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Feasibility of a R744 Compressor for Light Commercial Appliances

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ABSTRACT

During the last years, for meeting the Kyoto protocol requirements, R744 refrigerant has been studied as a possible alternative to HFC ones in light commercial appliances. New compressor designs and other new components have been developed to make them working with this refrigerant. Recently a working group within the International Electrotechnical Commission (IEC) has prepared a draft proposal to modify the IEC60335-2-34 covering motor-compressors using R-744 in transcritical applications. This environment confirms R744 to be one of the alternatives for replacing HFC's in this sector.

This work presents a new compressor platform designed to work with R744 covering a range from 200W to 1100W at 14ºF(-10ºC) of evaporating temperature for HMBP applications and from 200 W to 800W at -10ºF(-23,3ºC) of evaporating temperatures for LBP applications. Compressor samples have been tested at several reference conditions and their performances have been compared to the HFC's equivalent compressors.

Further tests with the new platform have been carried out on some commercial appliances checking the performance of the overall system and confirming the preliminary results obtained in the calorimeter tests.

Finally, other considerations have been taken into account and have been analyzed in order to have an overall vision of the feasibility of a compressor for light commercial appliances working with R744.

1.INTRODUCTION

R744 refrigerant is a focus of research to be used in many refrigeration applications as it has been shown in the last technical conferences and seminars where deep studies and preliminary field tests have been/are being performed: heat pumps (H. Mukaiyama, 2002) , air conditioning (Armin Hafner, 2004), several configurations of big commercial refrigeration systems (Eggen, 1998) , … all of them pointing to a promising future of the R744 use.

This paper analyze in an objective and constructive way the feasibility of compressors for light commercial appliances working in a R744 transcritical cycle based on the development program carried out so far. Several design aspects are commented and product performances are presented with a final evaluation of the product together with other aspects.

2. PLATFORM DESIGN CONCEPTS

2.1. Key aspects

Main differences when designing a R744 platform compared to current refrigerant compressor technology are the very high working pressures affecting housing design to ensure safety as well as no leakage to the ambient. Also the high pressure difference between suction and discharge affects piston-cylinder design to minimize piston force and flow leakage, i.e.: in regards with this last item is suggested the use of piston rings (Süss, 2004).

Another relevant difference is the high density of such refrigerant that can be a constraint for compressors of small cooling capacity aprox.<1kW because of small displacements requirement and consequently space limitations to allocate a reliable mechanism (ex. piston and piston-pin) and to allocate a reliable and efficient valves-valve plate system.

The third one, that contributes mainly to the efficiency, is the variation of density vs. temperature that is higher with R744 than with current refrigerants (for example a compressor working with R744 in a system @ -10ºC evap. temp. and with 40K of superheating, shows an improvement of volumetric efficiency around ~13% when superheating is reduced to 20 K and only around ~8-9% with R134a or with R404A). Colder compressor inlet temperature can also contribute to reliability of compressor and system in transcritical cycles where high discharge pressures and consequently high discharge temperatures may be reached. All this requires to take care of the internal suction heat transfer minimization in the new platform design.

2.2. Platform description

This is a single compression stage platform.

Range to be covered – The range covered by this platform goes from 200W to 1100W at 14ºF(-10ºC) of evaporating temperature for HMBP applications and from 200 W to 800W at -10ºF(-23,3ºC) of evaporating temperatures for LBP applications. This range is thought of 7 displacements covered by the combination of 2 bore diameters and its corresponding stroke. So far two displacements have been developed and validated: 1,42cc(CL15TB) and 2,50cc(CL25TB)

Mechanism - Different versions have been designed and several life tests have been conducted to arrive with success to the definitive mechanism. No details are described in this paper because they are being patented. No piston rings are used.

Housing - Considering all above explained, two versions of semi-hermetic housings have been designed. The first generation (Figure 1) was not optimized, mainly used for investigation purposes and know-how acquirement (compressor performance, mechanism life testing, sealing performance and its durability,...). After this step, and as a result of all the investigations carried out before, a second generation of housing (Figure 2) has been projected and built, complying with the latest version of the draft of the IEC60335-2-34 for motor-compressors working with R-744 where the strength resistance test is proposed to be 286 bar.

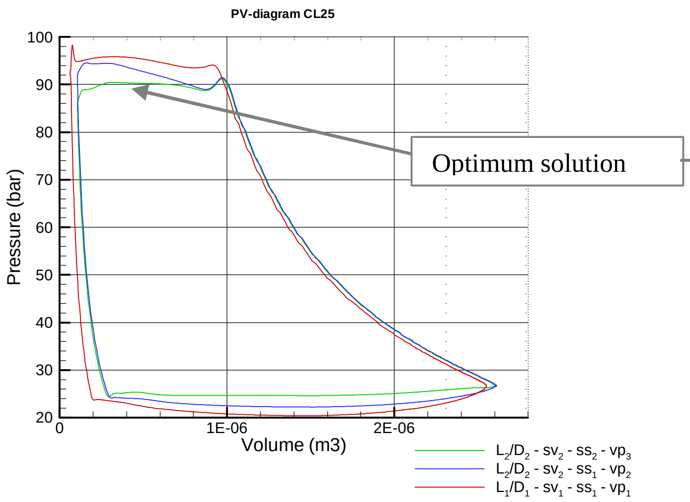
Figure 1. (Semi-hermetic housing 1st generation)

Figure 2. (Semi-hermetic housing 2nd generation)

Valves and valve plate design - Considering the higher pressure conditions and the new bore dimensions required due to small displacements for the R744, adequate suction and discharge reeds have been designed to ensure the safety taking care of not penalizing performances so much. Safety design criteria currently used for standard refrigerants based on internal background and literature(Grolier, 2000) have been adapted for this new refrigerant.

Motor - Motor technology is the same as currently used in our production facilities.

Advanced Calculus tools - In order to minimize the number of prototypes to be built and the laboratory tests advanced simulation codes like HCOMPv59(accurate simulation code of compressor developed by UPC, Univresitat Politècnica de Catalunya) interacting with FEA analysis have been used (Figure 3 and 4). This allows us arriving quickly to an optimum solution in terms of reliability and good performances.



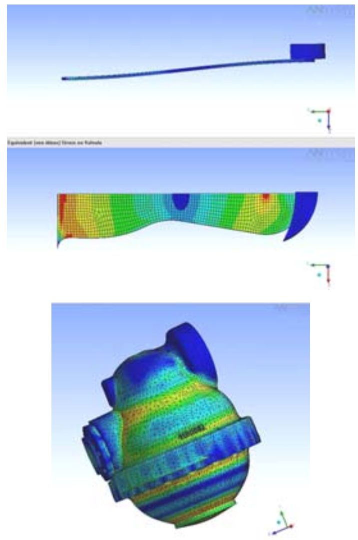


Figure 3. PV diagram CL25 – different configurations
L/D: Stroke/Diameter ratio , sv : suction valve
ss: suction stopper , vp: valve plate

Figure 4. Suction valve - upper side
Housing 2nd generation – lower side

3. PLATFORM PERFORMANCES

3.1. Cooling capacity and power consumption

As presented in previous technical conferences, several compressor units and design versions have been tested and verified (Rigola J., 2004 and Raush G., 2005). The details of the experimental setup where the tests have been performed are also described in the referenced papers.

Table 1 summarizes the performances of current platforms:

Table 1. Global CL15/25 Performances @reference cycle*

Model	Power cons. (W)	Cool. Cap. (W)	COP(W/W)
CL25	592	930	1.57
CL15	369	534	1.45

*reference cycle : Evap. Temp. -10ºC,
gas cooler pressure 85 bar, Inlet Compr. Temp:32ºC,
Outlet g.c. temp.:32ºC

In order to go more in depth with the mechanical design limits, further investigations have been carried out at lower evaporating temperatures as shown in table 2. In all cases, discharge compressor temperatures where found acceptable.

Table 2. Performance at low evap. Temp. of CL15TB @reference cycle*

Evap. Temp.(ºC)	Power cons. (W)	Cool. Cap. (W)	COP(W/W)
-23,3	296	306	1,04
-30	273	227	0,83
-35	251	181	0,72

*reference cycle : gas cooler pressure 85 bar,
Inlet Compr. Temp:32ºC, Outlet g.c. temp.:32ºC

Due to the nature of R744 transcritical cycle, for ambient temperatures higher than 30ºC it is going to be unavoidable to work at high discharge pressures for not loosing cycle efficiency. For this reason the compressor has been tested at different discharge pressures and volumetric and isentropic efficiencies have been evaluated as shown in figures 5 and 6 respectively.

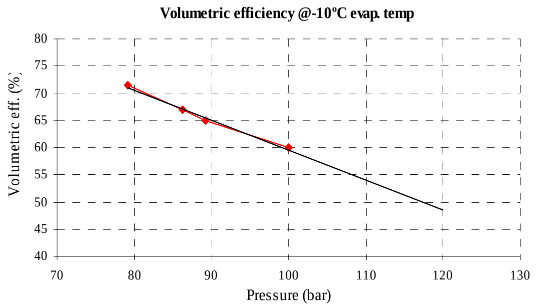


Figure 5. Volumetric efficiency

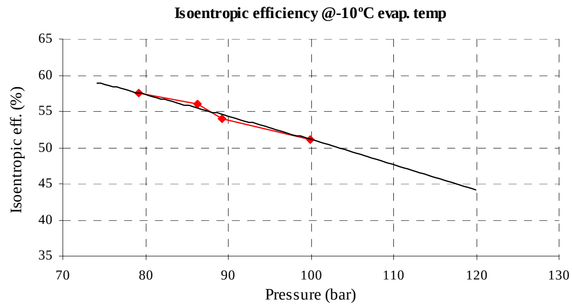


Figure 6. Isentropic efficiency

Ideal mass flow rate has been evaluated considering an ideal compressor without clearance volume running at nominal frequency. Isentropic work has been evaluated according the expression 1

$$w_s = RT_1 \frac{\gamma}{\gamma - 1}[\Pi^{(\gamma-1)/\gamma} - 1] \tag{1}$$

where R is the gas constant, T_1 is compressor inlet temperature. γ is isentropic index and Π is the compression ratio. The isentropic index has been evaluated as described by Perez-Segarra, 2005.

3.2. Noise

Noise has been measured on the compressor alone, not with the appliance.
As well known, the most important characteristics affecting the overall noise of the appliance are the Sound power level, Vibration level and Pulsation level.
Regarding sound power levels, preliminary results show higher levels than the equivalent compressor in R134a.
Vibrations are equivalents to the existing platforms with traditional refrigerants.
Gas pulsation is higher than current platforms and some modifications have to be implemented to achieve acceptable results. This work has already been performed with success.

As a conclusion two of the three main contributors to noise coming from the compressor are for the new platform in line with existing technology. The effect of the third one, the sound power level, will have to be confirmed by new experimental noise measurements on real appliances looking for the need, or not, of improvements but in a first approximation it does not seem it will become a too critical issue.

3.3. Comparison with R134a HMBP

In the table 3 are shown the results of this new compressor (CL15TB) compared with its equivalents in R134a HMBP. Two models of R134a HMBP are selected to make the comparison. One, GP12TB, refers to a standard efficiency product and the second, GLY90RAb, refers to the highest efficiency in the market of its cool. capacity level today.

Table 3. Cool. Cap.(W) / COP comparison

Evap. Temp.(ºC)	GP12TB**	GLY90RAb**	CL15TB*
-10	494/1,41	425/1,73	534/1,45
0	800/1,79	673/2,24	768/2,04
+7,2	1070/2,06	896/2,63	976/2,69

*reference cycle: gas cooler pressure 85 bar,
Inlet Compr. Temp:32ºC, Outlet g.c. temp.:32ºC
**reference cycle: ashrae cond. Temp.:+55ºC,
Inlet Compr. Temp:35ºC, Subcooling: 9K

Corresponding graphics of Table 3 are shown in figures 7 and 8:

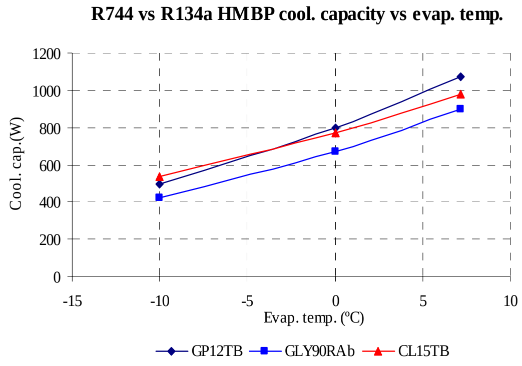


Figure 7. R744 vs R134aHMBP
Cool. Capacity vs evap. Temperature

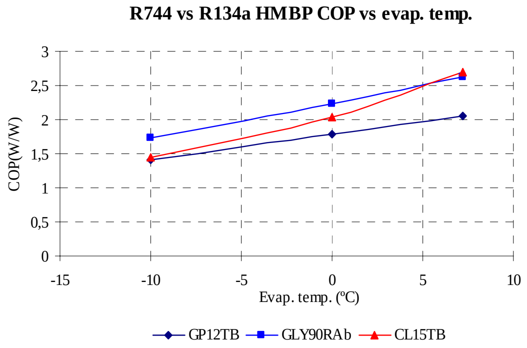


Figure 8. R744 vs R134a HMBP
COP vs evap. temperature

Regarding efficiency, the new platform is expected to perform between the standard and the high efficiency levels, but it will have to be confirmed on real application. Also regarding cooling capacity it will have to be confirmed on the application which is the real R134a equivalent compressor. At least the results are very promising and further optimization tasks can still be done.

3.4. Comparison with R404A LBP

In the table 4 are shown the results of this new compressor (CL15TB) compared with the equivalent in R404A LBP. With the same criteria as for the HMBP analysis, one model ML80FB that refers to standard efficiency product and another one MLY60LAb that refers to the highest efficiency in the market of its cool. capacity level today have been selected to make the comparison.

Table 4. Cool. Cap.(W)/COP comparison

Evap. Temp.(ºC)	ML80FB**	MLY60LAb**	CL15TB*
-10	686/1,43	582/1,8	534/1,45
-23,3	370/1,09	326/1,36	306/1,04
-35	187/0,79	166/0,96	181/0,72

*reference cycle: gas cooler pressure 85 bar,
Inlet Compr. Temp:32ºC, Outlet g.c. temp.:32ºC
**reference cycle: ashrae cond. Temp.:+55ºC,
Inlet Compr. Temp:32ºC, Subcooling: 23K

Corresponding graphics of Table 4 are shown in figures 9 and 10:

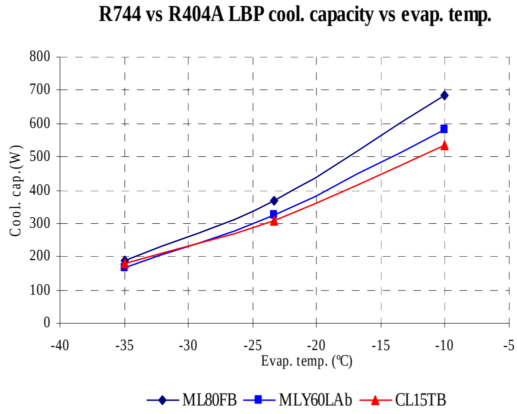


Figure 9. R744 vs R404A LBP
Cool. Capacity vs evap. Temperature

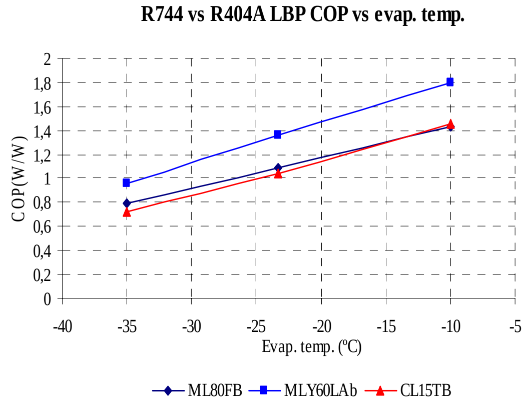


Figure 10. R744 vs R404A LBP
COP vs evap. temperature

The new platform confirms good cooling capacity tendency with no dramatic falling at low evaporating temperatures. On the other hand, efficiency is initially lower than the current standard level but not so far. Something that has to be confirmed on application test results (see section 4).

4. RESULTS ON APPLIANCES

4.1. LBP appliance

CL15TB has been tested on a LBP appliance (chest freezer) in order to investigate the limits of this new platform (figure 11) and detailed explanations on the cycle and on the application have been given by Jornet, 2006.

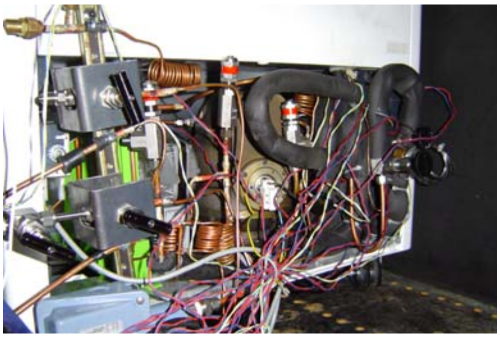


Figure 11. Instrumented CL15TB in a Freezer with control devices

The main conclusions of the results that were found are showed below:

- At higher ambient temperatures than 30ºC discharge gas cooler pressure has to be increased to not decrease the performance of the system (it is already known and experimentally verified for a transcritical cycle the high dependence of the efficiency of the system with the ambient temperature due to R744 critical temperature of 31ºC, Lozza 2004)
-At 43ºC of ambient temperature, evaporating temperatures of -22ºC and the averaged cooled room temperature of -15ºC were reached.
- At 35ºC of ambient temperature the cycle with R404A (and standard eff. compressor) shows 18% less of energy consumption than R744.
- The requirement of quite low temperatures in the cooled compartment (below -15 ºC) with ambient temperatures above 35 ºC highly penalizes the efficiency of the system at low ambient temperature (25 ºC).

- Further improvements on the application still can be done as well as on the compressor.
- It seems to be feasible to get the levels of standard efficiency with a single stage but difficult to reach the high efficiency levels.

4.2. HMBP appliance

Tests on a HMBP appliance are running.

5. OTHER CONSIDERATIONS

5.1. Weight

When analyzing the feasibility of the new R744 platform one of the key aspects will be the weight-cost.
In the table 5 is summarized the weight comparison of R744 platform with the current R134a equivalent one.

Table 5. Weight comparisons

CL15TB	GP12TB
16,2 kg.	12,1 kg.

The R744 platform is in a worse position respect to its R134a equivalent. Although the new platform contains fewer parts than the existing designs, the increase in weight for the R744 platform due mainly to the housing can make us think in a possible increase of cost for this new technology.

6. GLOBAL PICTURE

With the aim of summarizing the contents of the present paper, table 6 includes an evaluation of all the key aspects that can influence the success of the R744 platform consolidation.

Table 6. Overall feasibility picture

Concept	R744 HMBP platform	R744 LBP platform
GWP	+++	+++
EFFICIENCY*	+	-
NOISE*	~	~
WEIGHT	-	-

+++ Best, ++ good, + promising,
~ equivalent to current refrigerants, - bad
*to be confirmed on appliance

7. CONCLUSIONS

A new platform design suitable to work with refrigerant R744 has been presented. Several aspects related to performances have been put on analysis. New platform performs well for HMBP applications and need to be improved for LBP applications to not penalize the TEWI. Noise of new technology seems not to be a hard constraint to make it feasible.
Other parameters have been analyzed and it seems to be clear that at the end the cost will be to a great extent depending on the consolidation of this new refrigerant. Government implications will have great influence on it.

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