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Energy and Economic Analysis of an R744 Cooling System as a Replacement for an R404A System

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Abstract

High consumption of energy in HVACR industry need to be reduced according to intense fossil fuels usage. It is dangerous for our climate and then for our health and life quality of next generations. The main aim of the study is to compare two cooling systems with the same cooling capacity but with different working refrigerant. One of them is R404A (fluorinated gas) and another is R744 (carbon dioxide). The question is, which of the systems uses lower amount of energy and which of them has lower LCC. The 'carbon path' – CO_2 emmision is considered too. In the paper the configuration of the systems were established. The cycle with R404A is straight one stage compressor refrigeration system compare to supercritical compression refrigeration system with R744. The calculation process was done in Pack Calculation Pro software. It gives some databases with climate data which helps to find exploitation energy usage and energy cost with 'carbon path' calculations. For a system based on the use of R744 refrigerant, electricity consumption is lower than when using R404A refrigerant. Particularly large savings are generated in winter. Annual savings can be estimated at 28%. This is due to the difference in average annual EER of 1.15. Then, calculation introduced that total emission for the system with R404A is nearly 32% higher than in case of R744 supercritical compression system. The comparison done in this paper shows that supercritical compression systems with R744 is good alternative technology for those with fluorinated gases. However, some technical problems should be improved to make this technology much more efficient, cheaper and safe.

Keywords: energy efficiency, refrigerant, refrigerant replacement, f-gases

1. Introduction

The refrigeration sector is one of the most energy-intensive in Europe. It consumes about one-fifth of the energy consumed in the European Union and is responsible for about a quarter of the EU's greenhouse gas emissions in the EU [1]. In 2013, the refrigeration sector consumed about 1,100 TWh of electricity [2], equivalent to two years of electricity consumption in France [3]. The main drivers of high energy consumption in the cooling sector are inefficient technologies and the ever-increasing demand for cooling. Inefficient technologies are the main reason for the sector's high energy consumption. For example, the use of air conditioning systems that is both not correctly sized and not properly installed can result in significant energy losses.

The growing demand for cooling is also a key factor behind the high energy consumption in the cooling sector. Cooling demand is expected to increase significantly in the coming years due to population growth and the increasing use of air-conditioning systems.

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High energy consumption in the cooling sector is a serious problem, as it contributes significantly to greenhouse gas emissions and increases the EU's vulnerability to disruptions in the energy supply. To address these concerns, energy efficiency in refrigeration must be improved and shifted to low-carbon technologies.

2. Aim

This study aims to perform a techno-economic analysis of a compressor refrigeration system on R404a and R744 refrigerant, then compare the technologies used and economic and environmental impact factors.

2.1. Subject

Two refrigeration plants were analysed, both of 200 kW cooling power:

1. existing installation - refrigerant R404a;
2. a new installation - refrigerant R744;

The power corresponds to the demand of standard refrigerated warehouses for food storage and is reflected in actual conditions.

2.2. Tool

Pack Calculation Pro is a software used to calculate and compare annual energy consumption in refrigeration plants. The advantage of the program is the ability to implement modern solutions from the refrigeration sector, particularly concerning supercritical cycles based on carbon dioxide different from the currently used systems based on fluorinated refrigerants.

3. Calculation model

3.1. Meteorological data

The programme uses 8760 data points representing every hour of the year. The location selected for analysis is Warsaw. However, it is possible to freely select place from many locations around the world.

3.2. Compression refrigeration system with R404A

This is a classic and simple compression system for refrigeration with regeneration of heat placed behind the evaporator. The cooling capacity of the system is 200 kW.

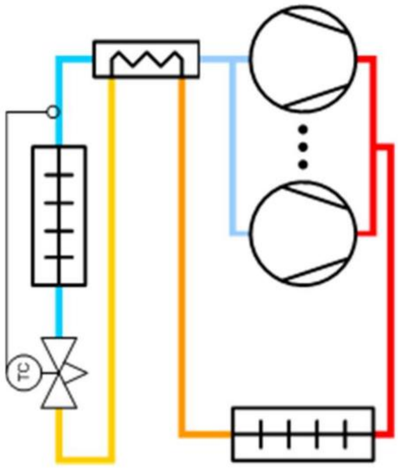

Fig. 1. Compression refrigeration system with R404A

The reference case uses 3 Bitzer 6F-40.2Y, R404A, 50Hz (CC) compressors. The total cooling power of the compressor is 211.0 kW. Design temperature conditions are specified as follows:

- evaporation temperature: - 10°C;
- condensing temperature: + 45°C (the condensation capacity is 309.7 kW)

Fig. 2. View of Bitzer compressor 6F-40.2Y, R404A, 50Hz (CC)

Due to condensation, the standard fin and tube heat exchanger was chosen for R404A refrigerant phase change. The operating temperatures of the condenser is specified, 12°C higher than ambient temperature but no less than 30°C. The subcooling is 2 K. There is no fan speed control.

3.3. Compression refrigeration system with R744

Refrigeration system with R744 (CO_2) as a working fluid differs from classic systems based on HFC refrigerants. The main difference is the use of gas cooler except classic condenser due to supercritical working temperature and pressure during summer season. In addition, one consider the use of parallel compressors for direct compression of R744 vapors coming from the liquid container.

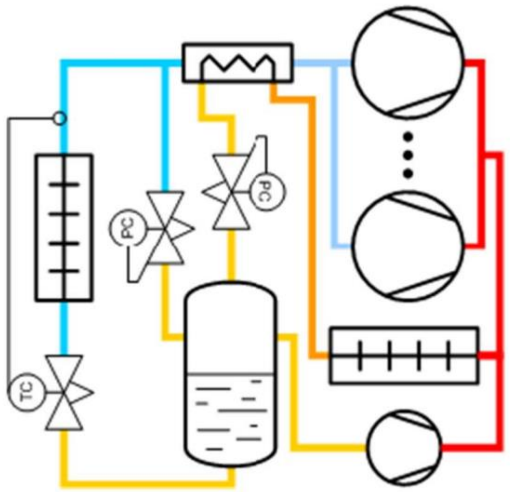

Fig. 3. Supercritical compression refrigeration system with R744

The system, based on CO_2 as a refrigerant, was equipped with four Dorrin compressors CD 4000 H, R744, 50Hz. The total cooling power of the system is 218.1 kW

- evaporation temperature: -10°C;
- condensing pressure: 95.0 bar (the condensation power is 348.6 kW)

Fig. 4. View of Dorin CD 4000H, R744, 50 Hz

4. Calculation results

4.1. Electricity consumption

Simulation results include the electricity consumed for compressor operation and fans and circulation pumps is shown in Fig. 5. and table 1.

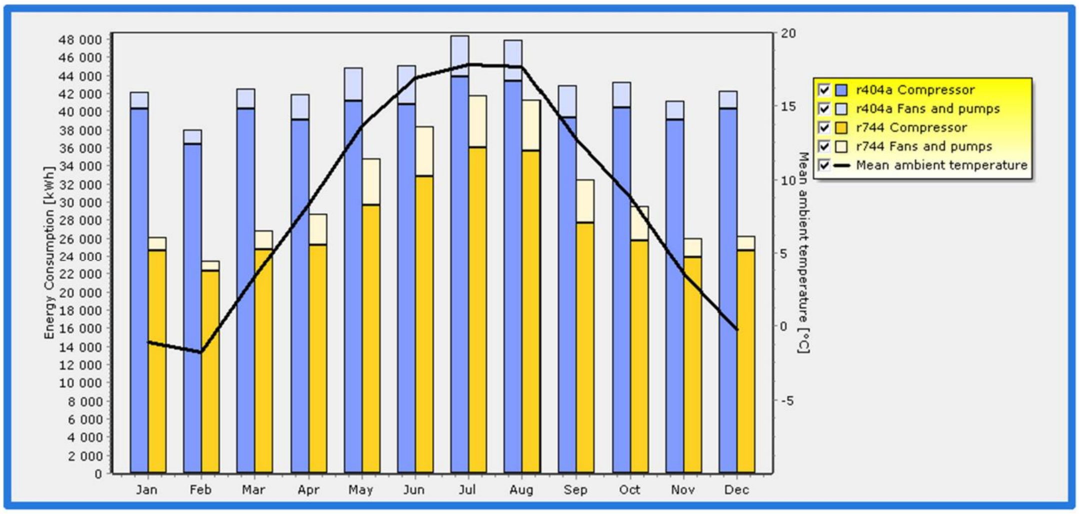

Fig. 5. Electricity consumption of analysed systems

Table 1. Values of month electricity consumption of simulated systems

Month	R404A			R744		
	Compressor [kWh]	Fans and Pumps [kWh]	Total [kWh]	Compressor [kWh]	Fans and Pumps [kWh]	Total [kWh]
January	40 307.4	1 816.9	42 124.3	24 605.1	1 433.1	26 038.2
February	36 406.7	1 584.6	37 991.3	22 223.9	1 190.7	23 414.6
March	40 307.4	2 172.7	42 480.1	24 688.8	2 092.8	26 781.6

Month	R404A			R744		
	Compressor [kWh]	Fans and Pumps [kWh]	Total [kWh]	Compressor [kWh]	Fans and Pumps [kWh]	Total [kWh]
April	39 105.4	2 749.1	41 854.5	25 193.4	3 418.6	28 612.0
May	41 114.7	3 745.2	44 859.9	29 646.4	5 111.5	34 757.9
June	40 818.7	4 290.0	45 108.7	32 814.1	5 540.4	38 354.5
July	43 832.5	4 527.5	48 359.9	36 050.9	5 730.8	41 781.7
August	43 375.5	4 527.9	47 903.4	35 584.5	5 734.6	41 319.1
September	39 311.4	3 481.1	42 792.5	27 704.0	4 741.9	32 445.9
October	40 400.3	2 861.2	43 261.5	25 769.4	3 696.1	29 465.5
November	39 007.2	2 122.0	41 129.2	23 878.0	2 080.3	25 958.3
December	40 307.4	1 887.7	42 195.1	24 609.4	1 601.0	26 210.4
Total	**484 294.6**	**35 765.8**	**520 060.3**	**332 767.9**	**42 371.8**	**375 139.7**
Monthly average	40 357.9	2 980.5	43 338.4	27 730.7	3 531.0	31 261.6

For a system based on the use of R744 refrigerant, electricity consumption is lower (Fig. 5, Tabale 1) than when using R404A refrigerant. Particularly large savings are generated in winter.

Table2. Calculation results

Results	**R404A**	**R744**
Load fulfilment		
% of time	100,0%	100,0%
% of Energy	100,0%	100,0%
EER		
Average EER	2.97	4.12
Energy consumption		
Pumps and fans [kWh]	35 766	42 372
Compressor [kWh]	484 295	332 768
Parallel comp. [kWh]	0	0

Results	**R404A**	**R744**
Total [kWh]	520 060	375 140
Savings		
Yearly energy savings [kWh]	-	144 921
Yearly energy savings [%]	-	27.9%

Comparing both cycles gives a clear picture of electricity consumption. Annual savings can be estimated at 28%. This is due to the difference in the average annual EER in level of 1.15.

4.2. Economic analysis

The investment costs of both installations were assumed in the considerations above. The estimated values were based on engineering practice related to currently constructed installations. The CAPEX factor is much higher with supercritical refrigeration. This is the result of high pressure on both the suction and discharge sides.

Tabela 3. Economic analysis results

Parameter	**R404A**	**R744**
Initial cost		
Cost of equipment [PLN]	1 440 000	1 872 000
Cost of installation [PLN]	0	0
Annual operating cost:		
Energy consumption [kWh]	520 060.34	375 139.70 (-144 921)
Cost of maintenance [PLN]	0	0
Result:		
Effective interest rate [%]	0.98	0.98
Internal rate of return [%]	-	31.35
Total annual cost [PLN]	520 060	375 140 (-144 921)
Payback time [years]	-	3,0
Total initial cost [PLN]	1 440 000 (23%)	1 872 000 (34%)
Present value of energy cost [PLN]	4 930 835 (77%)	3 556 802 (66%)
Life cycle cost [PLN]	6 370 835	5 428 802 (-942 032)

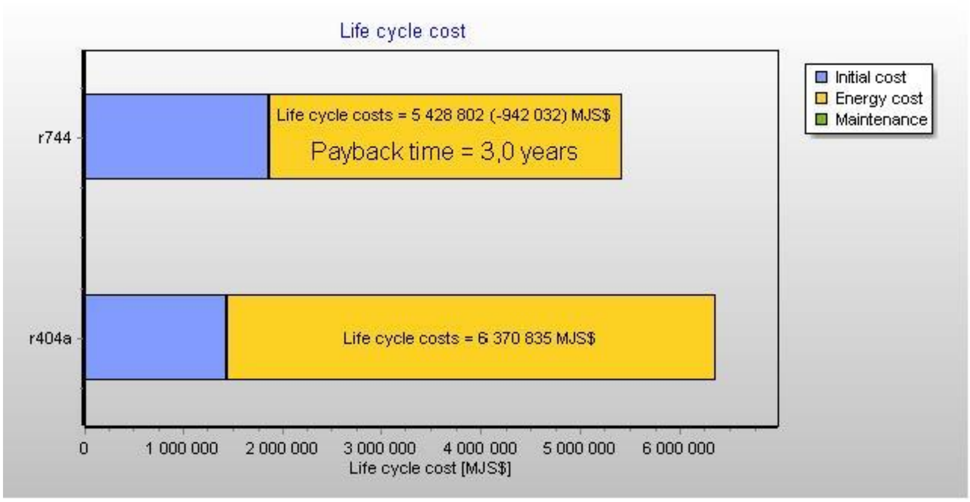

Fig. 6. Life cycle cost

The costs associated with maintaining both installations are negligible and were assumed to be at the same level. A significant difference in the life cycle of an installation can be seen due to electricity consumption.

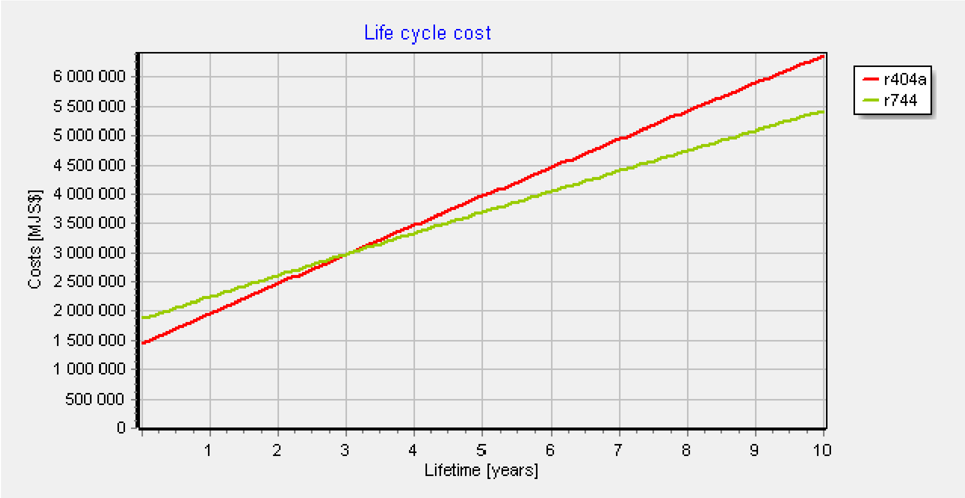

Fig. 7. Chart of costs related to the total life cycle of the installation

The price of electricity plays an important role in the economic analysis of an installation. Due to the higher efficiency of the more expensive r744 installation, each increase in electricity prices translates into a faster payback time for the installation. The economic stability of such an investment is therefore much higher.

5. Environmental conditions

One of the most important aspects when considering any modern investment is environmental friendliness. An analysis of this issue is presented in this chapter.

5.1. Comparison of refrigerants properties

R404A is an HFC refrigerant with a GWP of 3,922, which means it is a strong greenhouse gas that significantly contributes to global warming.

On the other hand, R744 is a refrigerant created from pure carbon dioxide and has a GWP of 1, making it a natural and environmentally friendly alternative to HFC refrigerants such as R404A. CO2 is non-toxic, non-flammable and easily available. However, R744 has a much higher operating pressure compared to refrigerants currently used, making it difficult to use in some applications. R744 systems also require specialized components and a different design approach compared to HFC systems.

5.2. Direct and indirect emissions

The negative impact of the installation on the environment can be divided into emissions:

- direct – loss/leakage of a toxic factor into the atmosphere and the possibility of recycling;
- indirect – emissions related to the emissions of electricity generating sources.

Table 4. Factor emission related to the total installation operation cycle

Parameter	R404A	R744
Refrigerant charge [kg]	200	250
Recycle rate [%]	60.0	60.0
Leakage rate[%/year]	5.0	5.0

The estimated filling of an installation with the same cooling capacity is higher in the case of CO_2. However, the GWP of this refrigerant is only 1 compared to 3922 for R404A.

Table 5. Shares in the total emission of subsequent components

Refrigerant	Leakage [kg CO_2]	Recycle loss [kg CO_2]	Indirect [kg CO_2]
R404A	392 200 (7.7%)	313 760 (6.1%)	4 420 513 (86.2%)
R744	125 (0.0%)	100 (0.0%)	3 188 687 (100.0%)

According to previous analyses, the share of direct emissions in the total emissions of a supercritical installation is negligible, which makes this factor highly desirable in pro-environmental solutions [7]. Compared to 13.8% for the reference system.

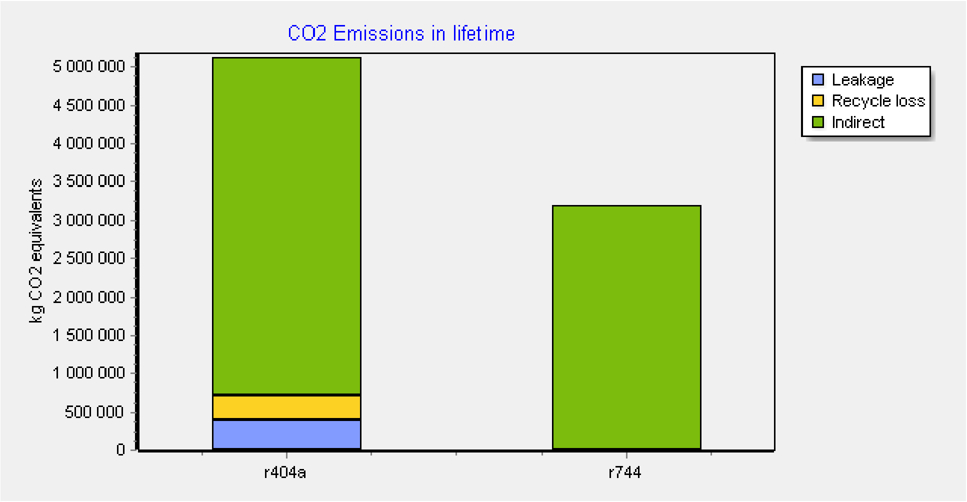

Fig. 8. Comparison of the total emissions of both refrigeration systems divided into components

Figure 8 shows a significant disproportion in the emission of carbon dioxide equivalent to the atmosphere over the analyzed 10 years of installation operation. The total emissions for the R404A system are nearly 32% higher than the opposing solution. The actual operating time of the installation may be even twice as high, which will only deepen the disproportions.

6. Conclusions

Research results show that refrigeration systems using carbon dioxide as a refrigerant are an effective alternative to traditional solutions. These systems are characterized by significantly lower energy consumption, which results in lower operating costs. However, higher investment costs related to the construction of this type of systems should be taken into account. From an environmental protection point of view, it should also be noted that systems based on R744 emit significantly less CO_2 equivalent into the atmosphere compared to systems using standard R404A. It can certainly be stated that refrigeration installations (and heating installations using heat pumps) using carbon dioxide in a supercritical cycle is a very perspective, not only in theoretical considerations. However, it should not be forget about the challenges related to the significant operating pressures of the system.

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