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USE OF HFC FLUIDS AS SUITABLE REPLACEMENTS IN LOW-TEMPERATURE REFRIGERATION PLANTS

Antonino La Rocca[1], Vincenzo La Rocca[2], Antonio Messineo[3] and Domenico Panno[2]
[1]Department of Mechanical and Manufacturing Engineering, University of Nottingham, United Kingdom
[2]Dipartimento dell'Energia, Università degli Studi di Palermo, Viale delle Scienze, Palermo, Italy
[3]Facoltà di Ingegneria e Architettura, Università Enna "Kore", Cittadella Universitaria, Enna, Italy
E-Mail: antonio.messineo@unikore.it

ABSTRACT

An experimental investigation of the performance of a low-temperature refrigerating unit working with R22 and a comparison of its performance when operating with replacement HFC fluids in accordance with the European Regulation CE-1005/2009 are presented in this paper. Plant working efficiency was tested with R22, as baseline, and then compared with four different HFC fluids: R413A, R417A, R422A and R422D. The refrigerating unit was a vapour-compression plant equipped with a reciprocating double-cylinder compressor able to keep the cold room at -20ºC. Lower values of the temperature at the end of compression and polytrophic exponent can be achieved with the HFC tested. Substituting the R22 led to refrigerating plant to underperform. The COP was lower for all the replacement fluids showing inferior energy efficiency and higher energy consumption. The TEWI parameter was also evaluated and compared for all the fluids tested in the present investigation, suggesting TEWI increments substituting the original fluid.

Keywords: refrigerating system, R22, R413A, R417A, R422A, R422D.

INTRODUCTION

The Regulation CE-1005/2009 has banned the use of R22 in Europe from the 31st December 2009, because it contains chlorine, although its use is allowed until the 31st December 2014 if recycled. The European Union Regulations, imposing the expiry dates mentioned above, regulates the collection of R22 during maintenance operations on each plant. The owner of the plant is responsible for the collection which has to be carried out according to the best practices suggested by refrigerating specialists who have to adopt suitable equipment. The collected R22 has to undergo suitable treatments if it has to be reused as a refrigerating fluid in maintenance operations on existing plants. Amongst all synthetic fluids, R22 is the most versatile and consequently the one that had the broadest distribution, eg. small reversible air-conditioning systems, large air-conditioning plants and plants for the storage of fresh and frozen products (supermarkets, hypermarkets, warehouses, etc.).

In recent years, the R22 represented a 97.2% of the HCFC substances used in the refrigeration sector [1] and it is likely to have a shortage of this substance in a few years because of the need of refilling the refrigeration plants currently operating with R22. Although R22 is still widely used in installations and plants [2-6], several other refrigerants are now being considered as alternative fluids. The replacement of a plant with a new one designed specifically for the new refrigerant is certainly an expensive option; a more attractive alternative is to adapt an existent plant by retrofitting or replacing directly the refrigerant with modifications to components and setup [8]. While for small systems a replacement of the entire system can be an option, for large systems such as fresh and frozen storage plants and large air-conditioning plants minor modifications to the existing plant are more desirable.

Alternative refrigerants available in the market have been evaluated for environmental and safety requirements, and compatibility with lubricant oil, filters, and sealing. However, in order to establish the best substitute for a specified system, it is necessary to estimate its energetic performance when operating with the new refrigerant.

In recent years, many researchers have been working on the development and characterization of refrigerants with higher energetic efficiency, and have specifically investigated the energetic performance of suitable replacements for the R22 [9-16]. R422D and the R417A are the most recommended drop-in fluids for air conditioning systems [17]; Rosato *et al*. [18] and Fernández-Seara *et al*. [19] investigated the heat transfer characteristics and the performance tested by Torrella *et al*. [2].

Llopis *et al*. [20] investigated the process of R22 substitution, either with drop-in or retrofitting processes, by presenting a theoretical and experimental analysis of the performance of R22, of two drop-in fluids (R422A, R417B) and a retrofit refrigerant (R404A), in a two-stage vapour compression plant over a wide range of evaporating temperatures for a fixed condensing temperature of 40°C. Experimental tests using R22, R413A, R417A, R422A and R422D were conducted by La Rocca and Panno [21] for air-conditioning applications. On the other hand, the aim of this paper is to evaluate the performance of a pilot refrigerating plant used in for low-temperature refrigeration applications (evaporation temperature equal to - 30°C), which originally ran on R22 and subsequently on other mixtures of HFC fluids, so that their possible use could be evaluated through simple retrofit operations.

EXPERIMENTAL APPARATUS

The plant analyzed in this investigation allows storing frozen food in a refrigerated room kept at -20 ºC. It is a vapour-compression plant equipped with a reciprocating double-cylinder compressor with the volumetric capacity of 14.70 m^3/h. The condensation of the used fluid is obtained by transferring the thermal energy to the external environment through the use of a condensation system made up by an air cooling fin battery. The experimental plant diagram showed in Figure-1; the cold room has the following internal dimensions: width 2.15 m, length 3.00 m, height 2.40 m with its internal volume of 15.48 m^3.

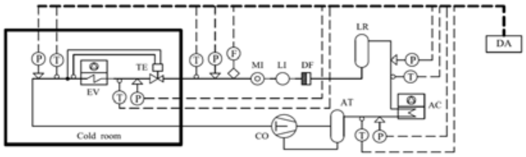

Figure-1. Layout of the experimental facility.

Figure-2 shows the used experimental facility located at the Cold Energy Technology Laboratory of the University of Palermo (Italy).

Figure-2. View of the experimental plant located at the cold energy technology laboratory.

Table-1 shows the characteristics of the main components of the refrigerating plant.

Table-1. Characteristics of the main components.

Dorin compressor, model: K300CS	Type	Reciprocating semi-hermetic two cylinders
	Volume risen up to 50 Hz	14.70 m^3/h
	Bore gauge	61 mm
	Stroke	29 mm
	Oil load	1.4 kg
	Oil type	Mineral 32 cSt
	Electric feeding	220-240V(Δ)-380-420V(Y)/3/50Hz
Dorin air condenser	Type	In copper pipes with aluminium finning
	Air flow	5200 m^3/h
	Number of fans	3
	Absorbed power	102 W at 50 Hz
Danfoss thermostatic expansion valve model TES2	Type	With outside pressure equalization
	Work range	-40 °C ÷ -15 °C
	Allowed work pressure	28 bar
Luve Contardo evaporator model S3HC 47 E 80	Type	In copper pipes with aluminium finning
	Air flow	2700 m^3/h
	Number of fans	1
	Absorbed power	175 W

The main operational parameters such as temperatures, pressures and mass flow rate are monitored and recorded via data acquisition system with 30 channels. Fluid pressure and temperature are measured at the inlet and outlet section of each component using T-type (constantan-copper) thermocouples, and piezoelectric pressure transducers. The mass flow rate is measured at the exit of the liquid receiver placed on the bottom of the condensing unit using a Coriolis mass meter. Details of sensors used in this investigation are provided in Table-2.

Table-2. Measurement equipment.

Measured amount	Sensor	Measurement field	Uncertainty
Temperature	Thermocouple type T	-40 ÷ 125 °C	± 0.15 °C
Absolute pressure	Piezoelectric	0 ÷ 10 bar 0 ÷ 30 bar	± 0.2 % FS ± 0.5 % FS
Mass flow meter	Coriolis effect	0 ÷ 5 kg/s	± 0.2 %

The feeding pipelines of the various components have been thermally insulated with cylinder muffs in expanded elastomeric made of synthetic rubber (Armaflex) 25 mm wide.

PERFORMANCE ANALYSIS OF THE PLANT WITH DIFFERENT FLUIDS

Experimental tests have been carried out with the aim of analyzing the performance of the refrigerating plant after the replacement of the fluid in use. The aim was to evaluate the performance of an existing plant, designed and built to run with R22, after retrofit operations with HFC fluid mixtures (R413A, R417A, R422A and R422D); one of the objective of the present work was to assess whether the R22 replacement fluids would be suitable in terms of energy efficiency and environmental impact.

The tests were carried out with no changes to the refrigerating plant components; only the thermostatic throttling valve was adjusted to regulate the flow with new fluid. In particular, the throttling valve was adjusted at every test to maintain a superheating value of 5°C at the outlet of the evaporator. During the tests, the evaporation temperature was kept constant at -30°C. The tests were carried out once steady state conditions were achieved, i.e., temperature oscillation within ±0.3°C, low pressure side oscillations ±5 kPa, and high pressure side ±20 kPa. In the present investigation, the evaporation temperature was maintained at -30°C, with superheating of 5°C, to mimic the plant's ordinary running conditions.

The NIST Standard Reference Database 23 (REFPROP) was used to obtain enthalpies, for each of the fluids investigated, at the measured pressure and temperature within the cycle. Refrigerating power was calculated as product of the mass flow rate and the enthalpy difference between the evaporator's inlet and outlet.

EXPERIMENTAL TEST RESULTS

Figure-3 shows the COP variation as function of the condensation temperature for each of the fluids analyzed in this investigation. All the HFC mixtures considered as replacement fluid underperformed showing inferior energy efficiency compared to the R22. The energy efficiency decreased with the following ranking order: R413A, R417A, R422D and R422A. Air condensing machines, the COP variation is less sensitive for high condensing temperatures, e.g. summer time; while it is more substantial in winter.

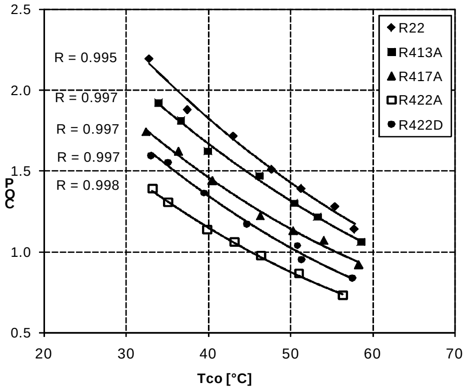

Figure-3. COP vs. condensation temperatures.

COP decrease significantly when replacing the R22 with HFCs. At a condensing temperature of 35°C the drop in COP is equal to 10.42% for the 413A; while it decreases further of 38.38% when R422A is used. Figure-4 shows refrigerating power versus the final compression temperatures for the different fluids at fixed performance conditions. It should be noted that the final compression temperature of R22 is considerably higher in comparison to the other fluids; this leads to a higher thermal stress for the compressor. Conversely, HCF fluids show lower temperatures values being then more suitable for usage with high external temperatures (air-condenser).

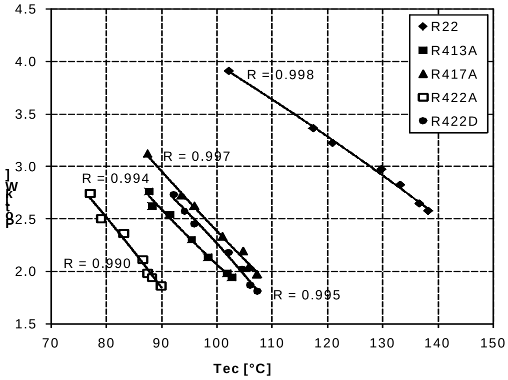

Figure-4. Refrigerating power vs. final compression temperature.

The change of the compression ratio for different condensing temperature for each of the fluids is given in Figure-5. Again the performance of R22 is better if compared to all of the alternative fluids that have been tested; this is because the compression ratio is kept at lower values under the same condensation temperatures.

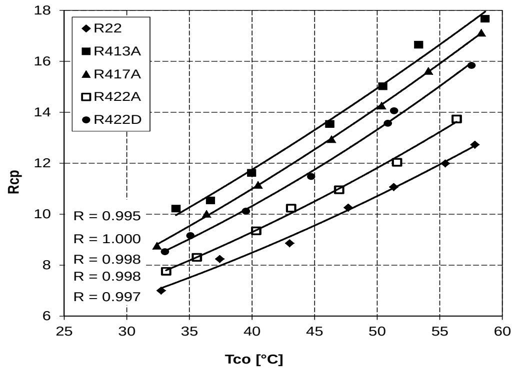

Figure-5. Compression ratio vs. condensation temperature.

Finally, Figure-6 shows the compression polytrophic exponent values plotted against the condensation temperatures. The alternative fluids R413A, R417A, R422A and R422D have lower exponents than R22. This aspect has positive effects on the compressor performance.

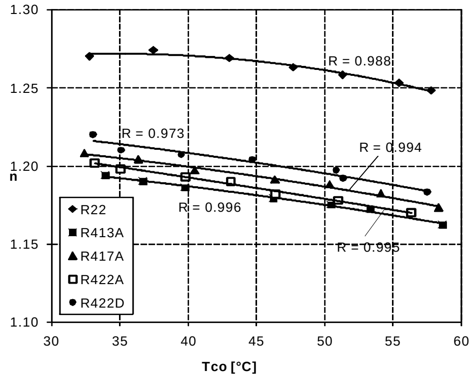

Figure-6. Polytrophic exponent vs. condensation temperature.

ENVIRONMENTAL ANALYSIS

The environmental impact related to the replacement of the R22 with HFC mixtures with regards of its effect on the ozone layer and its contribution to the greenhouse effect on our planet are analysed in this section. With regards to the first aspect, the change from R22 (ODP = 0.055) to HFC mixtures (ODP = 0) is undoubtedly an advantage, as the HFCs do not contain chlorine and therefore would not damage the ozone layer. Whereas, the TEWI allows evaluating the incidence which each fluid would have on the greenhouse effect. TEWI is a parameter that takes into account the direct greenhouse effect caused by the release into the atmosphere of a refrigerating fluid and the greenhouse effect caused by CO_2 emitted to power the plant [22-24]:

$$TEWI = CO_{2,\ d.e.e.} + CO_{2,\ i.e.e}$$

where

- $CO_{2,d.e.e.}$ = direct CO_2 emission equivalent;
- $CO_{2,\ i.e.e}$ = indirect CO_2 emission equivalent.

The direct greenhouse effect is given by:

$$CO_{2,\ d.e.e.} = C \cdot CEY \cdot SL \cdot GWP\ [kg\ CO_2]$$

where

- C = charge of refrigerant in the plant [kg];
- CEY = refrigerant charge emitted per year [7%];
- SL = operation life [year];
- GWP = kg CO_2 • kg refrigerant^{-1}.

With regards to the experiences gained from our plant, the direct contribution to the greenhouse effect has been evaluated on the basis of the quantity of fluid in use (R22, R413A, R417A, R422A, R422D) charged in the plant and estimating an annual loss of refrigerant equal to 7% of the charge. Table-3 shows the direct greenhouse effect of the various fluids in terms of annual quantity in Kg CO_2 released in the environment.

Table-3. Direct greenhouse effect of tested refrigerants.

Refrigerant	Charge [kg]	GWP (ITH=100)	Direct contribution [kg CO_2]
R22	6.5	1500	10,237
R413A	10.5	1770	19,514
R417A	8.5	1950	17,404
R422A	8.0	2530	21,252
R422D	6.5	2230	15,220

The indirect greenhouse effect is:

$$CO_{2,\ i.e.e} = a \cdot (Pot / COP) \cdot N \cdot SL$$

with

- a = kg CO_2 emitted per kWh generated;
- Pot = refrigerating power in the plant;
- COP = coefficient of performance;
- N = hours of equipment operation per year;
- SL = service life (year of equipment operation).

To evaluate the $CO_{2,\ i.e.e}$ the following values have been used:

- a = 0.45 [kg CO_2 • kWh^{-1}];
- N = 1000 [h • year^{-1}];
- SL = 15 [year].

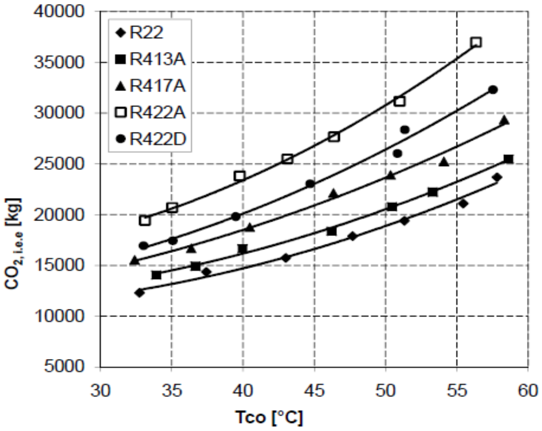

Figure-7. Indirect greenhouse effect vs. condensation temperature.

Figure-7 shows the indirect greenhouse effect plotted in relation to the condensation temperature for each fluid. R22 is the one that gives a better performance thanks to its higher energy efficiency.

Figure-8 shows the TEWI in relation to the condensation temperature. As the GWP of R22 is lower compared to the other fluids and also the COP gives better results, it follows that the TEWI of the plant operating with R22 has a favorable value compared to substitutive fluids.

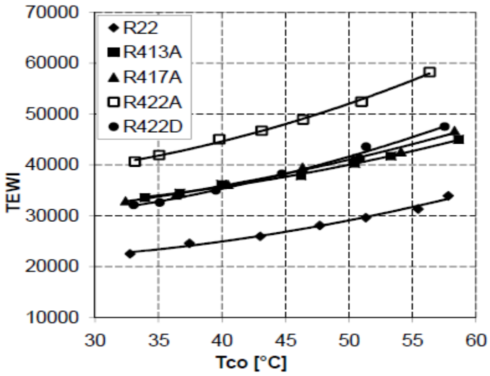

Figure-8. TEWI vs. condensation temperature.

Therefore, R22 allow for lower quantity of CO_2 to be released while the plant is running. Tables 5 and 6 show the TEWI values and the relative percentage variations compared to R22, evaluated maintaining the condensation temperature at 35°C and 55°C; this is acceptable for areas with mild climates during winter and summer periods.

Table-4. TEWI changes of the various fluids compared to R22 for a condensation temperature equal to 35°C.

Fluid	TEWI	Percentage of change
R22	23,409	0.00
R413A	34,008	45.28
R417A	33,802	44.40
R422A	41,847	78.77
R422D	32,824	40.22

DISCUSSIONS

The replacement of R22 by the HFC fluid mixtures analyzed in this work for an existing vapour-compression plant is a viable option due to low cost, compatibility with lubricant and components; a further advantage is the lower the final compression measured when using HFC fluid mixtures.

Table-5. TEWI changes of the various fluids compared to R22 for a condensation temperature equal to 55°C.

Fluid	TEWI	Percentage of change
R22	31,729	0.00
R413A	42,734	34.68
R417A	44,101	38.99
R422A	56,624	78.46
R422D	45,451	43.25

However, the energy efficiency of the plant has at least to be kept at the values achieved with R22 if not improved; otherwise, its operation would result in an increase in the plant’s running costs, due to lower energy efficiency. This leads to serious consequence on the environment which is unacceptable even as a temporary solution, and in contradiction with the greenhouse gasses reduction which the European Union aims to achieve.

Attention has to be paid to the choice of a replacement fluids that is compatible with the environment (natural or synthetic) and able to ensure a maximum energy efficiency and the lowest possible environmental impact.

When choosing the refrigerating plant, the environmental effects during the entire life-cycle should be taken into account; the optimal choice from the energy-environment point of view should be based on TEWI. Factors to be taken into account when selecting new solutions are:

- The GWP of the fluid in use;
- The quantity if energy demanded in the plant during its life-cycle;
- Production mode of the primary energy required for the plant, with the aim of determining the quantity of CO_2 released into the environment during the life-cycle of the plant;
- The quantity of fluid in use released by the plant during its life-cycle;
- Analysis of the energy required, necessary for the manufacturing of the plant, in relation to the choice of planning design.

An approach that takes into account the aforementioned elements makes it possible to make a choice oriented to the energetic optimization and the protection of the environment.

It is necessary to find alternative solution for existing plant working with R22 that have good performances, low environmental impact, safety of use and low costs.

CONCLUSIONS

Replacing HCFCs and especially R22 in functioning systems is a topical problem since it has been banned by the Regulation CE-1005/2009. Retrofitting is often not a simple task as it involves the replacement of the lubricating oils, the thermostatic expansion valve and other accessories.

Experiments were performed on R22, as reference fluid, and the alternative fluids on a vapour-compression system equipped to monitor temperature, pressure and the mass load of the refrigerants. The alternative fluids (R413, R417A, R422A and R422D) tested in this investigation can easily replace R22 without having to change the lubricant and the accessories. This makes replacement a particularly simple operation that can be carried out without any special technical equipment and at a very low cost.

Substituting the R22 proved to be detrimental since the different replacement fluids give a less satisfactory rendering due the system being sized for the given original fluid. The COP experimental measurements show that replacement fluids underperformed showing inferior energy efficiency which leads to higher consumption of energy that would be reflected in greater environmental impact.

Safe and reliable working conditions for the refrigerating plant can be achieved when using the alternative fluids as indicated by the lower values of the temperature at the end of compression and for the polytrophic exponent.

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