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A PERFORMANCE-ENHANCING ADDITIVE FOR VAPOR-COMPRESSION HEAT PUMPS: ADDITIONAL TEST RESULTS

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ABSTRACT

This paper describes test results of vapor-compression heat pumps operating with a performance-enhancing additive that increases the effective latent heat of vaporization of the working fluid. A previous paper presented test results for a system operating with HFC-134a refrigerant, polyol ester (POE) lubricant, and a scroll compressor. Those results showed that use of the additive resulted in increased COPc compared to tests without the additive. This paper presents additional test results with other compressor types, refrigerant types, and lubricants. The effect of different additive concentrations on various system performance parameters were examined. Various heat source and heat sink conditions, simulating air-conditioning conditions, were investigated. The results of compressor life tests to investigate the effect of tetraglyme on compressor life and wear are also discussed.

INTRODUCTION

Previous research on a hybrid vapor-compression/absorption heat pump has resulted in the development of a performance-enhancing additive for vapor compression heat pumps (Ref. 1). This patented additive, tetraethylene glycol dimethyl ether (tetraglyme), has been evaluated in the past as an absorbent for HCFC and HFC refrigerants for absorption heat pump applications (Refs. 2-6). Tetraglyme is nontoxic, nonflammable, nonvolatile (boiling point of 527°F), and is not classified a hazardous material. Tetraglyme has an extremely high affinity for HCFC and HFC refrigerants and has a significant heat of solution when mixed with these refrigerants in the liquid phase. This heat of solution characteristic of the tetraglyme/refrigerant pair results in an increase in the cooling capacity of the working fluid during the evaporation process, since the total latent heat of the working fluid is the sum of the heat of vaporization and the heat of solution. It is this feature that enhances the performance of vapor-compression heat pumps when tetraglyme circulates through the system with the working fluid.

A previous paper described test results performed on a heat pump operating with HFC-134a refrigerant, POE lubricant, and a scroll compressor (Ref. 1). Operating conditions to simulate air-conditioning and heat pump systems were investigated. Those results showed that adding tetraglyme to the working fluid resulted in increased system performance. Tetraglyme concentrations of 0-50 wt% in the lubricant were evaluated, and COPc was found to increase with increasing tetraglyme concentration. Increases in COPc as high as 20 % were observed for specific operating conditions, with a tetraglyme concentration of 20-30 wt% in the lubricant being optimum for that specific hardware configuration. Lubrication and wear tests, performed using the Falex pin and vee block method, showed that increasing the tetraglyme concentration from 0 wt% to 40 wt% in POE lubricant resulted in decreased wear.

TEST RESULTS

Test results will be presented to compare system performance for various concentrations of tetraglyme in the lubricant for the following oil/refrigerant/compressor combinations: 1) HFC-134a refrigerant, POE lubricant, and a hermetic reciprocating compressor; 2) HCFC-22 refrigerant, mineral oil lubricant, and a hermetic reciprocating compressor; 3) HFC-134a refrigerant, PAG lubricant, and an automotive reciprocating compressor; and 4) HFC-134a refrigerant, PAG lubricant, and an automotive sliding-vane rotary compressor. The effect of the additive on system performance when an oil separator is present at the compressor discharge will also be described.

Test Stand Description

The heat pump test stand was designed for cooling capacities in the 2-5 ton range. The purpose of the tests was to evaluate the effect of the tetraglyme concentration in the lubricant on system performance parameters. The test stand was capable of accommodating various compressor types. Water-to-refrigerant heat exchangers were used. The system was also equipped with various cycle components such as an oil separator, suction line accumulator, liquid receiver, and filter/drier, all of which could be independently used or bypassed. For the tests described in this paper, a TXV was used. System temperatures, pressures, flows, and power consumption were recorded using a data acquisition system. The temperatures of the heat source and heat sink inlet water temperatures were controlled and used as set points for the various operating conditions. To simulate air conditioning conditions, the evaporator inlet water temperature was held constant at 50°F and the condenser inlet water temperature was held constant in the range of 70°F to 120°F.

HFC-134a Refrigerant, POE Lubricant, And Hermetic Reciprocating Compressor

Table 1 presents the effect of tetraglyme concentration in the lubricant on system performance parameters. This table shows that COPc improvements ranging from 5-10 % were achieved, depending on tetraglyme concentration and condenser water inlet temperature. System capacity, compressor power requirement, and refrigerant flow rate increased with increasing tetraglyme concentration. The use of tetraglyme was also found to increase isentropic compressor efficiency. Tetraglyme was found to have a small effect on system temperatures and pressures. The compressor suction pressures increased from 1-3 psi and the compressor discharge pressures increased from 1-14 psi when tetraglyme was present. The pressure difference across the compressor increased from 1-12 psi but the pressure ratio decreased slightly. The compressor suction temperature decreased from 1-9 °F and the discharge temperature decreased from 1-17 °F when using tetraglyme. Evaporator exit superheat decreased from 2-14 °F but condenser exit subcooling increased from 4-7 °F when using tetraglyme.

HCFC-22 Refrigerant, Mineral Oil Lubricant, And Hermetic Reciprocating Compressor

Table 2 presents the effect of tetraglyme concentration in the lubricant on system performance parameters. This table shows that the use of tetraglyme in the HCFC-22/mineral oil system had negligible impact on system performance. COPc, system capacity, and compressor power requirement had negligible change as the tetraglyme concentration in the lubricant varied. Variations in refrigerant flow were seen, but no correlation with tetraglyme concentration is seen. The isentropic efficiency values of Table 2 were inaccurate due to faulty readings from the pressure transducer at the compressor suction. This was an unexpected result since the tetraglyme/HCFC-22 solution has similar hydrogen bonding and heat of solution characteristics as the tetraglyme/HFC-134a solution (Refs. 2-6). The addition of tetraglyme to the system had negligible impact on system temperatures and pressures. There was negligible variation on suction or discharge temperatures or pressures, or on evaporator superheat and condenser subcooling. Similar results were seen for a semi-hermetic reciprocating compressor.

HFC-134a Refrigerant, PAG Lubricant, And Automotive Reciprocating Compressor

There were subtle differences to the test stand made for automotive compressor testing. First, a motor drive with two pulleys was configured to provide for operating the compressor at 1100 RPM and 3900 RPM (idle and highway compressor speeds). Second, shaft power to the compressor was measured with an inline torquemeter. Third, no refrigerant flow measurements were made.

Table 3 presents the effect of tetraglyme concentration in the lubricant on system performance parameters at 3900 RPM. This table shows that COPc improvements ranging from 4-9 % were achieved, depending on tetraglyme concentration and condenser water inlet temperature. System capacity and isentropic compressor efficiency increased with increasing tetraglyme concentration in the lubricant, while compressor shaft power was decreased with increasing tetraglyme concentration. The use of tetraglyme resulted in reduced discharge temperatures, but had little impact on any of the other system temperatures or pressures.

Table 1 - Effect of Tetraglyme Concentration on System Performance Parameters (HFC-134a, POE Lubricant, Reciprocating Compressor, 50°F Evap. Water Inlet Temp.)

Cond H_2O Inlet Temp (°F)	Tetraglyme in Lubricant	COPc	Capacity (Btu/hr)	Compressor Power (W)	Isentropic Efficiency (%)	Refrigerant Flow (lb/min)
110	0 wt%	1.98	22617	3338	66.5	5.6
	10 wt%	1.99	23406	3434	65.7	6.0
	20 wt%	2.08	23605	3323	67.3	5.9
	30 wt%	2.06	23548	3346	67.3	6.1
100	0 wt%	2.13	23065	3170	65.6	5.3
	10 wt%	2.19	23967	3203	65.9	5.5
	20 wt%	2.24	24310	3178	66.9	5.7
	30 wt%	2.26	23492	3047	67.5	5.4
90	0 wt%	2.29	23288	2968	65.2	5.1
	10 wt%	2.35	24873	3094	65.2	5.4
	20 wt%	2.4	25025	3054	66.2	5.5
	30 wt%	2.48	25772	3042	67.9	5.7
80	0 wt%	2.42	23469	2832	64.6	4.9
	10 wt%	2.52	25386	2946	64.6	5.3
	20 wt%	2.54	25490	2931	65.9	5.3
	30 wt%	2.68	26929	2935	66.1	5.6
70	0 wt%	2.58	24234	2745	61.8	4.7
	10 wt%	2.72	27032	2911	65.0	5.4
	20 wt%	2.69	25765	2797	64.6	5.1
	30 wt%	2.81	25410	2646	65.9	4.9

Table 2 - Effect of Tetraglyme Concentration on System Performance Parameters (HCFC-22, Mineral Oil, Reciprocating Compressor, 50°F Evap. Water Inlet Temp.)

Cond H_2O Inlet Temp (°F)	Tetraglyme in Lubricant	COPc	Capacity (Btu/hr)	Compressor Power (W)	Isentropic Efficiency (%)	Refrigerant Flow (lb/min)
120	0 wt%	2.32	21964	2773	85.2	5.0
	10 wt%	2.33	21998	2767	118.7	4.9
	20 wt%	2.31	21850	2764	89.3	4.6
110	0 wt%	2.57	23300	2652	85.1	5.7
	10 wt%	2.57	23216	2645	118.5	4.9
	20 wt%	2.61	23604	2643	89.1	5.1
100	0 wt%	2.82	24285	2522	84.5	5.2
	10 wt%	2.78	23806	2502	126.7	5.3
	20 wt%	2.80	24063	2512	90.3	4.9
90	0 wt%	3.07	25052	2389	89.3	5.2
	10 wt%	3.09	25188	2387	120.2	5.4
	20 wt%	3.10	25246	2379	89.7	5.3
80	0 wt%	3.34	25950	2273	89.4	5.5
	10 wt%	3.39	26231	2260	84.3	5.4
	20 wt%	3.34	25582	2241	111.9	5.4
70	0 wt%	3.63	26018	2095	95.1	5.1
	10 wt%	3.57	25696	2106	85.1	4.9
	20 wt%	3.56	25205	2072	114.9	5.1

Table 3 - Effect of Tetraglyme Concentration on System Performance Parameters (3900 RPM) (HFC-134a, PAG Lubricant, Automotive Reciprocating Compressor, 50°F Evap. Water Inlet Temp.)

Cond H_20 Inlet Temp (°F)	Tetraglyme in Lubricant	COPc	Capacity (Btu/hr)	Compressor Power (W)	Isentropic Efficiency (%)
120	0 wt%	1.13	11506	2989	40.1
	10 wt%	1.22	12106	2892	42.6
	20 wt%	1.20	11695	2847	45.2
110	0 wt%	1.22	12011	2873	38.8
	10 wt%	1.32	12702	2811	40.8
	20 wt%	1.30	12230	2746	43.6
100	0 wt%	1.30	12352	2775	36.6
	10 wt%	1.38	12890	2725	38.6
	20 wt%	1.41	12872	2661	41.4
90	0 wt%	1.43	12997	2666	34.8
	10 wt%	1.51	13428	2608	37.0
	20 wt%	1.54	13634	2582	38.5
80	0 wt%	1.55	13699	2585	32.5
	10 wt%	1.62	14039	2535	34.2
	20 wt%	1.65	14201	2511	35.7
70	0 wt%	1.67	14218	2496	30.6
	10 wt%	1.75	14662	2455	31.4
	20 wt%	1.74	14260	2398	32.6

HFC-134a Refrigerant, PAG Lubricant, And Automotive Sliding-Vane Rotary Compressor

Table 4 presents the effect of tetraglyme concentration in the lubricant on system performance parameters at 1100 RPM. This table shows that COPc and capacity both decreased, from 2-6%, when using tetraglyme. There was little change in compressor power and a slight increase in isentropic compressor efficiency when using tetraglyme. The use of tetraglyme resulted in reduced discharge temperatures, but had little impact on any of the other system temperatures or pressures.

Table 4 - Effect of Tetraglyme Concentration on System Performance Parameters (1100 RPM) (HFC-134a, PAG Lubricant, Automotive Sliding-Vane Rotary Compressor, 50°F Evap. Water Inlet Temp.)

Cond H_20 Inlet Temp (°F)	Tetraglyme in Lubricant	COPc	Capacity (Btu/hr)	Compressor Power (W)	Isentropic Efficiency (%)
120	0 wt%	1.59	9168	1687	55.0
	10 wt%	1.49	8502	1664	59.6
110	0 wt%	1.95	10015	1504	57.8
	10 wt%	1.88	9526	1485	61.1
100	0 wt%	2.37	10980	1352	58.2
	10 wt%	2.25	10232	1330	62.0
90	0 wt%	2.72	11254	1209	58.8
	10 wt%	2.64	10852	1203	61.7
80	0 wt%	3.25	12165	1094	57.4
	10 wt%	3.11	11506	1083	60.2
70	0 wt%	3.70	12371	978	54.1
	10 wt%	3.63	12112	975	57.9

Effect of Oil Separator At Compressor Discharge

A series of experiments examined the impact of an oil separator on the performance improvement of the additive. The oil separator return both the lubricant and the tetraglyme to the compressor suction, since tetraglyme is nonvolatile. These experiments showed that when the oil separator was used, the performance benefits seen previously with tetraglyme were eliminated. These results suggest: 1) the performance benefits are not the result of a higher-efficiency compression process, and 2) the performance benefits are occurring in components other than the compressor, and are due to circulation of the additive with the lubricant throughout the cycle. The likely mechanism for the performance benefits of tetraglyme are in the heat of solution characteristic of the tetraglyme/refrigerant mixture.

DISCUSSION

To examine the lubricant/tetraglyme circulation behavior throughout the cycle, refrigerant samples were taken from the liquid leaving the condenser. This refrigerant was then completely vaporized, leaving a nonvolatile liquid residue. This nonvolatile residue was then weighed to determine its weight fraction in the total working fluid, and the weight fraction of tetraglyme in the liquid residue was determined via gas chromatography. The tetraglyme fraction of the nonvolatile liquid residue was typically the same as the weight fraction of tetraglyme originally added to the lubricant. Table 5 presents the liquid residue fractions obtained for the experimental conditions discussed earlier, as well as conditions discussed in a previous paper (Ref. 1). Also included in Table 5 is the percent increase in COPc obtained for the 110°F condenser inlet water condition.

Table 5 indicates that there is a correlation between the amount of tetraglyme and lubricant circulating in the system and the percent increase in COPc. This correlation can more easily seen in Figure 1, which is a plot of percent increase in COPc versus the wt% nonvolatile liquid residue. This plot incorporates all of the data of Table 5, and indicates that there is an optimum level of tetraglyme/lubricant circulation that results in the largest COPc increase. Low oil/tetraglyme circulation rates (such as the HCFC-22/mineral oil system) result in little or no performance improvement. Conversely, systems with high oil/tetraglyme circulation rates also result in reduced system performance, possibly because of heat transfer penalties in the heat exchangers. While the data in Figure 5 is a mix of refrigerants, lubricants, compressor types, and tetraglyme concentrations, the dotted line in Figure 5 shows a possible trend of COPc increase to nonvolatile residue level.

Table 5 - Nonvolatile Liquid Residue Levels

Refrigerant/Lubricant/Compressor	Tetraglyme Added To Lubricant	Nonvolatile Liquid Residue	COPc Increase*
HFC-134a	0 wt%	0.56 wt%	n/a
POE	10 wt%	0.59 wt%	0.5 %
Hermetic Reciprocating	20 wt%	1.09 wt%	5.1 %
	30 wt%	1.38 wt%	4.0 %
HFC-134a	0 wt%	0.24 wt%	n/a
POE	10 wt%	0.78 wt%	5.8 %
Hermetic Scroll	20 wt%	1.46 wt%	8.7 %
HCFC-22	0 wt%	0.60 wt%	n/a
Mineral Oil	10 wt%	0.58 wt%	0.0 %
Hermetic Reciprocating	20 wt%	0.57 wt%	1.6 %
HFC-134a	0 wt%	1.9 wt%	n/a
PAG	10 wt%	2.6 wt%	8.2 %
Automotive Reciprocating	20 wt%	No Data	6.6 %
HFC-134a PAG	0 wt%	5.5 wt%	n/a
Automotive Sliding-Vane Rotary	10 wt%	6.7 wt%	- 3.6 %

* 50°F Evaporator Inlet Water and 110°F Condenser Inlet Water

COMPRESSOR LIFE TESTS

Compressor life tests were performed to compare compressor operation and wear metal analysis for various compressors operating with 0 wt%, 10 wt%, and 20 wt% tetraglyme in the in the lubricant. Various compressor types, with various refrigerants and lubricants, were tested. Table 6 presents a summary of these tests.

The semihermetic reciprocating compressors operating with HFC-134a/POE showed a slight reduction in iron, lead, aluminum, and tin as tetraglyme concentration increased. Little variation in wear metals was seen with tetraglyme concentration in the scroll compressors operating with HFC-134a/POE. The hermetic reciprocating compressors operating with HFC-134a/POE had slight increases in copper, iron, and zinc as tetraglyme concentration increased, but significantly lower levels of phosphorus as tetraglyme concentration increased. The reciprocating and scroll compressors operating with HCFC-22/mineral oil had no difference in wear metals as tetraglyme concentration increased, only slightly higher levels of water (since tetraglyme has a higher water content than mineral oil). The scroll compressors all had significant levels of phosphorus detected (at all tetraglyme concentrations). Two of the three rotary compressors failed, the result of refrigerant leakage from the system. All three rotary compressors had significant levels of phosphorus. The failed rotary compressors also had significant levels of iron and copper.

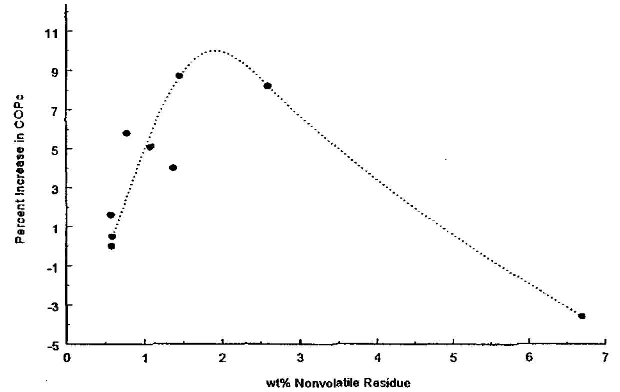

Figure 1. Percent increase in COPc versus wt% nonvolatile residue.

The automotive reciprocating compressors operating with HFC-134a and 20% tetraglyme/80% PAG lubricant suffered three successive failures, all the result of refrigerant and lubricant leakage in a metal gasket of the compressor. This metal gasket is coated with a hydrogenated nitrile butadiene rubber (HNBR) elastomer. Compatibility tests suggested that there is only a minor effect with HNBR elastomer, however, this minor incompatibility could have caused the problem. Surprisingly, the sample with 0 wt% tetraglyme had significant increases in iron and aluminum, while the 10 wt% tetraglyme had only small increases in copper and aluminum. No 20 wt% tetraglyme sample was analyzed due to the compressor leaks and loss of working fluid.

CONCLUSIONS

The use of tetraglyme was found to improve the COPc of HFC-134a/POE systems operating at air conditioning conditions. Benefits in performance were seen with both scroll and reciprocating compressors (including automotive compressors), with scroll compressors having COPc increases as high as 20%. Systems with oil separators prevent the tetraglyme from circulating to the evaporator, and prevent the additive from providing a performance benefit. There were no performance benefits seen with automotive A/C systems operating with rotary compressors. There were negligible performance benefits seen with systems that use HCFC-22 and mineral oil.

The experimental data indicate that the performance benefit from tetraglyme is due to the increase in the effective latent heat of the tetraglyme/refrigerant mixture during evaporation/condensation, which results from the heat of solution of this mixture. This results in an increase in the cooling capacity of the working fluid on a per mass basis during the evaporation/condensation process. The controlling factor in determining the amount of performance benefit is the amount of oil/tetraglyme mixture that circulates with the refrigerant. Low circulation levels result in negligible amounts of tetraglyme reaching the evaporator, resulting in negligible performance benefits (as with the HCFC-22/mineral oil systems). High circulation levels result in a reduction in heat transfer, resulting in lower system performance (as in the automotive rotary-vane compressor systems). Oil/tetraglyme circulation rates from 1-3 wt% appear to provide the most benefit. The optimum level of tetraglyme may be system and compressor dependent. No negative impact on compressor life or lubrication was seen on adding 10 wt% or 20 wt% tetraglyme to the lubricant in either HFC-134a or HCFC-22 systems.

Table 6 - Status of Compressor Life Testing			
Compressor	**Tetraglyme**	**Refrigerant**	**Hours and Status**
Semi-hermetic Recip.	0 %	HFC-134a	7109 continuous; 2423 on/off
Semi-hermetic Recip.	10 %	HFC-134a	7148 continuous; 2394 on/off
Semi-hermetic Recip.	20 %	HFC-134a	6032 continuous; 2799 on/off
Hermetic Scroll	0 %	HFC-134a	2542 (internal weld failure)
Hermetic Scroll	0 %	HFC-134a	5526 (internal weld failure)
Hermetic Scroll	10 %	HFC-134a	437 (internal weld failure)
Hermetic Scroll	10 %	HFC-134a	6003 continuous; 2840 on/off
Hermetic Scroll	20 %	HFC-134a	6003 continuous; 3000 on/off
Hermetic Reciprocating	0 %	HFC-134a	4514 continuous
Hermetic Reciprocating	10 %	HFC-134a	4095 continuous
Hermetic Reciprocating	20 %	HFC-134a	4543 continuous
Hermetic Reciprocating	0 %	HCFC-22	4541 continuous
Hermetic Reciprocating	10 %	HCFC-22	4540 continuous
Hermetic Reciprocating	20 %	HCFC-22	4536 continuous
Hermetic Scroll	0 %	HCFC-22	4806 continuous
Hermetic Scroll	10 %	HCFC-22	4808 continuous
Hermetic Scroll	20 %	HCFC-22	4808 continuous
Hermetic Rotary	0 %	HCFC-22	3142 continuous
Hermetic Rotary	10 %	HCFC-22	2874 (failure)
Hermetic Rotary	20 %	HCFC-22	2745 (failure)
Automotive Reciprocating	0 %	HFC-134a	803 (900 rpm continuous); 379 (5500 rpm on/off)
Automotive Reciprocating	10 %	HFC-134a	803 (900 rpm continuous); 379 (5500 rpm on/off)
Automotive Reciprocating	20 %	HFC-134a	803 (900 rpm continuous); 48 (5500 rpm on/off; leak)
Automotive Reciprocating	20 %	HFC-134a	19 (5500 rpm on/off; leak)
Automotive Reciprocating	20 %	HFC-134a	312 (5500 rpm on/off; leak)

Future work on this technology is continuing, focusing on the use of tetraglyme for commercial refrigeration, exploration of methods to increase the tetraglyme circulation rate in HCFC-22 air conditioning systems, and investigation of tetraglyme with HCFC-22 replacements (i.e. R-407C and R-410A).

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