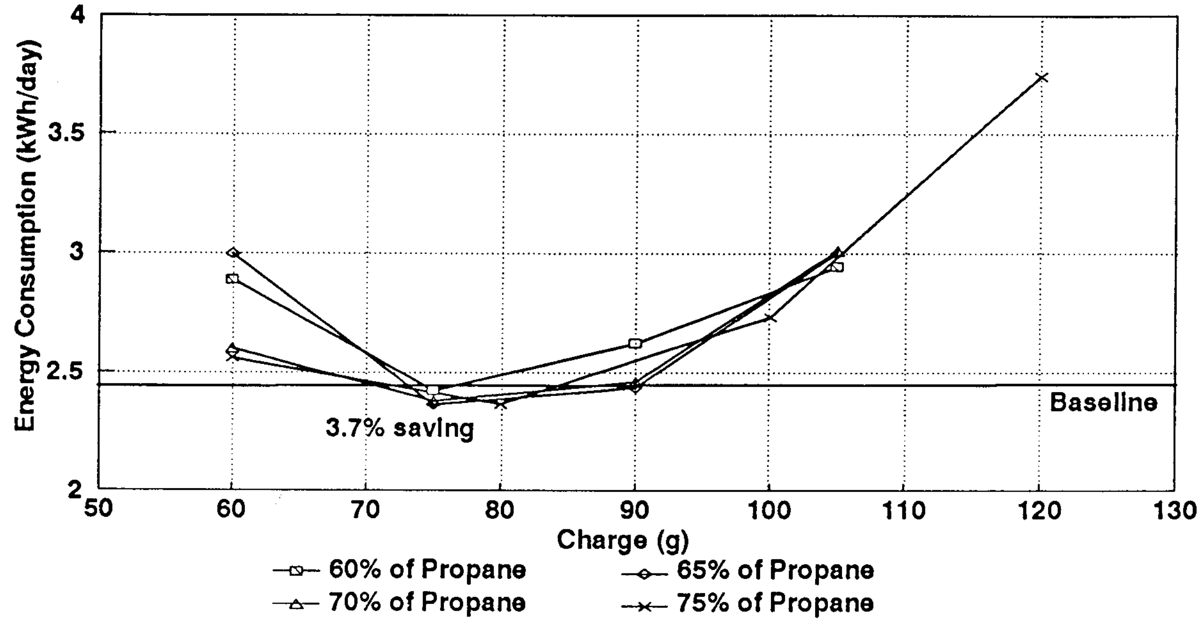

Figure 2: Energy consumption vs. charge with 4 ft. additional capillary tube

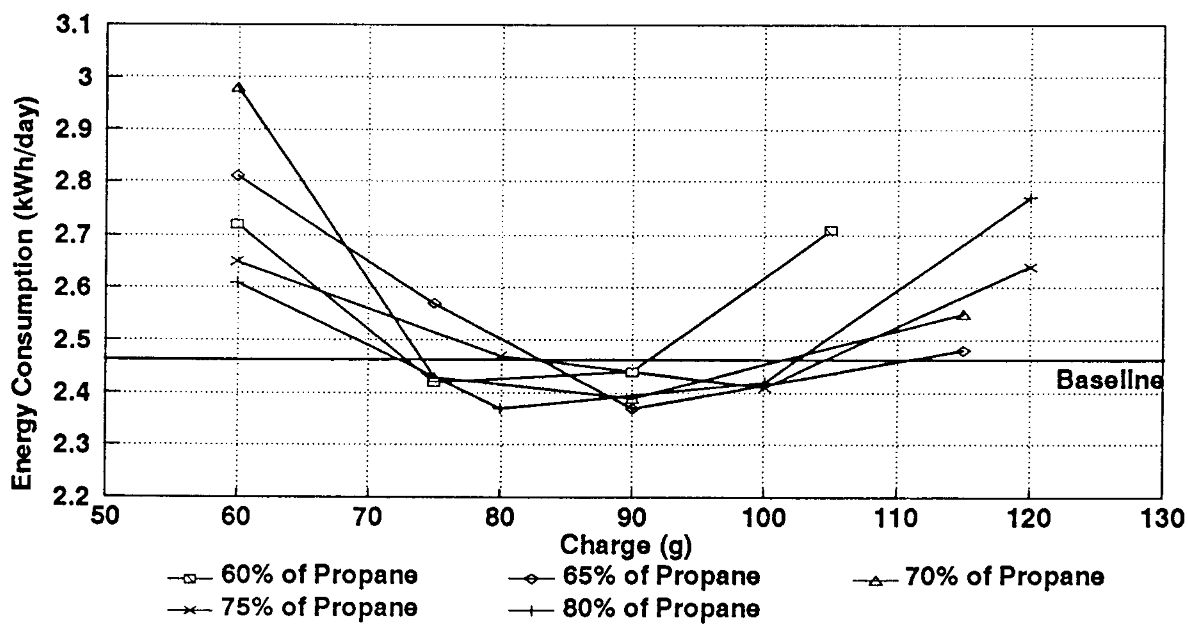

Figure 3: Energy consumption vs. charge with 8.6 ft. additional capillary tube

Table 4 Summary of the drop-in test results

Refrigerant	R12		R290/R600	
Min. energy consumption [kWh/day]	2.46		2.29	
Compressor on-time [min]	12.0		9.25	
Total cycle time [min]	26.0		28.0	
On-time ratio [-]	.46		.33	
Additional capillary tube length [ft]	-		5.0	
Refrigerant charge [g]	240		70	
Avg. freezer compartment temp. [°C] (F)	-15.6	(3.9)	-16.0	(3.2)
Avg. food compartment temp. [°C] (F)	3.3	(37.9)	4.1	(39.4)
Avg. evap. pressure during on-time [kPa] (psia)	123	(17.8)	146	(21.2)
Avg. cond. pressure during on-time [kPa] (psia)	975	(141.4)	1139	(165.2)

Modified-Lorenz-Meutzner Cycle Refrigerator Test Results

The following table summarizes the experimental results of the modified-Lorenz-Meutzner cycle refrigerator.

Table 5 Summary of the modified-Lorenz-Meutzner cycle refrigerator test results

Test Code	Refrigerant	Cycle	Charge (gm)	X_{mc} (%)	E.C. (kWh/day)	Saving (%)	T_{freez} (°F)	T_{food} (°F)	PR	On-time ratio
[1]W2100391	R12	RK	177	100	1.831	0.0	4.7	38.1		0.400
[2]W2121791	R12	RK	310	100	1.690	7.7	5.0	38.5	9.4	0.392
W2040293	R290/n-c5	MLM	180	50/50	1.544	15.7	4.8	40.4	7.2	0.395
W2061693	R290/R600	MLM	145	48/52	1.520	17.0	5.1	38.8	8.1	0.380
W2062393	R290/R600/n-c5	MLM	157	42/39/19	1.496	18.3	5.1	40.2	8.3	0.410

[1] Baseline test with Rankine (RK) cycle
[2] The R12 Test after the hardware was amended for modified-Lorenz-Meutzner (MLM) cycle

The first data row belongs to the baseline test of the original 18.0-cubic-feet, single-evaporator refrigerator that runs with R12 on a Rankine cycle. For the baseline test, no changes were made to the original unit except the installation of the thermocouples to measure the freezer and food compartment temperatures. The rest of the table describes the results of the tests conducted after the unit hardware was modified to the two-evaporator arrangement. The second row shows 7.7% energy savings, relative to the baseline, in the two-evaporator unit using R12. It is believed that the savings are due to the increased evaporator area and that a part of the evaporation occurred at the higher temperature food compartment. The remaining three rows of Table 5 correspond to the tests conducted on the two-evaporator unit with hydrocarbon mixtures operating under the modified-Lorenz-Meutzner cycle. The following observations are made regarding the modified-Lorenz-Meutzner cycle tests.

1. The energy savings with R290/n-c5, R290/R600, and R290/R600/n-c5 are 15.7%, 17.0%, and 18.3%, respectively. Since the food compartment temperature for different tests varies slightly (Table 5), the factor, that 0.55°C (1°F) higher food compartment temperature results in about 0.5% lower energy consumption around 3.3°C (38°F), normalizes the respective energy savings to 14.6%, 16.7%, and 17.3%. Subtracting 7.5% (corrected for the higher food compartment temperature) due to the hardware modification, the respective mixture effects in the modified-Lorenz-Meutzner cycle savings are 7.1%, 9.2%, and 9.8%. It is thought that R600 as the third component in the binary mixture R290/n-c5 helps straighten out the temperature profile to release the pinch point. So, the energy savings of the ternary

mixture R290/R600/n-c5 is 2.7% higher than that of the R290/n-c5 mixture.

2. The R12 charge increased from 177 gm to 310 gm when the original unit was modified to the two-evaporator configuration. The increase came from the increased evaporator volume, bigger filter-dryer, and larger suction-to-liquid-line heat exchanger. The charge of the hydrocarbon mixtures in the two-evaporator unit is 41.9% to 53.2% less than the R12 charge in the two-evaporator unit. With less charge of hydrocarbons, cycling losses are lower and the risk of fire is also reduced.
3. The operating pressure ratio in the modified-Lorenz-Meutzner cycle is 11.7% to 23.4% lower than the baseline pressure ratio, which partly explains the improvement in the energy efficiency.

CONCLUSIONS

The following conclusions are drawn from the experimental study of the drop-in tests and the modified-Lorenz-Meutzner cycle tests in domestic refrigerators with hydrocarbon mixtures.

1. The hydrocarbon blend R290/R600 (propane/n-butane) is an attractive substitute for R12. In drop-in tests savings of up to 6.5% could be achieved with a mixture composition of 70/30 and 70 gm of charge.
2. The experimental results of the binary hydrocarbon mixtures, R290/n-c5 (propane/n-pentane) and R290/R600, showed 14.6% and 16.7% energy savings in the modified-Lorenz-Meutzner cycle refrigerator.
3. The ternary R290/R600/n-c5 mixture with 17.3% energy saving has a better performance than the binary mixtures of R290/R600 and R290/n-c5.

Despite the promising test performance of hydrocarbons, their commercial refrigeration application is impeded by flammability concerns.

ACKNOWLEDGMENT

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