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PERFORMANCE AND LEAKAGE INVESTIGATIONS OF REFRIGERATION AND AIRCONDITIONING SYSTEMS USING REFRIGERANT MIXTURES AS WORKING FLUIDS

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ABSTRACT

In spite of the advantages of zeotropic refrigerant mixtures [1], the industrial applications of mixtures have been very limited up to now. The major problem is seen in the leakages occuring in refrigeration plants and so a possible change in composition. Another disadvantage is that no simple methods for determination of the concentration inside the cycle are available.

This paper presents the results of investigations with a zeotropic mixture of a wide boiling point difference in order to evaluate the mentioned problems with significant effects by:

- leakage experiments and computer-simulations to determine the change in composition by leakages,
- simple determination of mixture concentration in the cycle.

In comparison to this mixtures with a wide boiling temperature difference as a worst case a similar investigation was made with a mixture with smaller boiling point difference as a real case for the substitution of R502 in supermarket systems by a newly developed ternary mixture.

INTRODUCTION

The use of many common refrigerants, such as R11, R12, R22 or R502 will come under restriction because of their high Ozone Depletion Potential **ODP** or Global Warming Potential **GWP**. Thus, there is a need for new working fluids in refrigeration cycles. The number of pure environmentally benign fluids which are available as alternatives is limited. Mixtures of those pure refrigerants expand the list of environmentally acceptable substitutes. Zeotrope refrigerant mixtures have been investigated extensively during the last ten years [7], [8]. They offer energetic advantages in some applications, e.g. in heat pumps, and allow the development of new cycle concepts.The application of mixtures, especially zeotropic ones, might produce some problems which are not known from pure fluids or azeotropes. Changes in the cycle equipment might be necessary. For example common thermostatic expansion devices may eventually not be usable for zeotropes and must be replaced by electrical or electronic devices. Moreover, a leak in the cycle might lead to a change of the composition of the mixture and, therefore, to a change of the performance. In addition, the refilling procedures become more complicated, too. However, mixtures are seen as the only alternatives to the refrigerant R502 in single stage low temperature applications and finally for R22 substitution in this temperature range.

Investigations with zeotropic mixtures were carried out at the Institute of Refrigeration, Hannover University. The objective of this project was first to investigate leakages of mixtures with a wide boiling point difference, investigations for measuring the concentration inside the cycle and expansion devices for zeotropic mixtures. Due to the wide boiling point difference and the availability of non chlorine containing fluids at the time of the beginning of the project the mixture R23/R152a was chosen for this investigations.

If a "drop-in" substitute for existing equipment is demanded, near-azeotropic mixtures with only a small temperature glide during the phase change might even be the only acceptable alternative to replace existing single component refrigerants. The azeotrope refrigerant mixture R502 has been phased out in Germany already for new supermarket applications. Some manufacturers changed the equipment to use the refrigerant R22, but for low temperature applications two stage compression or liquid injection into the suction side of the compressor is needed, and this refrigerant will also be phased out in Germany within the next 8 years. Therefore, a conversion of existing systems from R502 to R22 does not seem to be economical. Because of the big amount of systems which will run until the year 2000, a drop-in refrigerant with properties similar to those of R502 is needed.

Investigations with a near azeotropic mixture were performed at the Institute of Refrigeration with a supermarket cabinet in order to compare the refrigeration capacity with R502, the discharge temperature, the oil behaviour and the change in composition during leakages and after refilling.

SPECIAL PROBLEMS WITH ZEOTROPIC MIXTURES

Leakages

A major problem arises due to the leakages occuring in refrigeration plants. Leakages may change the composition of the mixture and so affect the capacity and COP of the plant. Especially at the places where two phase flow occurs, e.g. in the evaporator and condenser or directly behind the expansion valve, a leak can change the circulating composition more compared to one phase flow.

Högberg et al. [2] has theoretically investigated leakages with the mixtures R22/R142b and R22/R114. The change in composition increases with increasing boiling point temperature difference. Blaise et al. [3] and Kruse and Hesse [4] have measured leakages in real refrigeration plants. Blaise observed leakages in a refrigeration plant with a total mass of 1000 kg R12/R114. Kruse and Hesse investigated leakages in a small automotive air conditioner system with the mixture R22/R114. The leakages were created behind the expansion valve (two phase flow), behind the evaporator (single phase vapor) and the condenser (single phase fluid). The experiments were stopped when approximately 50% of the charged mass was leaked out. As a result, Blaise has measured only small changes in the composition. Kruse and Hesse measured a change in concentration by 8% during a leakage test behind the expansion valve. The concentration of R22 has increased and that means the liquid R114 must have leaked.

Leakage Experiments With R23/R152a

The leakage experiments with the mixture R23/R152a were carried out at an automotive air-conditioning system located in an environmental chamber. The principle of the system and the locations of the leaks are shown in Figure 1. The leakages were realized using needle valves and the flow was controlled by a flow meter and the leaked gas was analysed by a gaschromatograph. Furthermore gas samples were taken out of the system during the leakage experiment and the circulating composition was measured with a gaschromatograph. The experiments were stopped when about 50% of the refrigerant had leaked out. The investigations showed that in case of leakages at places where the refrigerant is in a one phase state, a leak did not change the composition remarkably.

For the visualization of the flow in the two phase region a glas tube was built into the horizontal line between the expansion valve and the evaporator. Figure 1 shows the refrigerant flow and the application of the needle valves for the leakage experiments. The mass fraction of the mixture changed from 20% to about 26% only by the different solubility of the refrigerants in the oil, measured before opening the valves.

Liquid leakage behind the expansion valve

The result of a leakage experiment using the valve at the bottom of the tube (see Figure 1) where mainly liquid refrigerant leaked out is shown in Figure 2. The experiments were performed over a period of 300 minutes with a total refrigerant loss of 34.3%. For liquid leakages from the two phase region, the concentration of the circulating refrigerant increases.

Vapour leakage behind the expansion valve

Figure 3 shows a result of a leak test using the needle valve at the top of the horizontal tube (see Figure 1). The result shows that the concentration by vapour leaks from the two phase region decreases. The leakage experiments can be summarized as follows.

- leakages from one phase region (vapour or liquid) did not remarkably influence the concentration of the system,
- leakages from the two phase region can increase or decrease the concentration by leaking liquid or vapour depending on the location of the leak,
- small leakages did not influence the concentration until bubbles in the sight glass in front of the expansion valve can be seen.

Leakage Computer Simulation

For the calculation of the shift in composition caused by leakages a computer model was written. The results are shown in Figure 4 and in Figure 5. Using a versatile computer program to calculate the properties of the refrigerants by the Lee-Kessler-Plöcker method, the leakage model can be used for new ozone friendly zeotrope refrigerant mixtures.

CONCENTRATION MEASUREMENT

Another problem related to the leakages is the refilling procedure of the refrigeration system working with zeotropic mixtures. In practice it is important to have simple methods to measure the concentration of the remaining refrigerant mixture in the plant. The following methods were investigated:

The first method to determine the concentration is by measuring the pressure and temperature in front of and behind the expansion valve when the plant is operating. Assuming an isenthalpic throttling, the concentration can be calculated by an equation of state for the thermodynamic properties e.g. by the Lee-Kessler-Plöcker equation. Figure 6 shows the result of this method during a leakage experiment. There is a good correspondence between the calculation and the measurement by gaschromatography.

In the second and the third method, a sample of the refrigerant mixture is taken into a special measuring vessel behind the condenser during operation of the system. The concentration can be calculated by measuring the pressure, the temperature, the mass of the sample or the liquid and the vapor volume. With the known total volume of the vessel and the known liquid and vapor density of the mixture, the concentration can be calculated iterively. Figure 7 shows the result of this method. The increasing error with the increasing mass fraction is caused by the Lee-Kessler-Plöcker equation of state, because the interaction parameter of the mixture is only an estimation as no measured values are available.

REFRIGERANT MIXTURES FOR SUPERMARKET APPLICATIONS

SUVA HP81, a trademark of DuPont, is a nearly azeotropic refrigerant mixture of HFC-125 (38% by mass), HC-290 (2% by mass) and HCFC-22 (60% by mass) [5].

The task of this project was to compare a supermarket application with R-502 and HP81 under test conditions according to the German standard DIN 8954 [6]. Especially the performance and the system behavior are of main interest as well as also the change of composition by a leakage in the system.

Experimental Setup

The experiments were performed at the Hannover University, Institute of Refrigeration, in an environmental chamber which enables the performance of the tests according to DIN 8954. The chamber guarantees that the air temperature, the humidity, the velocity of the air and the vertical gradient of the temperature are within the required limits according to DIN 8954.

During the tests a constant temperature of 25°C and a constant relative humidity of 60% in the environmental chamber was controlled by an electronic control system. For the tests a frozen food cabinet produced by a German manufacturer was used. The cabinet operates on the principle of a cold air stream through vertical ducts and through the fins of the evaporator continuously circulating as a layer above the storage room with the test packages.

The cabinet temperature is regulated by a control unit according to the temperature of the air in the vertical air duct which has passed the evaporator. The control unit switches the compressor off and closes a solenoid valve in the liquid line in front of the expansion valve if this air temperature inside the cabinet remains under an adjustable value.

For defrosting the evaporator the compressor is switched off every twelve hours. For this purpose the solenoid valve in the liquid line is closed and the electrical heaters which are located in the evaporator are switched on. The defrosting is stopped when the temperature sensor exceeds an adjustable value or the defrosting period exceeds 45 minutes.

The storage room was filled up to the loading limit with packages according to DIN 8951. The packing and the arrangement of the packages for temperature measurement was done according to that standard.

The compressor/condenser unit consists of an hermetic Copeland compressor Type D2DL 400 and a water-cooled condenser. The complete refrigerating plant is shown in the schematic diagram Figure 8. To adjust the compressor inlet temperature to a constant temperature of 25°C during operation, the refrigerant was superheated to this temperature by an additional water heated heat exchanger in the suction line. The temperature was controlled by an electronically regulated heater. Behind the compressor the refrigerant is liquefied and subcooled in a water cooled tube bundel heat exchanger. The water inlet temperature and the mass flow was controlled by a thermostatic regulation valve and a control valve. The liquefied refrigerant was fed to the freezing cabinet and after passing an internal heat exchanger the liquid was expanded by the thermostatic expansion valve to the evaporating pressure. The evaporator inside the cabinet is a fin tube type heat exchanger. The refrigerant inlet at the evaporator is split up into three parallel passes leading through the evaporator wherein the refrigerant evaporates.

The measurements were done using a Hewlett Packard Data Acquisition System with a microcomputer (HP 310) and a Data Acquisition (HP 3852A).

The temperature measurements at the plant were done with thermocouples of the Ni-CrNi type. The thermocouples for measuring the circuit temperatures were placed inside the refrigerant line for most accurate temperature measurement. Before installation, the thermocouples were calibrated in a thermostat bath. The temperature inside this bath was measured with precision thermometers (1/100 K scale) between -45°C and +150°C.

For the pressure measurements absolute pressure transducers of types Transamerica Instruments BHL-3040-00-01M, 0..10 bar gage for low pressures and BHL-3040-00-01M5, 0..25 bar for the high pressures on the discharge side were used.

The measurement of the electrical power consumption of the compressor was carried out by a real power transducer with a current output 0...20 mA. Furthermore, the energy consumption of the cabinet and the compressor was measured separately by an electric meter.

The mass flow rate of the cooling water through the condenser was measured several times a day. A continuous measurement was not installed because of a high equality of the mass flow caused by the pump. For a measurement, the mass flow was diverted into a bucket for a definite period. Afterwards, the mass in the bucket was weighed and the mass flow could be determined and stored in the computer.

For the HP81 test an analysis of the refrigerant mixture was carried out with a Shimadzu GC9A gaschromatograph and a Shimadzu GC-R3A integrator. This gaschromatogaph has a thermal conductivity detector. The refrigerant was injected into the GC using a 1ml precision syringe. Measurements using the same gas sample gave a maximum deviation about ±0.5% by mass in normal operation. With minimized impurities of air in the syringe, the measurements were in the range of ±0.2% accuracy. A comparison of the samples for calibration with a sample of HP81 from the liquid line of the full cylinder proved a very high conformity. The samples were taken out of the cycle at the suction side of the compressor, using an evacuated glass vessel with a filter in order to prevent the inlet of oil into the gaschromatograph.

TEST RESULTS

The temperature test packages during the HP81 test were about 0.5 K lower compared to R-502 by the same adjustment of the thermostat (see Figure 9 and Figure 10). The air temperatures of HP81 are slightly lower compared to R-502 showing so at least the same performance of the mixture.

The cycle discharge pressures of HP81 are higher compared to R-502, the evaporating pressure is nearly equal. During the leakage experiments, the discharge pressure is lower compared to normal operation and the evaporating pressure is equal.

The temperature at the discharge valve (t_{VD}) is about 8K higher compared to the temperature measured outside the compressor (t_{V2}). At normal operation, the temperature at the discharge valve with R-502 is about 126°C and 138°C with HP81. During permanent operation, the temperature with R-502 is 135°C and with HP81 151°C. During the leakage experiment, the temperatures at the discharge valve were slightly lower compared to normal operation.

After running the tests with R-502 and HP81, the analysis of the measured data has shown that HP81 has a slightly better energy consumption compared to R-502. In order to prove this fact, a test with R-502 was performed again. The results showed that in the second test with R-502 the same energy consumption was measured, but the temperature of the test packages was slightly higher.

LEAKAGE TEST WITH HP81

Leakages in refrigeration cycles using near azeoptropic or zeotropic refrigerant mixtures can lead to a shift in the composition of the mixture if the refrigerant is in a two phase region, e.g. during heat exchange or behind the expansion valve.

The task of this part of the program was to investigate the change of the composition if a leakage behind the expansion valve has occured. The tubes were mounted in such a way, that the leaking refrigerant is mostly of the gascous phase to have most critical composition shifts. The mass flow out of the system was controlled by a needle valve and measured with a bubble counter in order to determine the mass of the leaked refrigerant.

In order to simulate small leakages, one leakage experiment was done over a period of 5 days. After this test, 50% of the mass was leaked out. The system behavior did not change remarkably untilthe first bubbles were seen in the sight glass before the expansion valve, and after that also only minimal in contrary to the mixture with the wide boiling point. The following composition was measured at the end of the leakage test:

R22	R125	R290
63,7%	34,7%	1.6%

The refrigerant was taken out of the plant after the leakage test to weigh the mass and afterwards refilled into the cycle. New refrigerant from the cylinder was added and then the concentration of the mixture was measured again by gaschromatography:

R22	R125	R290
60,3%	37,7%	1,9%

As a result of this leakage test it can be stated that the very small change in concentration even after a leakage of 50% of mass did not have any influence on the system behavior.

CONCLUSIONS

The influence of leakages on the circulating composition using a mixture with a wide boiling point difference, e.g. R23/R152a, is very small, if only very small bubbles occured in the sight glass in front of the expansion device. The change in composition by bigger leakages depends on the boiling points of the refrigerant as well as on the location of the leak, and an increase or decrease of the concentration by leaking liquid or vapour is possible depending on the location of the leak.

The determination of the concentration is also possible with simple methods and a good correspondence between the calculations and the measurements was shown.

In a summary, the results of the comparison of R-502 and HP81 with a frozen food supermarket cabinet under test conditions accordiing to DIN 8954 are as follows:

- The temperatures of the test packages with HP81 are slightly lower compared to R-502.
- The energy consumption of HP81 was slightly better in the first test with R-502 and equal at the second test.
- The discharge temperature of HP81 was about 15 K higher compared to R502.

- The leakage experiments showed at the beginning nearly no and later only a small shift of the composition even after 50% of the mass had leaked out. After refilling only a very small change in compostion was measured.

- The investigations to determine the mass and the concentration of refrigerant inside the compressor showed that the mass fraction of refrigerant solved in the oil is only 1% and the different solubility of the components did not have an influence on the circulating compostion.

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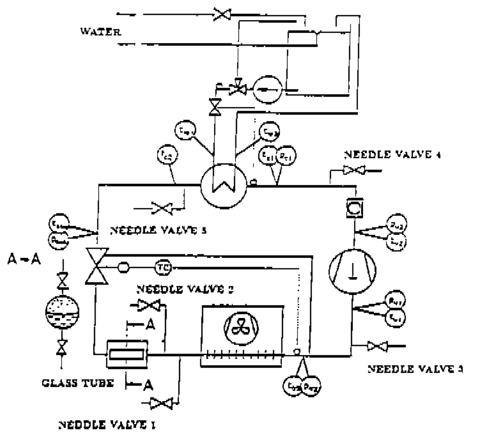

Figure 1: SCHEMATIC DIAGRAM OF THE AUTOMOTIVE AIRCONDITIONING CYCLE

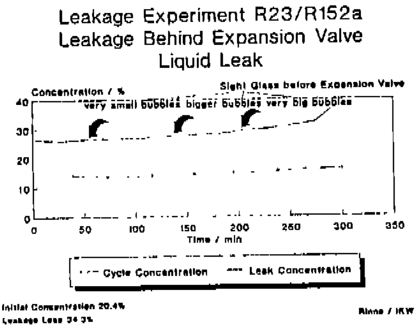

Figure 2:

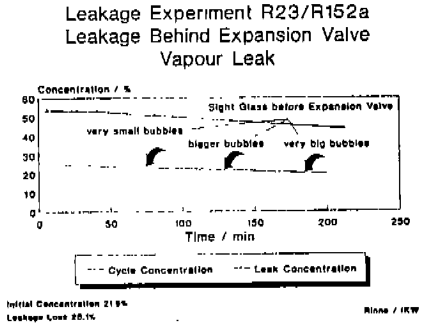

Figure 3:

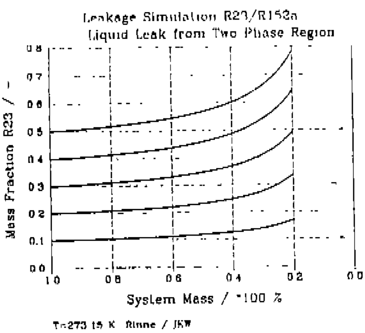

Figure 4:

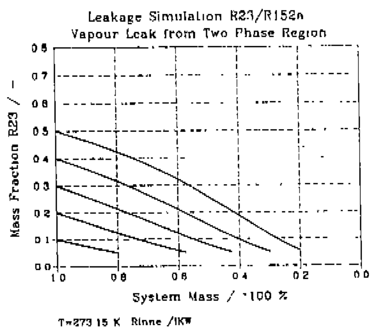

Figure 5:

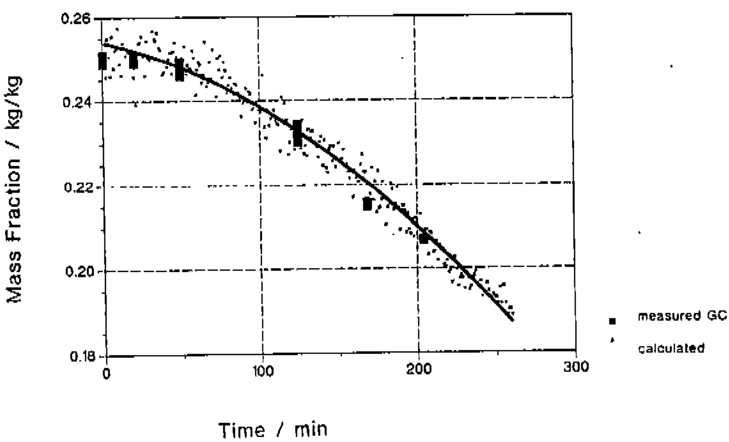

Figure 6: CONCENTRATION MEASUREMENT DURING LEAKAGE EXPERIMENT

Concentration Measurement R23/R152a
Test Samples in Vessel
p,T,m Measuring, Conc. Calc. w. LKP

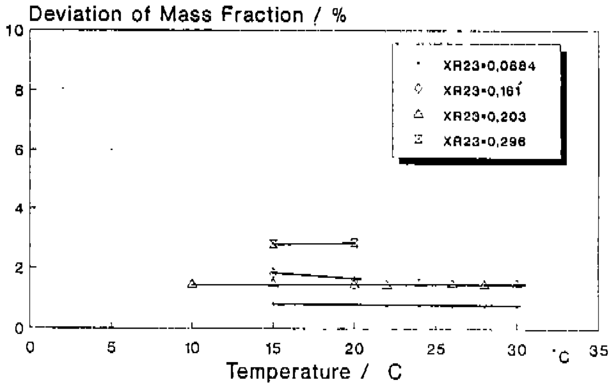

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Figure 7:

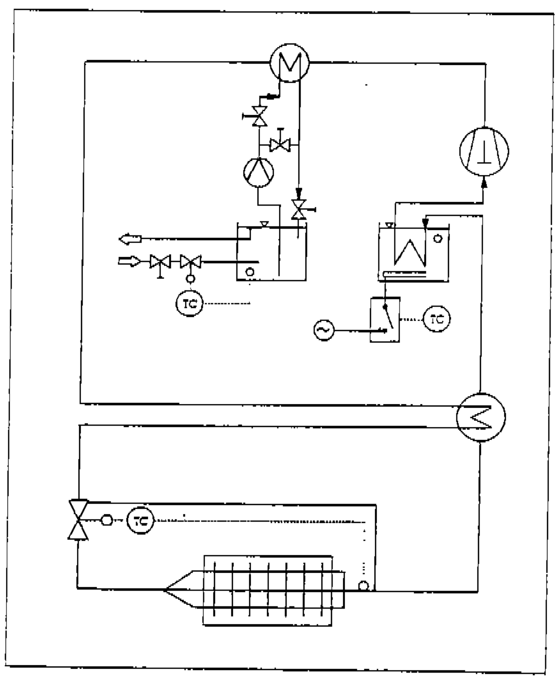

Figure 8:

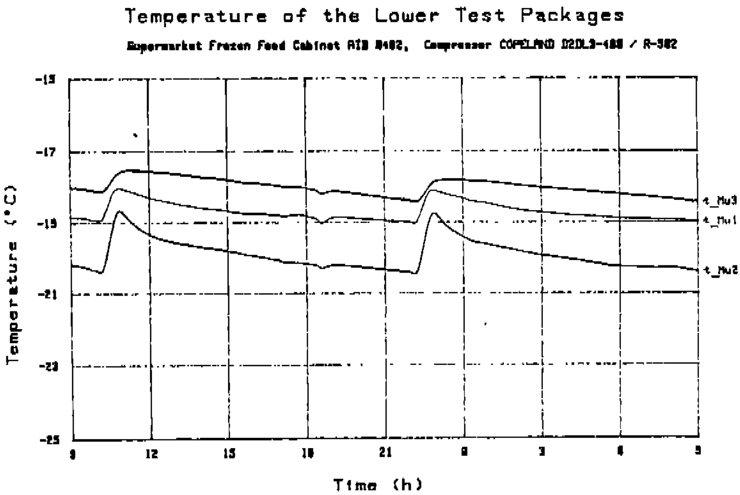

Figure 9:

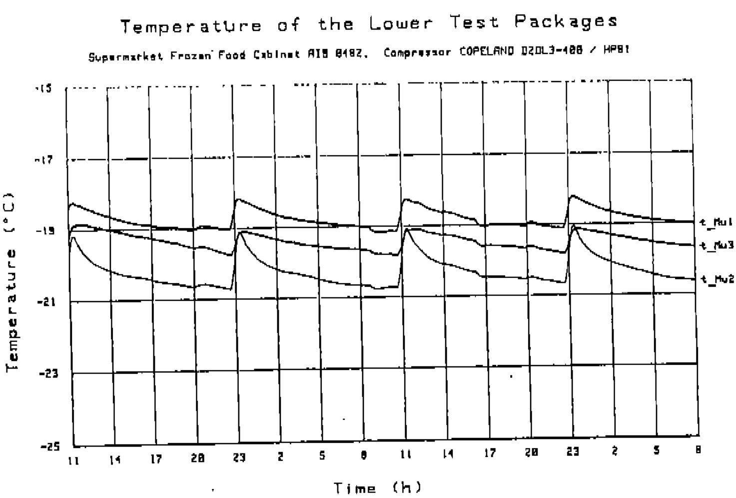

Figure 10: