CONTRIBUTIONS REGARDING THE USE OF CO_2 REFRIGERANT IN HEAT PUMPS

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Abstract: *The restrictions imposed to refrigerants as a result of the negative impact on environment have brought the natural refrigerants to the forefront. Among these agents the carbon dioxide CO_2 (R744) distinguishes itself. The paper brings into light the main properties of carbon dioxide used within the heat pumps, and the improving technologies of energetic performances, analyzing, on the basis of some simulations, the influence of some parameters on the improvement of energetic performances of heat pumps in a compression phase using CO_2 as refrigerant.*

Key words: *carbon dioxide, heat pump, gas cooler, performance.*

1. Introduction

All along the last decades, the scientific investigations in the field of refrigerating plants, of heat pumps and of air conditioning installations have led to restrictions concerning the use of refrigerants, as a result of their negative impact on the ozone layer and climatic changes.

In view of protecting the ozone layer and reducing the negative impact of greenhouse gases (carbon dioxide - CO_2, methane - CH_4, nitrous oxide - N_2O, hydrofluorocarbons – HFCs, perfluorocarbons – PFCs and sulphur hexafluoride - SF_6) [13] upon the environment, in conformity with the Montreal Protocol (1987) and of Kyoto Protocol, a series of measures have been imposed for stopping the production and use of chlorofluorocarbons (CFCs) and then of hydrochlorofluorocarbons (HCFCs) and their replacing with hydrofluorocarbons (HFCs), characterized by a minimum impact upon the ozone layer and climate substituting then with natural refrigerants. The natural refrigerants, of which the carbon dioxide is part present the lowest impact upon environment.

2. History of Carbon Dioxide

Recognized as natural refrigerant even from 1850, the carbon dioxide (CO_2) (also known as carbonic acid or carbonic anhydride) was proposed, as refrigerant, within the vapor compressed systems, patented by Alexander Twining, was later widely used especially in marine refrigeration and air conditioning. The major discoveries and contributions in the field of carbon dioxide utilization are owed to the following [3]:

- Thaddeus S.C. Lowe – obtained a patent in 1867 in order to build a refrigerating plant, and an ice machine as well as equipment for

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transporting frozen meat on board of ships;
- Carl Linde – designed a machine in 1882;
- W. Raydt – got a patent in 1884 for designing a refrigerating system of mechanically compressing vapor for producing ice;
- J. Harrison – got a patent in 1884 for making a device to produce carbon dioxide for use as refrigerant;
- Franz Windhausen – got a patent, in 1886, for designing a compressor using carbon dioxide;
- Hall – brought along technological improvements and built, in 1890, the first two stage cycle CO_2 installation.

Owing to the non-toxic and non-inflammable character (as different from NH_3 and SO_2), CO_2 got ahead and was used in installations on board of ships and buildings and after 1900 in the field of air-conditioning.

After 1930 it was gradually replaced by chlorofluorocarbons (CFCs), characterized by low pressures, high efficiency and low costs, but due to CFCs contribution to destroying the ozone layer and owing to researches initiated by Gustav Lorentzen (1989, 1993) the interest for CO_2 has revived (see fig.1).

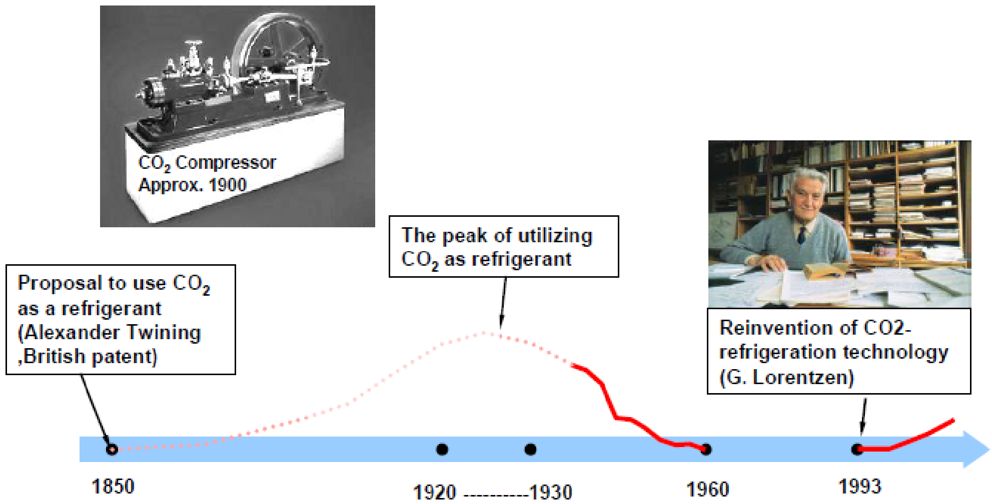

Fig. 1. *History of CO_2 using [8]*

From a global perspective (see table 1) one notices for 2020 a tendency of using natural refrigerants. CO_2, due to their remarkable properties (low impact on environment, non-toxic and non-inflammable character, the provision of high temperatures for heating agents as a result of transcritical cycle) makes it proper for usage in heat pumps and refrigerating plants in the commercial and industrial fields [9].

3. Characteristics of CO_2 As a Refrigerant

Carbon dioxide (R744) is a natural refrigerant, non-toxic and non-inflammable, characterized by zero impact on the ozone layer (Ozone depletion potential ODP=0) and an insignificant contribution to increasing greenhouse effect (Global warming potential GWP=1). The following useful properties of R744 are also considered [4]:

- Good compatibility with normal lubricants and materials used in the afferent installations;
- High refrigerating volumic capacity;
- High operating pressures;

Domains and tendencies for using refrigerants [12] Table 1

		Refrigeration										**Air Conditioning**			
Refrigerant	Region	Domestic household refrigerators		Mobile containers trucks		Light commercial		Commercial		Industrial		Air conditioning		Heat pumps	
		50… 300 W		100… 10000W		150… 5000W		>5000W		>100000 W		All		All	
		Today	2020	Today	2020	Today	2020	Today	2020	Today	2020	Today	2020	Today	2020
CO_2	Europe	N/A	N/A	Limited	Some	Limited	Some	Some	Main	Some	Main	N/A	N/A	Some	Some
	N America	N/A	N/A	Limited	Some	Limited	Some	Some	Main	Some	Main	N/A	N/A	Some	Some
	World (rest)	N/A	N/A	Limited	Some	Limited	Some	Some	Main	Some	Main	N/A	N/A	Main	Main
NH_3	Europe	N/A	N/A	N/A	N/A	N/A	N/A	Limited	Some	Main	Main	N/A	N/A	N/A	Some
	N America	N/A	N/A	N/A	N/A	N/A	N/A	Limited	Some	Main	Main	N/A	N/A	N/A	Some
	World (rest)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Main	Main	N/A	N/A	N/A	N/A
HC	Europe	Main	Main	N/A	N/A	Main	Main	Limited	Main	Limited	Some	Limited	Some	Some	Some
	N America	Limited	Some	N/A	N/A	Limited	Some	N/A	N/A	Limited	Some	N/A	N/A	N/A	N/A
	World (rest)	Main	Main	N/A	N/A	Main	Main	N/A	N/A	Limited	Some	N/A	N/A	N/A	N/A
HFC	Europe	Some	Limited	Main	Some	Main	Some	Main	Some	Some	Limited	Main	Some	Main	Some
	N America	Main	Main	Main	Main	Main	Main	Main	Main	Some	Some	Main	Main	Main	Main
	World (rest)	Some	Some	Main	Main	Main	Main	Main	Main	Some	Some	Main	Main	Main	Main

Main refrigerant; Some use; Limited use and only niche applications; Not applicable or unclear situation

- Small dimensions of components;
- Transcritical cycle operation.

Among the main characteristics of transcritic cycle are included the following: higher operating pressures as compared with the traditional cycle (30…130 bars) and the fact that the refrigerant does not condensate but isobarically cools down inside a gas cooler [2]. The temperature of R744 agent will gradually decrease as the water will get hot, preserving a constant temperature difference along the heat exchange (see fig. 2), a fact that will lead to low irreversible heat losses [7].

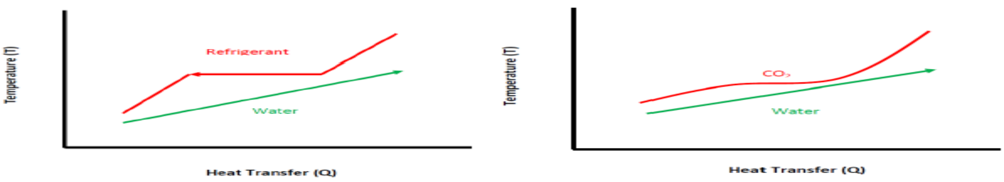

Fig. 2. *Temperature-heat diagrams for water heating [*

Refrigerant characteristics [6],[7] Table 2

Refrigerant	R-410A	R-407C	R-744
Practical examples of commercialization	Residential air-conditioning, Packaged air-conditioning, Commercial water heater	Packaged air-conditioning, Chiller, Commercial water heater	Residential water heater, Commercial water heater
ODP	0	0	0
GWP	1900	1600	1
Flammable or explosive	No	No	No
Toxicity	No	No	No
Critical temperature [°C]	72.5	86.8	31
Critical pressure [bar]	49.6	46	73.8

The main characteristics of using R744 refrigerant with heat pumps as compared with R410A and R407c are presented in table 2.

As a result of these properties the heat pumps using R744 as refrigerant are suitable to use both for heating and producing hot water at high temperatures [10].

4. CO_2 Heat Pumps. Technological Developments

In view of improving the performances of heat pumps with CO_2, the discoveries in the domain have brought afore new technologies in building compressors and heat exchangers.

By using swing compressors, which combine a vane and a roller (see fig. 3), the slips between the vane and roller are eliminated along with gas losses, thus the performances of heat pumps also increase [7].

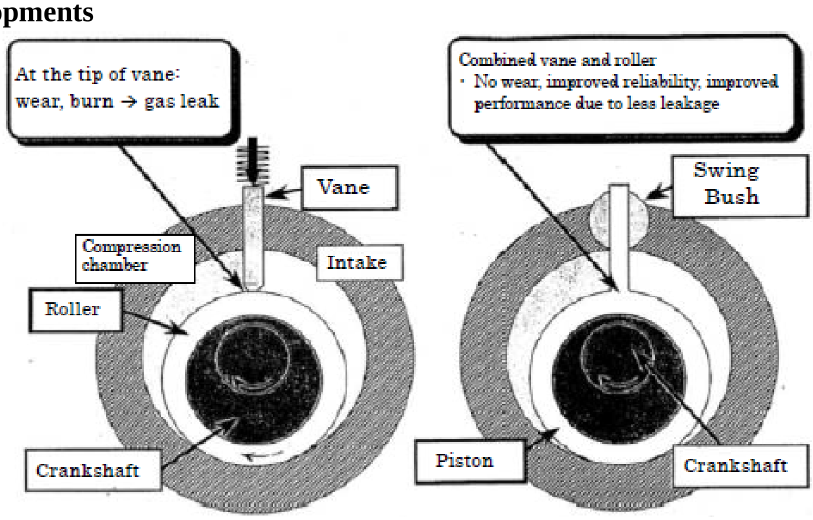

Fig. 3. *Rotary versus swing compressors* [7]

Taking into consideration that the expansion process of CO_2 brings about an improvement of heat pumps using CO_2, a special interest will be given to ways of recuperating expansion energy. Such an improvement can be obtained by coupling an expander compressor (see fig. 4). In this case the isenthalpic expansion will be replaced by an isentropic expansion bringing about expansion energy recuperation.

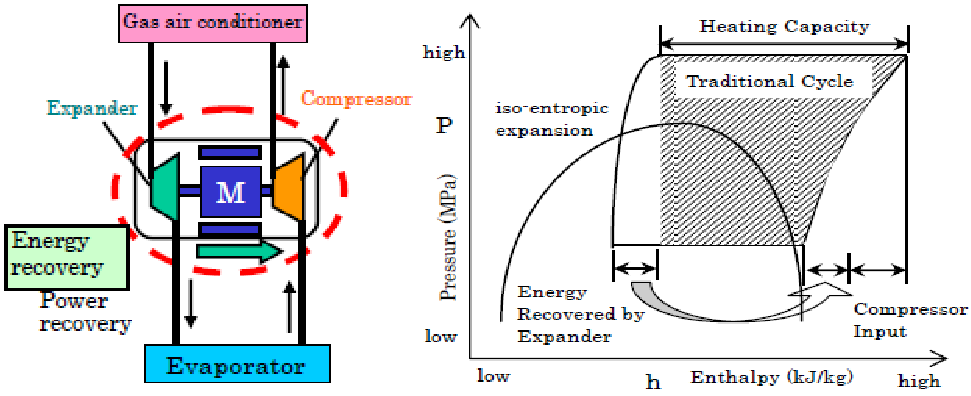

Fig. 4. *Principle of expander compressor* [7]

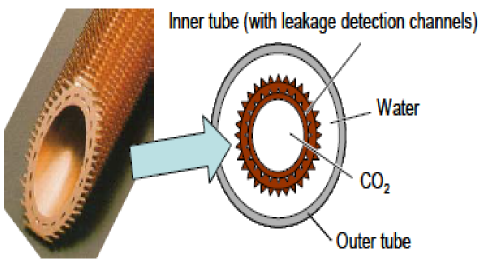

Fig. 5. *Double tube water heat exchanger* [5]

As heat exchangers are concerned, due to high pressures, instead of plate heat exchangers gas coolers, double walls heat exchangers are used, in view of preventing the mixing of CO_2 with water, in case of some CO_2 leaks (see fig. 5).

Due to its weight, high cost and the problems of reducing dimensions, new models of heat exchangers were developed (see fig. 6), with smaller dimensions and weight, eliminating the danger of leaks and CO_2 mixing with water, thus providing a better heat transfer.

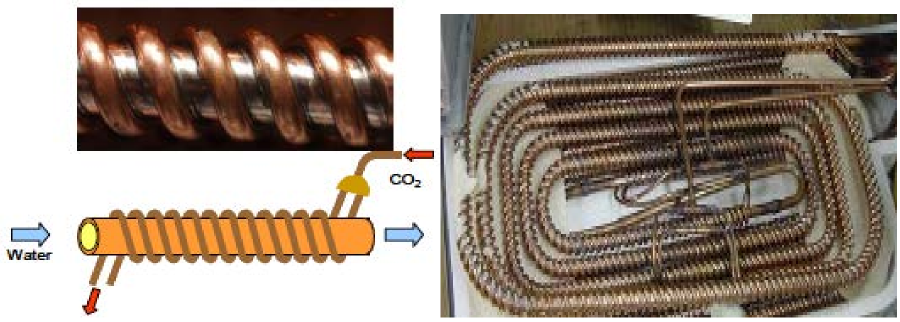

Fig. 6. *Developed heat exchanger [5]*

5. The Analysis Of Energetic Performances Of CO_2 Heat Pumps. Case Study

In view of evaluating the energetic performances of heat pumps using CO_2 as refrigerant, a case study was effected, starting from a heat pump operating with one-stage transcritical cycle with CO_2.

The analysis of transcritical thermodynamic cycle and the heat pump performance has been achieved with Cool Pack program.

The following input data have been considered:

- Heating capacity: 4.5 kW;
- Evaporator temperature: -10^{0}C, -5^{0}C, 0^{0}C, +5^{0}C, +10^{0}C;
- Gas cooler outlet temperature: 35^{0}C;
- Gas cooler pressure: 90bar, 100bar, 110bar, 120bar, 130bar.

Taking into account the fact that in the case of transcritical cycle the pressure at the level of the gas cooler does not depend only on R744 agent temperature and the heat pump can operate at various values of pressure [2] an optimum pressure has been determined.

The variation of the coefficient of performance (COP) of heat pump was presented in Figure 7 for different evaporator temperatures and different pressures at the level of the gas cooler.

In accordance to Figure one observes that the maximum values of heat pump performances correspond to an optimum pressure of 90 bars.

Also once the temperature of heat source increases the heat pumps performance also increases.

For the value of optimum pressure, in conformity with Figures 8 and 9, a variation of evaporator pressure is observed, from 26.49 bar (evaporator temperature -10^{0}C) at 45.02 bar (evaporator temperature +10^{0}C) and a temperature variation at the level of the gas cooler from 74.7^{0}C (evaporator temperature +10^{0}C) at 98.7 ^{0}C (evaporator temperature -10^{0}C).

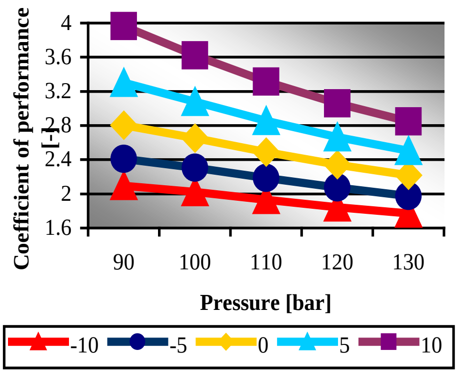

Fig. 7. *COP values for different gas cooler pressures and evaporator temperatures for a heat pump using R744 as refrigerant*

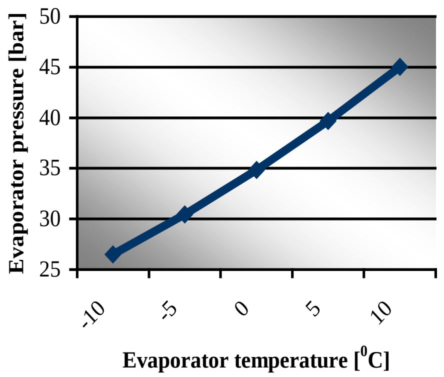

Fig. 8. *Evaporator pressure values for different evaporator temperatures*

Increasing the value of the R744 temperature within the simulation at the outcome of the gas cooler to 40^{0}C, 45^{0}C and 50^{0}C, the optimum pressure of the gas cooler will increase with the increase of temperature so: 90 bar for 35^{0}C, 100 bar for 40^{0}C, 110 bar for 45^{0}C and 130 bar for 50^{0}C.

As the coefficient of performance is concerned the best values have been obtained for the maximum value of heat source temperature (evaporator temperature +10^{0}C).

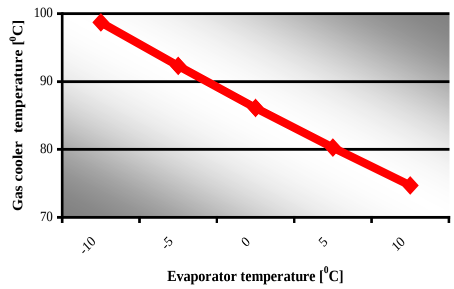

Fig. 9. *Gas cooler temperature values for different evaporator temperatures*

Analyzing the COP variation for evaporator temperature of +10^{0}C and various temperatures of R744 agent at the outlet from the gas cooler, considering the optimum pressure for each case (see fig. 10), one notices that once the temperature decreases at the outcome of the gas cooler the performance of the heat pump increases, that is the increase of temperature interval for accomplishing the heat exchange increases, too.

6. Conclusions

As a result of the exceptional properties of CO_2, the zero impact upon the ozone layer and its insignificant contribution

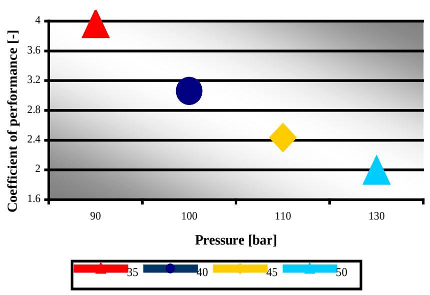

Fig. 10. *COP values for different gas cooler pressures and outlet temperatures for a heat pump using R744 as refrigerant (evaporator temperature +10*^{0}C)

to intensify the greenhouse effects, the heat pumps utilizing CO_2 as refrigerant represent performant solutions for providing heat and hot water at high temperatures in living spaces.

References

1. Anwar, Z.: *Experimental investigation of heat recovery from R744 based refrigeration system*. Master of Science Thesis Energy Technology, Stockholm, 2011.
2. Bensafi, A., Thonon, B.: *Transcritical R744 (CO_2) heat pumps*. Technician's Manual. Centre Technique des Industries Aerauliques et Thermiques. Rapport 2414173, 2007.
3. Bodinus, W.S.: *The rise and fall of carbon dioxide systems*. In: ASHRAE Journal; 1999, p. 37-42.
4. Boian, I., Chiriac, F.: *Pompe de căldură (Heat pumps)*. Bucureşti, Matrix Rom, 2013.
5. Kasai, K., Shibata, Y.: *Development of a new type heat exchanger for natural refrigerant CO2 heat pump water heaters*. In: Proceedings of Fifth International Conference on Enhanced, Compact and Ultra-Compact Heat Exchangers: Science, Engineering and Technology, USA, 2005, p. 221-225.
6. Maina, P., Huan, Z.: *A review of carbon dioxide as a refrigerant in refrigeration technology*. In: South African Journal of Science, Vol. 111, No. 9/10, 2015, p. 1-10.
7. Taira, S.: *The development of heat pump water heaters using CO_2 refrigerant*. Daikin industries.
8. Vestergaard, N.P.: *CO_2 Refrigerant for Industrial Refrigeration. Part I - Sub-critical refrigeration cycles*. Available at: http://www.phi-usa.com/Papers/ CO_2-presentation-LAM-2003-06.pdf. Accessed: 20.09.2016

9. Tofan, B.A., Serbanoiu, I., Burlacu, A., *Environmental and Financial Assessment for a CCHP District Plant in a City in Romania*, The Bulletin of the Polytechnic Institute of Jassy, Tomme LXI (LXV), Issue 4, Construction. Architecture Section, 2015, p.147-156
10. Popovici, G.C., Balan, M.C, Verdes, M., Ciocan, V., Burlacu, A., Tofan, B.A., *Integrated System for Producing, Transporting and Consuming the Unconventional Energy for a Residential Building*, Applied Mechanics & Materials, 2014, Issue 658-659, p425-430
11. *** *CoolPack software*. Available at: http://en.ipu.dk/. Accessed: 22.10.2016.
12. *** *Danfoss.Be ready for the F-gas regulation.* Available at http://files.danfoss.com/TechnicalInfo/Dila/01/DKRCC.PB.000.M1.02.pdf. Accessed: 20.09.2016.
13. *** *Kyoto Protocol.* Available at: http://unfccc.int/kyoto_protocol/items/3145.php. Accessed: 19.09.2016.