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Evaluation of N-Butane as a Potential Refrigerant for Household Compressors

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ABSTRACT

In recent years the household compressor manufacturers have reduced the energy losses inside the compressors resulting in a positive effect on the energy consumption in the cabinets. In the following, N-butane, which is a natural and non ozone depletion refrigerant, is compared to refrigerants presently used in household compressors.

1. INTRODUCTION

As described by the National Oceanic and Atmosphere Administration (Fahey, 2004) a change in global climate is expected due to the greenhouse effect resulting in an increase of the temperature and of the sea level. One initiative in reducing the green house effect is to develop household compressors and refrigerants with lower energy consumption. The ozone depletion neutral refrigerant N-butane (R600), which is not widely used, could be a potential refrigerant for household appliances. N-butane has a slightly higher Rankine COP level compared to isobutane and a much higher COP than R134a of which the latter is still used in household appliances around the world.

In order to evaluate both the strengths and the disadvantages using N-butane in Low Back Pressure (LBP) applications the following aspects will be treated: 1) Theoretical comparison of relevant refrigerants, 2) a comparison of N-butane calorimeter measurements with isobutane and 3) an evaluation of reliability results.

Additionally the intention of this the article is to provide some inspiration on how theoretical and practical comparisons of refrigerants can be made.

2. Comparison of N-butane with other refrigerants

2.1 Background for comparison of refrigerants

In the evaluation of N-butane some key loss factors have been selected and compared for a range of the most widely used refrigerants in household appliances (isobutane and R134a). In addition two refrigerants which are used for light commercial applications (propane and R404A) are compared. If one wants to introduce a new refrigerant in cabinets a cooling capacity of a specific level is needed and therefore the refrigerants have to be compared at the same capacity.

In the case where the stroke volume and speed are constant the relative capacity to isobutane $\varepsilon_{isobutane}$ can be calculated by:

$$\varepsilon_{\text{Isobutane}} = \frac{(\rho_{suction} \cdot \Delta h_{evaporating})_{\text{Refrigerant}}}{(\rho_{suction} \cdot \Delta h_{evaporating})_{\text{Isobutane}}} \quad (1)$$

The Rankine COP is calculated using two isobars, one isentropic and one isenthalpic at Low Back Pressure (LBP) CECOMAF standard, see Table 1.

The theoretical clearance volume efficiency η_{cl} is calculated by assuming no leakage during expansion:

$$\eta_{cl} = 1 - \frac{\rho_{discharge}}{\rho_{suction}} \cdot \frac{V_{cl}}{V_{stroke}} \quad (2)$$

The leakage coefficient can be calculated according to Bartmann (1970). However in order to compare at the same capacity a correction for the stroke volume is needed. Due to stresses in the crank etc. the stroke length can vary within some interval, and therefore the main adjustment of capacity must be done by changing the cylinder bore. The corrected leak coefficient C_{leak} is

$$C_{leak} = \frac{p_1^{\,2} - p_2^{\,2}}{\eta \cdot p_1 \cdot v_1} \quad \cdot \quad \frac{1}{\sqrt{\varepsilon}} \quad (3)$$

Leak coefficient · *Capacity correction*

The influence of suction side pressure drop is discussed by Süss *et. al.* (2000) by investigating the capacity reduction at the same pressure drop for the refrigerants. Another important factor to take into account is the magnitude of the pressure drop at the specified condition and capacity for the various refrigerants. In the comparison in Table 1 this is done by calculating the relative pressure drop for each refrigerant. The fully developed pipe flow is used as reference:

$$\Delta p = \frac{1}{2} \cdot \rho \cdot \left(\frac{\dot{m}}{\rho \cdot A} \right)^2 \cdot f \cdot \frac{L}{D} \quad (4)$$

Here the friction factor f is calculated by the Prandtl Analogy. The mass flow used for each refrigerant corresponds to the same capacity. The relative pressure drop $\gamma_{Isobutane}$ is calculated by:

$$\gamma_{\text{isobutane}} = \frac{\Delta p_{\text{Refrigerant}}}{\Delta p_{\text{Isobutane}}} \quad (5)$$

By multiplying the relative pressure drop $\gamma_{Isobutane}$ with the relative sensitivity for each refrigerant by the method used by Süss *et. al.* (2000), the theoretical relative suction side pressure drop for each refrigerant can be found.

The theoretical relative influence of suction gas heating can be found using the same method as described for suction side pressure drop. In order to find the relative magnitude of suction gas heating at the same capacity for each refrigerant, the Colburn Analogy for fully developed pipe flow is used (Chapman, 1989).

2.2 Results of the theoretical comparison of N-butane with other refrigerants

An overview of the relative capacity and theoretical COP for different refrigerants can be seen in Figure 1. It is seen that a higher capacity corresponds more or less to a lower theoretical COP.

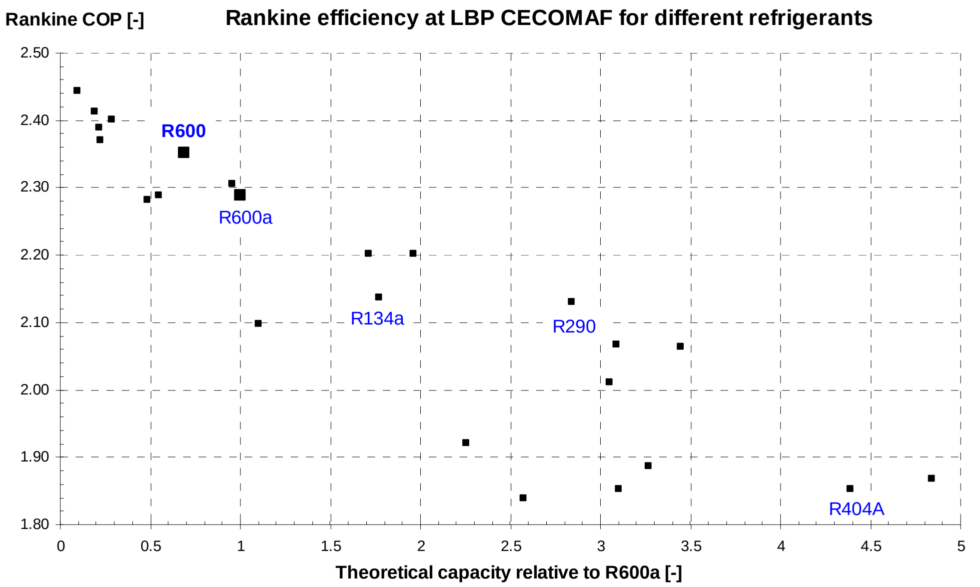


Figure 1: Comparison of theoretical capacity and COP for a reverse Rankine cycle without any losses.

It is also seen that N-butane, isobutane and propane all are on the upper limit of the band at their respective capacity level, this emphasizes their potential for low energy consumption.

Table 1: Comparison of selected refrigerants at LBP CECOMAF condition

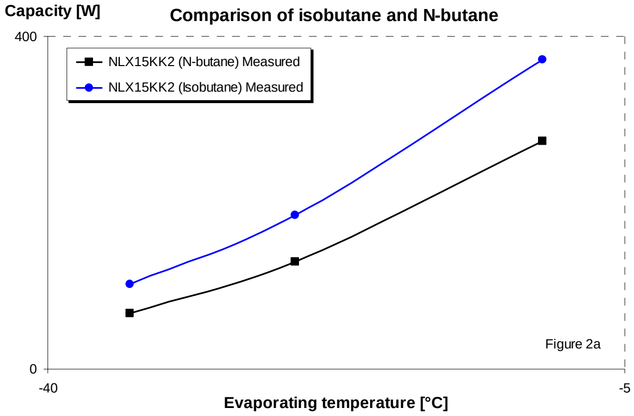
	R600a (isobutane)	**R600 (N-butane)**	**R134a**	**R290 (propane)**	**R404A**
Theoretical relative capacity $\varepsilon_{isobutane}$ [%]	100	69	177	284	310
Theoretical Rankine COP [-]	2.29	2.35	2.14	2.13	1.85
Theoretical clearance volume efficiency at 1% of stroke volume [%]	88	86	87	91	90
Theoretical relative leakage coefficient C_{leak} [-]. Compared at same theoretical capacity.	100	65	321	258	719
Theoretical relative suction side pressure loss [%]. Compared at same theoretical capacity.	100	250	74	22	44
Theoretical relative influence on suction gas heating [%]. Compared at same theo. capacity.	100	102	96	102	109

As seen in Table 1, N-butane has a higher COP than isobutane, if no losses are present in the compressor. However N-butane is more sensitive to clearance volume, suction side pressure drop and suction gas heating. It is only with respect to leakage that N-butane is less sensitive than isobutane. For light commercial applications propane has a high theoretical COP level and it is also relativly insensitive to the losses listed in Table 1.

Calculations on N-butane (Bjerre and Scavenius, 2004) using a comprehensive compressor model indicate that the advantage in Rankine COP will be lost due to the higher sensitivity to the loss factors.

3. Comparison of calorimeter results using N-butane

The compressors selected for the measurements have a stroke volume of 14.7cm^3 and designed for the use of isobutane as refrigerant. They are widely used for the highest energy level, A++, cabinets in Europe. The comparison below is based on a compressor series of 7 compressors which are first measured on a calorimeter according to the ISO R917 standard with isobutane. Without changing the compressors the refrigerant has been changed to N-butane and the compressors have been remeasured on the calorimeter. All comparisons are made at 55°C condensing temperature.



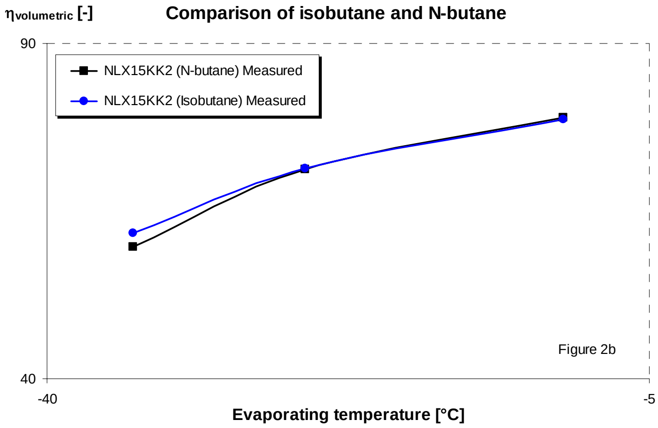
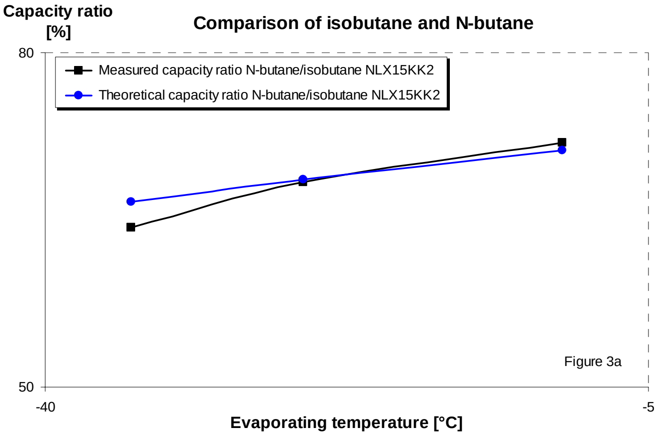


Figure 2a: Capacity for NLX15KK2 using isobutane and N-butane. Figure 2b: Comparison of volumetric efficiency. Measured at 55°C condensing temperature. Average of 7 compressors.

Before the measured results are discussed it should be mentioned that the form of the curves depends on the compressor design. Another design might have higher or lower level of leakage, pressure drop, heating etc., and this will influence the form of the curve.

As seen in Figure 2 and 3, the capacity of N-butane is lower than isobutane at same stroke volume. The volumetric efficiency tends to be lower at low evaporating temperatures and above -25°C the volumetric efficiency is on the same level. At the rating point LBP CECOMAF (-25/55/32/32) the COP/η_{motor} is more or less on the same level. N-butane has a slightly lower COP at low evaporating temperatures but it increases more rapidly at higher evaporating temperatures. It is important to note that the capacity is not the same. Further investigations show that the lower level of COP/η_{motor} with isobutane can be explained by the higher capacity and therefore a higher pressure drop.



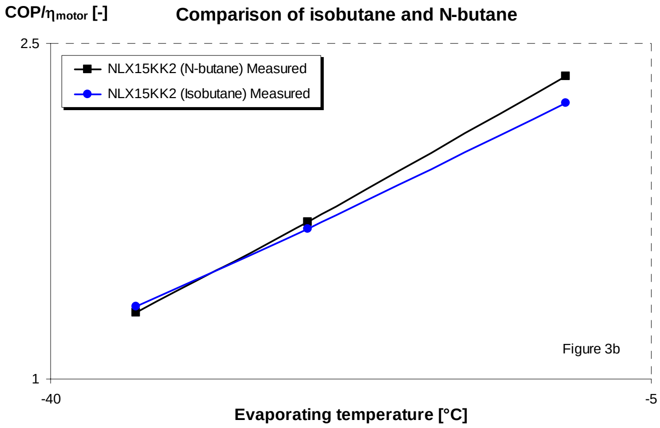


Figure 3a: Capacity ratio NLX15KK2 isobutane/N-butane. 3b: Comparison of COP/η_{motor}. Measured at 55°C condensing temperature. Average of 7 compressors.

In Figure 3a the measured capacity of N-butane divided with the capacity of isobutane is compared to the theoretical ratio without any losses. The curvature of the volumetric efficiency also indicates that the lesser sensitivity on leakage can not compensate for the higher sensitivity on clearance volume and suction gas heating at low evaporating temperature with the present compressor design.

Noise measurements show a decrease of ca. 2dB by using N-butane, however the capacity of the compressors is also about 70% of isobutane. This is in accordance with expectations.

4. Results of lifetime test using N-butane

Table 2: Comparison of lifetime results isobutane and N-butane

Compressor: **14.7 cm^3**
Oil: **5 cSt. mineral oil**

Refrigerant	**R600**	**R600**	**R600a**	**R600a**
Run time [h]	6300	6300	8000	8000
Condition	Low load	High load	Low load	High load
Wear	0-1	1-2	1	1-2
Cu-plating	0-1	0-1	0-1	0-1
Valve deposits	0	0	0	0

0 = as new 1-2 = acceptable 3-4 = not acceptable

According to the life time tests N-butane is suitable in the NLX15KK2 compressors with 5cSt mineral oil. This was also expected since the pressures are lower with N-butane compared to isobutane.

5. CONCLUSIONS

The theoretical evaluation shows at LBP CECOMAF that N-butane (R600) has:

- 2.8% higher theoretical COP compared to isobutane (R600a)
- About 70% of the capacity of isobutane
- 10% higher theoretical COP compared to R134a

The measurements show that the higher theoretical COP of N-butane compared to isobutane can not be found in the measurements. This is caused by the higher sensitivity to clearance volume, suction gas pressure drop and heating, compared to isobutane. However the COP level of N-butane in the present compressor design is at the same level as isobutane, which today is the refrigerant giving the highest COP on the market.

Lifetime test show acceptable results. The wear tendency is comparable with isobutane.

N-butane is an option for reaching high COP levels in household appliances, but it does not offer significant advantages to isobutane on existing isobutane stroke volumes. However it opens the possibility to extend the range to lower capacity by using the existing compressor designs. The disadvantages are that the cost and size are unchanged.

NOMENCLATURE

COP	Coefficient of Performance	(-)
f	Friction factor	(-)
h	Enthalpy	(J/kg)
L/D	Length/Diameter	(-)
$\dot{m}$	Mass flow	(kg/s)
V	Volume	(m^3)
ε	Relative capacity	(-)
γ	Relative pressure drop	(-)
η	Efficiency	(%)
ν	Kinematic viscosity	(m^2/s)
ρ	Density	(kg/m^3)

Subscripts

cl	Clearance volume
leak	Leakage

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