Experimental Characterization of Small Reciprocated Compressor Working With Azeotropic Blends of Alternative and Natural Refrigerants

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EXPERIMENTAL CHARACTERIZATION OF SMALL RECIPROCATED COMPRESSOR WORKING WITH AZEOTROPIC BLENDS OF ALTERNATIVE AND NATURAL REFRIGERANTS

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ABSTRACT

Different working fluids (R134a – R600a, R152a – R600a) based on the alternative/natural refrigerant azeotropic blends (so-called the "*breeding*" mixtures) are considered to provide a trade off decision among contradictory requirements: oil-refrigerant compatibility, component fractionation, flammability, energy consumption and global warming potential. To confirm theoretical prognosis the hermetic reciprocated compressor, labeled GL60AA, from "Zanussi", with a nominal refrigerating capacity of about 0.1kW is tested using both pure substances (R134a, R152a, R600a) and their azeotropic mixtures by means of specially designed characterization test rig according to ISO 917 standard. Synthetic and mineral oils have been used to study an influence of mixture composition and oil type on the energy efficiency of compressor. It was found out that a "breeding" of R134a or R152a by the natural refrigerant addition leads to an increasing in COP and refrigerating capacity. The best compressor characteristics are observed at azeotropic compositions. The comparative analysis of compressor characteristics concerning interaction of azeotropic mixtures with mineral and synthetic oils is presented.

1. INTRODUCTION

The last two decades the attention of the scientific community has been mainly attracted to the alternative refrigerants that have been designed in order to replace the wide spread synthetic refrigerants containing chlorine that causes the ozone depletion in the atmosphere. Newly developed chlorine-free refrigerants have disadvantages in the sense of their Global Warming Potential (GWP), and because of that, the interest is growing in new applications of the well-known natural fluids in refrigeration and air-conditioning systems. There are many refrigerant options potentially available as replacement for CFCs and HCFCs, but each of these options has problems of their own.

There are following opportunities to offer mixtures compatible with nature in advanced refrigeration technologies:

- to turn back to the classic natural refrigerants like ammonia, water, carbon dioxide, propane, isobutane and reproduce all disadvantages for old refrigerants but to have no ozone depletion potential (ODP) and negligible GWP, as a final result;
- to reduce hazards from use of a new family of alternative refrigerants - halocarbons HFCs (R32, R134a, R125, etc) that have non-zero greenhouse effect and unknown damage potentials for environment in future via the azeotropic mixtures with natural components - *naturalization of alternative refrigerants* , as a transition result.

The objective of this paper is to test different working fluids (R134a – R600a, R152a – R600a) based on the alternative/natural refrigerant azeotropic blends (so-called the "*breeding*" mixtures) which provide a compromise among contradictory requirements such as refrigerant-lubricant oil compatibility, component fractionation, flammability, energy consumption and global warming potential.

This paper is organized as follows. In Section 2 the refrigeration cycle calculations (coefficient of performance, cooling capacity, pressure ratio and other indexes) for binary mixtures are presented. Theoretical models of thermodynamic and phase behavior on the base of the Redlich-Kwong-Soave (Redlich, Kwong, 1949; Soave, 1972) equation of state are used to provide a performance characteristics estimation. Experimental phase equilibria data for the binary mixtures of natural and alternative refrigerants (R134a, R152a) + R600a for the temperature range 220...300K at the azeotropic compositions are given. In section 3 we perform experimental characterization of small reciprocated compressor working with azeotropic blends of alternative and natural refrigerants to check theoretical predictions. Synthetic and mineral oils were used to study an influence of mixture composition and oil type on energy efficiency of compressor. It was found out that a "breeding" of R134a or R152a by the natural refrigerant R600a leads to an increasing in COP and refrigerating capacity.

2. THEORETICAL AND EXPERIMENTAL BACKGROUND

Here we consider the operation of refrigeration system, which is simulated by the reverse Rankine cycle. The main processes in the single-stage vapor compression cycle include isentropic compression, isobaric cooling + condensation + subcooling, throttling, and isobaric cooling + evaporation + superheating. The following design specifications are chosen: evaporator and condenser temperatures, net refrigerating effect - $\boldsymbol{q}_0^0$ and condenser/ evaporator pressure ratio - $\boldsymbol{P}_r < 10$. Thermodynamic properties of working fluids and appropriate design specifications are simulated by the one-fluid Redlich-Kwong-Soave (RKS) model of EoS**.** The RKS EoS is used in the form:

$$P = RT/(V-b) - a/(T^{0.5}V(V+b)), \tag{1}$$

where the EoS parameters a and b of mixture depend on the mole fractions x_i and x_j of the components i and j and on the corresponding parameters a_{ij} and b_{ij} for different pairs of interacting molecules:

$$\begin{gathered} a = \sum_{i=1}^{2}\sum_{j=1}^{2} x_i x_j a_{ij} = \sum_{i=1}^{2}\sum_{j=1}^{2} x_i x_j (1-K_{ij})\sqrt{a_{ii}a_{jj}}\,, \\ b = \sum_{i=1}^{2}\sum_{j=1}^{2} x_i x_j b_{ij}\,. \end{gathered} \tag{2}$$

The performance characteristics and cycle nodal points are calculated from known engineering thermodynamics relations. Environmental aspects are considered via combination of direct and indirect global warming contributions - Total Equivalent Warming Impact (TEWI) criterion. The complete set of design specifications includes specific refrigerating effect, volumetric capacity, specific adiabatic work, condenser/evaporator pressure ratio, coefficient of performance, adiabatic power, TEWI criterion and flammable concentration.

To identify binary interaction parameters K_{12} in the RKS model and to find azeotropic concentrations the measurements of the vapour-liquid equilibria were carried out by the standard static method for a wide range of temperatures (from 80 to 330K) and pressures up to 4 MPa. The experimental apparatus is composed of a thermostat (temperature measurement accuracy is ± 0.02 K) and scheme for composition measurements (with an accuracy of ± 0.2 wt %). The vapour-liquid equilibrium cell is an ampoule with inner volume about 5 cm^3. A quartz crystal pressure transducer is connected to the sample solution that enables direct pressure measurements. The uncertainty in pressure measurements is estimated ± 0.2 kPa. The temperature of the sample solution is measured by an 84.8Ω sheathed platinum resistance thermometer. The uncertainty in temperature measurements is estimated to be ± 0.02 K including calibrated result for the sheathed platinum resistance thermometer. The purities of samples were 99.98 wt % for main pure components investigated here. Compositions of the fluid phase for the mixtures were determined by gas chromatograph calibrated with the pure components of known purity. The pressure was measured by a set of reliable pressure gauges after thermodynamic equilibrium between the liquid and vapor phases had been established. The dependence of the total pressure of the binary mixtures on liquid phase composition has been studied in the temperature range 203 –313 K. The results are presented in Tabl. 1. Values of K_{12} obtained from experimental data can be estimated as 0.1691 and 0.1664 for R152/R600a and R134a/R600a, correspondingly.

Table 1: Azeotropic and critical concentrations, critical and normal boiling points of refrigerant mixtures

Mixtures	Critical solubility temperature, K	Azeotropic concentration, mole/mole	Critical concentration, mole/mole	Boiling point,K (P_b = 0.1013MPa)
R134a/R600a (RC)	218.6	0.70/0.30	52/48	239.80
R152a/R600a (RD)	188.8	0.70/0.30	48/52	243.85

The ignition risk is based on formation of a flammable concentration resulting from release of refrigerant. Since any release of flammable material will always produce a flammable concentration during the transition from 100% refrigerant to 100% air, such concentration boundaries were evaluated (Khmel'njuk, 2003). Experimentally based results for flammable concentration region are presented in Fig.1.

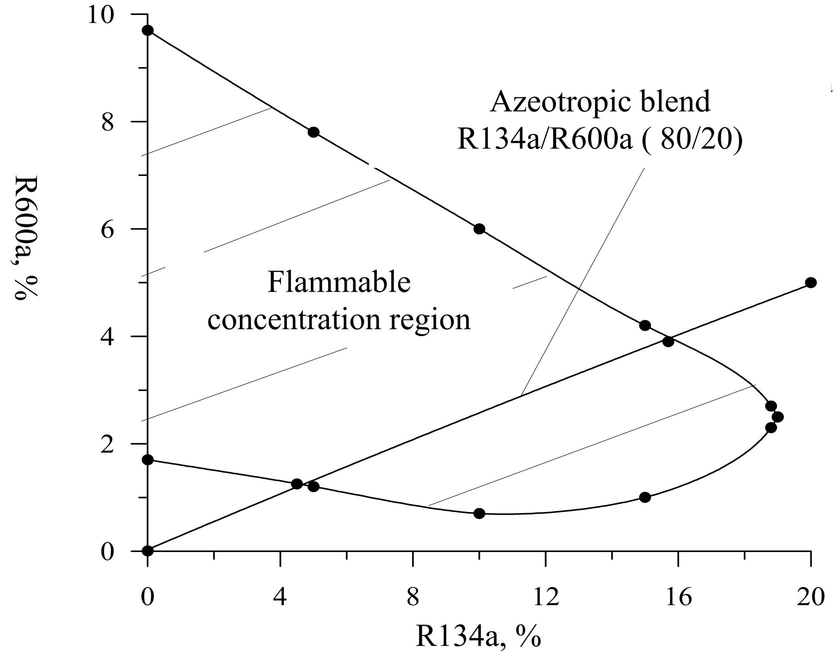

Fig. 1. Flammability concentration limits of air-isobutane mixture for different contents of R134a

Multi-criteria analysis algorithm was applied to compare two blends under consideration (Mazur et al., 1994) by the following way.

- Thermodynamic properties and design characteristics of vapor compression cycle are calculated for specified external conditions.
- The best value of design characteristics K_i^0 is chosen for each refrigerant. The set of "ideal" indexes K_i^0 is presented by the vector criterion ***K*** which is calculated via thermodynamic properties.
- Discrepancy between "ideal" and real design indexes is defined by

$$D_i = 1 - K_i / K_i^0 \tag{3}$$

- The generalized criterion is written as

$$\boldsymbol{D} = \sum_{i=1}^{N} |D_i| \tag{4}$$

- Minimum value of ***D***-criterion corresponds to the best refrigerant among concurrent working fluids.

Results of comparison have demonstrated thermodynamic advantages of refrigerant blend R134a/R600a.

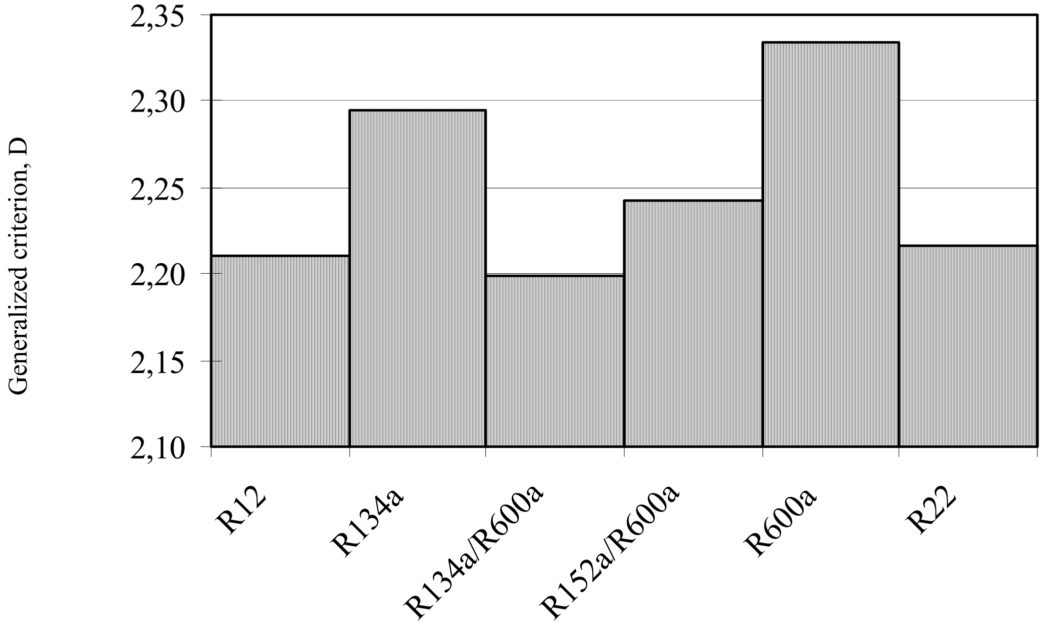

Figure 2. The comparative analysis of refrigerants

3. EXPERIMENTAL CHARACTERIZATION OF SMALL RECIPROCATED COMPRESSORS. RESULTS AND DISCUSSION

To confirm theoretical prognosis the hermetic reciprocated compressor, labeled GL60AA, from "Zanussi", with a nominal refrigerating capacity of about 0.1kW has been characterized using three pure substances (R134a, R152a, and R600a) and their azeotropic mixtures by means of specially designed characterization test rig according to ISO 917 standard.

Synthetic and mineral oils were used to study influence of mixture composition and oil type on energy efficiency of compressor. Simulation of the refrigerant-lubricant phase behaviour is of importance for most of compression refrigeration systems that require a good miscibility of the refrigerant-lubricant combination. Lubricants being under consideration for refrigeration fluids include mineral oils, alkylbenzene, polyalkyleneglycol (PAG) or polyolester (POE). Most of them, especially properties of mineral oils are difficult to simulate and there is a lack of proper information on their phase behaviour. For example, R134a tends to liquid-liquid immiscibility with non-polar hydrocarbons and polyhydrocarbons due to polarity. On the contrary, there are some polar polyethers fully miscible in the temperature range of interest. This tendency corresponds to the shifts in global phase diagrams due to unlike pair interactions parameters increasing.

Changing the polymer structure one can observe transitions between different types of phase behaviour including types III, IV or V in classification of Scott, van Konynenburg (1980). Type III behaviour is considered as the most unfavorable for refrigeration applications. Presence of lubricants leads to saturation curve shift, which can be interpreted as an increase of pseudocritical temperature for the one of components. This reflects in reshapes of the boundaries of azeotropic behaviour region, which can be destroyed in presence of lubricants.

It was found that a "breeding" of R134a or R152a by the natural refrigerant addition leads to growth of COP and refrigerating capacity. The best compressor characteristics were observed at azeotropic compositions. The comparative analysis of compressor characteristics concerning interaction of azeotropic mixtures with mineral (HF12-18M) and synthetic oils (synthetic ester refrigeration lubricants SW 22 - Castrol Icematic SW) was carried out.

Variations of isobutane (R600a) concentration in mixture were performed in two different conditions. Increase of R600a concentration in mixtures containing mineral oil improves the solubility of mixture (problem of refrigerant replacement after repair works of compressor or aggregate). If the synthetic oil is used as a component in mixture, then increase of R134a concentration will reduce ignition risk. Recent investigations demonstrate a decrease of COP and refrigerating capacity in case of R600a inclusion to a R134a. Best characteristic of compressor were obtained at azeotropic concentration of RC.

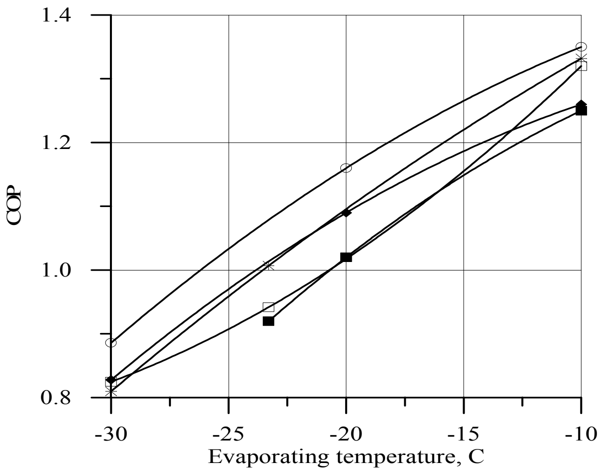

Figure 3. Coefficient of performance versus evaporating temperature for GL60AA compressor
Tsuc = 32°C, *Tcon* = 55°C
Mineral oil: ○-R152a/R600a (75/25), ✷ - R152a/R600a (60/40), ■ - R152a/R600a (50/50);
Synthetic oil: ◆ - R152a/R600a(75/25), □ - R134a.

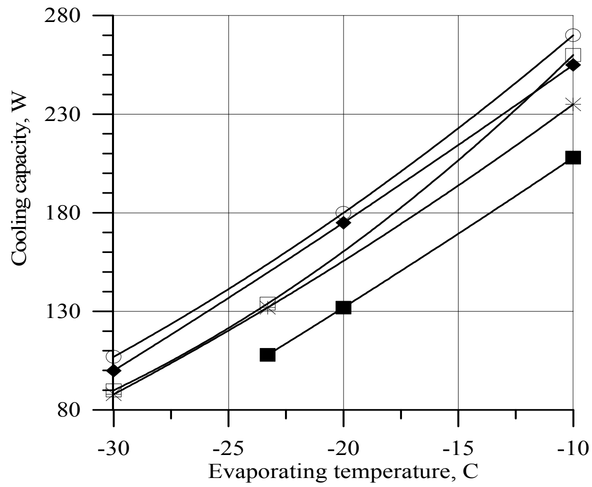

Figure 4. Cooling capacity versus evaporating temperature for GL60AA compressor
Tsuc = 32°C, *Tcon* = 55°C
Mineral oil: ○-R152a/R600a (75/25), ✷ - R152a/R600a (60/40), ■ - R152a/R600a (50/50);
Synthetic oil: ◆ - R152a/R600a(75/25), □ - R134a.

There is a negligible growth of refrigerating capacity for compressor using mineral oil in comparison with synthetic oil by increasing boiling temperature. Refrigerating capacity of compressor working with mixture R134a-R600a was approximately 15% higher in comparison with mixture R152a-R600a and pure refrigerants R12 and R134a. It is confirmed that the azeotropic blends are more preferable in hermetic compressors with mineral oils. However, power consumption of compressor using synthetic oil was 3..5 W higher (in comparison with mineral oil) throughout the boiling temperatures range. Growth of consumed power evidently depends on higher values of viscosity of refrigerant and synthetic oil mixture. Increasing refrigerating capacity by usage of mineral oil can be explained with a small solubility in RC and RD mixtures and consequently lesser influence to the thermodynamical properties of refrigerant-synthetic oil mixture. Similar dependencies are observed by R152a / R600a mixture with different concentration of R600a (Fig.3 - 4). It can be concluded, that applications of R134a/R600a and R152a/R600a mixtures are more preferable in systems equipped with hermetic compressor filled with mineral oil. Best characteristics had been shown at azeotropic concentrations of RC and RD mixtures (Fig. 5 and 6).

It can be stated, that compressor operating with RC mixture has a 15% more refrigerating capacity if RD-mixture would be used or R12 and R134a, which have similar values of refrigerating capacity. However, compressor COP driven with RD has a maximum values 2…6% more than compressor operating with RC, in particular in boiling temperature range of -20 …-10 ºC. Investigation proves the perspective of RC and RD mixtures application as an alternative to R12.

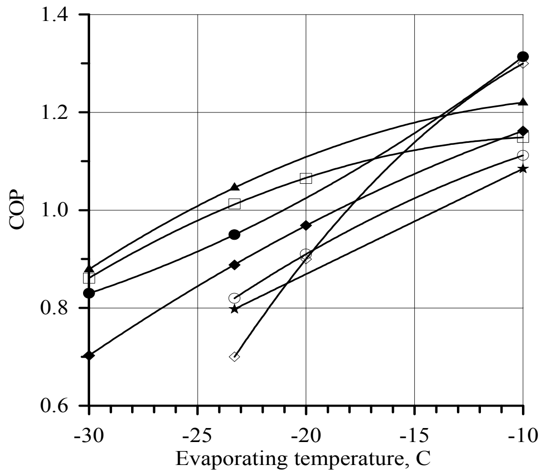

Figure 5. Cooling capacity versus evaporating temperature for GL60AA compressor
Tsuc = 32°C, *Tcon* = 55°C
Mineral oil: ▲ -R134a/R600a (80/20), ◆ - R134a/R600a (70/30), **O** - R134a/R600a (60/40), ★ - R134a/R600a (50/50), ◇ - R600a;
Synthetic oil: □ - R134a/R600a (80/20), ● - R134a

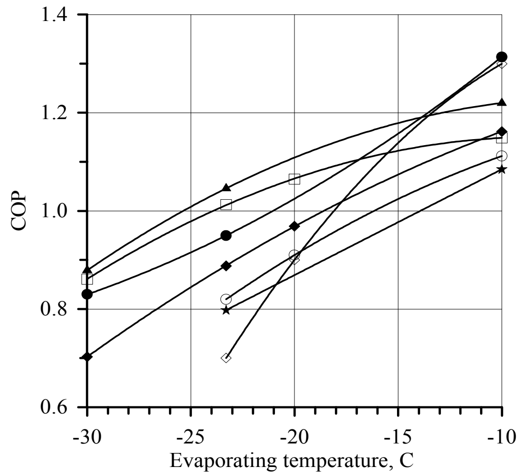

Figure 6. Coefficient of performance versus evaporating temperature for GL60AA compressor
Tsuc = 32°C, *Tcon* = 55°C
Mineral oil: ▲ -R134a/R600a (80/20), ◆ - R134a/R600a (70/30), **O** - R134a/R600a (60/40), ★ - R134a/R600a (50/50), ◇ - R600a;
Synthetic oil: □ - R134a/R600a (80/20), ● - R134a

4. CONCLUSIONS

The R134a / R600a (80/20) blend shows nearly the same results with propane-isobutane mixtures, but the blend is more acceptable for technical exploitation, due to improvement of refrigeration rates for refrigerating machines operating with R134a. This leads to a possibility of natural refrigerants addition to the wide used synthetic refrigerants (breeding) and to positive effect in the system properties.

NOMENCLATURE

P	Pressure	T_{suc}	Suction temperature
R	Gas constant	a,b	Equation of state constants
x	Composition	K_i^0	"Ideal" performance characteristics
TEWI	Total Equivalent Warming Impact		
T	Temperature		**Subscripts**
k_{ij}	Binary interaction parameter	i,j	Components i,j
T_{con}	Condensation temperature		

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