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Replacement of the refrigerant in a Vapor-Compression Cooling System: Case Study of the Data Center

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Abstract

Many refrigerants traditionally used in vapor-compression cooling systems are designated for their negative impact on the environment with a high Global Warming Potential and an Ozon Depletion Potential. Replacement of refrigerants faces many environmental and technical issues, including reducing the negative impact on the environment, improving the parameters of the system, and addressing the minimum requirements for the alteration of components. The case study presented in this article is focused on the analysis of the performance parameters of the vapor-compression cooling system of the information technology company Data Center and explores the benefits of replacing the current refrigerant. The installed power of the computer equipment in the server room is 48 kW and represents space with significant cooling loads throughout the year. The calculation of the theoretical cooling load of the Data Center is performed and the results show good alignment with current system parameters. Using the data collected from the current system with R410A as the refrigerant parameters, the system was assessed. To reduce the impact of the system on the environment, the R454B refrigerant is accessed as an alternative to R410A and new system parameters are calculated. The analysis showed that refrigerant replacement is technically feasible and will result in improvement of system parameters, reduction of energy consumption, and reduction of the negative environmental impact.

Keywords: Vapor-compression cooling system**;** Refrigerants; Global Warming Potential; Data Center.

1. Introduction

The refrigerants represent the working substance that circulates through components of cooling systems and heat pumps. The refrigerant absorbs heat from the cooled space or medium during evaporation at low temperature and pressure, and is released to the atmosphere at high temperature and pressure [1]. The negative effect of cooling systems on the environment is present through a double effect; leakage into the atmosphere and indirect emissions of greenhouse gases as a result of system electricity consumption [2]. The effect of refrigerants on the environment is marked via the Global Warming Potential (GWP) and the Ozon Depletion Potential (ODP), where higher values of GWP and OPD represent more harmful refrigerants. Bosnia and Herzegovina signed the provisions of the Montreal Agreement, which refer to the reduction in the use and elimination of such refrigerants. It primarily refers to chlorofluorocarbons (CFC) and hydrochlorofluorocarbons (HCFC). As an alternative, the fourth generation of synthetic cooling fluids is generated, with the main goal of reducing its GWP [3].

As a contribution to the topic, the analysis of a Data Center vapor-compression cooling system with R410A refrigerant is presented. Taking into account its high GWP, refrigerant replacement is analysed and new system parameters are evaluated, showing that system parameters can be improved and the negative effect of the cooling system on the environment can be reduced.

2. Refrigerant replacement

When selecting a refrigerant, one should primarily pay attention to its environmental impact parameters, system purpose, and type of installation. The use of the refrigerant should be optimized in the best possible way. Table 1. lists the sectors of application and the most common cooling fluids used within individual sectors as the well as most commonly used alternative refrigerants.

Refrigerant	Chemical composition	Substitution for	GWP	Application	Notation
R134a		R12, R22	1300	Household appliances	Suitable for substitutions
R404a	143a/125/134a 52/44/4	R502, R22	3260	Mobile refrigerators for frozen goods	Pseudo azeotropic
R417a	600/134a/125 3,5/50/46,5	R22	2138	Water coolers, refrigerated cabinets	Temperature sliding
R410A	32/125 50/50	R22	2088	Split systems	High pressure
R23		R13	11700	Cascade cooling devices	High GWP

Table 1. Sectors of application of refrigerants [4]

Replacement of R22 with R410A was the focus of studies in the previous period [5], but better alternatives for R410 are investigated [5]. R410A is a chemically stable non-toxic mixture of two refrigerants (50 / 50%) with a temperature slide of 0.1 ° C at atmospheric pressure. The use of R410A is most common in vapor-compression split systems. R410A does not damage the ozone layer with zero ODP; however, it has rather high GWP, therefore, it is not a best long-term solution as a replacement for R22. According to [6] the best alternatives to R410A are the R466A and R452B with a GWP lower by 22-33%. RS-53 (R470A) is a new non-flammable replacement for R410A with a low GWP of less than half that of R410A. RS-53 (R470A) has a thermodynamic performance similar to R410A with the corresponding system efficiency and cooling load. R452B results in a system cooling load of R410A, with operating pressures approximately the same, and the replacement of existing system components is minimized. The R452B and the R447B are tested, and results have shown that these two refrigerants can offer almost the same cooling characteristics as the R410A under conditions where the outside temperature is less than 35 ° C [7]. Some of the mixtures that have been proven to be good replacement fluids for R410A are R454B, R452B, R447A, R459A and HPR2A. In this article, R454B is analysed as an alternative refrigerant for the Data Center for cooling system instead of R410A.

3. Data Center cooling system case study

The characteristics of the system, the calculation of the required cooling load, and the proposed measure to replace the cooling fluid are presented.

3.1. Data Center

The Data Center contains many computer servers and supporting equipment. In addition to computer servers, which are the basis of every Data Center, some other important components are installed, namely: internet equipment, telecommunication equipment, cooling systems, UPS systems along with a fire protection system and an access control system, which makes it very modern and safe. The layout of the Data Center rooms and the cooling system is shown in Figure 1.

Architectural data include values of surface area and construction of external walls, windows, roof, ceiling toward unheated space, and interior walls towards non air-conditioned adjacent spaces. These data are used to calculate the cooling load of the Data Center. The outer wall consists of solid brick 26 cm, lime and gypsum plaster 2 cm, cement screed 10 cm, and thermal insulation installed with polystyrene plates 10 cm. Floor construction is concrete slabs made of stone aggregates with a total thickness of 21 cm, polystyrene slabs with a thickness of 1 cm for thermal insulation, and a surface layer of homogeneous PVC material with a thickness of 2 cm. The ceiling consists of 35 cm of stone aggregate concrete slabs, 2 cm of gypsum and lime gypsum plaster, 2 cm thick polystyrene slabs, and 1.5 cm thick bituminous plaster. The windows are made of PVC material with "IZO" glass, partitioned with gypsum boards from the rest of the room to minimize the penetration of light and better insulation.

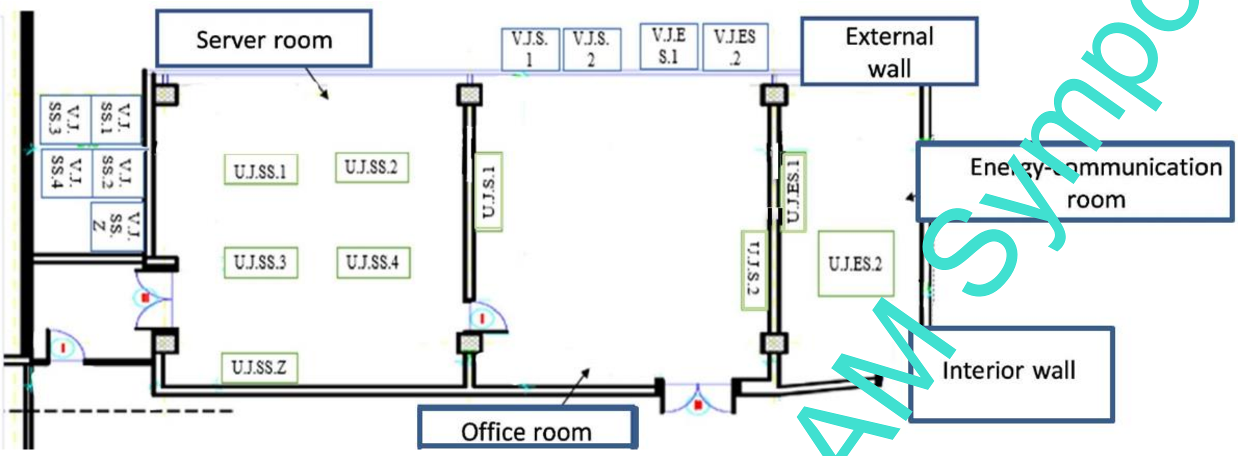

Fig. 1. Layout of the rooms and cooling system of the Data Center

The floor surface area, the volume of the room and designed room temperatures for the Data Center are shown in Table 2.

Room	Parameter	Value
Server room	Floor surface area	58,14 m^2
	Room volume	148,26 m^3
	Designed temperature	22 °C
Office room	Floor surface area	56,43 m^2
	Room volume	143,90 m^3
	Designed temperature	20 °C
Energy-communication room	Floor surface area	28,19 m^2
	Room volume	71,88 m^3
	Designed temperature	20 °C

Table 2. Architectural data of the Data Center

3.2. Analysis of the current cooling system

In Table 3 the parameters of the vapor-compression cooling system installed in the Data Center are shown.

No.	Location	Refrigerant	Marked in Figure 1
1.	Server room	R410A	U.J.SS.1
2.	Server room	R410A	U.J.SS.2
3.	Server room	R410A	U.J.SS.3
4.	Server room	R410A	U.J.SS.4
5.	Server room	R32	U.J.SS.Z
6.	Energy- communication room	R410A	U.J.ES.1
7.	Energy -communication room	R410A	U.J.ES.2
8.	Office room	R410A	U.J.S.1
9.	Office room	R410A	U.J.S.2

Table 3. Cooling equipment of the plant according to the premises

A total of five cooling units are located in the server room, four of which are currently active, and one serves as a backup unit. All five units are under-ceilinged, and each of the indoor units has its outdoor unit (marked as VJ in Fig. 1.). The active outdoor cooling units are Super Digital Inverters, connected to ceiling-type indoor units, and they use the R410A refrigerant as the working medium. The spare outdoor unit uses R32 refrigerant R32 as the working medium. In the office room, there are 2 internal cooling units that are used when needed. In the energy-communication room, 2 cooling units are installed, one of which is a wall unit, and the other is a ceiling unit (cassette).

3.3. Calculation of the theoretical cooling load

The theoretical cooling load is calculated using the IntegraCAD computer program [8], that is in line with the standard [9]. Input data are climatic data for location of Data Center (Sarajevo), architectural data (orientation, surface area and construction of external walls, windows, roof, ceiling towards unheated space and interior walls towards non-air-conditioned adjacent spaces) and designed temperatures. Climatic data is integrated in the computer program. The maximum calculated cooling load for cooled spaces is shown in Table 4.

Room	**Theoretical cooling load Q_c [W]**
Server room	43.825
Meeting room	3.446
Energy-communication room	22.812

Table 4. Calculated cooling load

From Table 4.3, it can be seen that the total cooling effect according to the current loads for the server room is 43,8 kW, and for the complete Data Center it is 70,08 kW.

3.4. Analysis of the selected cooling unit system

The detailed analysis of the performance characteristics of the vapor-compression cooling unit with R410A refrigerant is presented. The installed units have the configuration of a cooling system as shown in Figure 2, with an evaporator, two compressors, a condenser, two expansion valves, a flash chamber (steam separator) and a direct contact heat exchanger. The evaporator unit is installed inside the cooled space, and other components are installed outside (noted in Figure 1. as VJ). Due to the mode of operation, there is no additional overheating of the saturated steam and subcooling of the condensate, as can be noticed in Figure 2, showing the logp-h diagram of the cooling process.

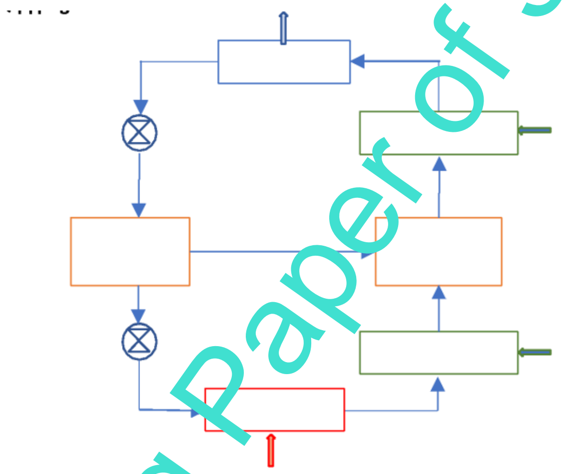

Fig. 2. Schematic representation of the cooling system

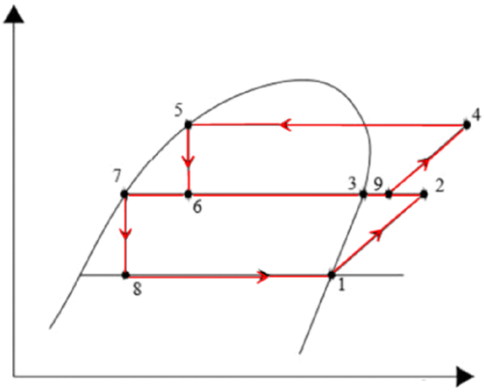

Fig. 3. Log *p-h* diagram of the cooling process

Using the logph diagram of R410A, the process parameters with associated temperatures, pressures, and enthalpies are determined for each state, as shown in Table 5.

System state	Temperature, [K]	Pressure, [bar]	Enthalpy, [kJ/kg]
1	285	11,42	424
2_i	305	16,97	434,7
2	307	16,97	436
3	299	16,97	426,4
4_i	329	25,21	446,9
4	330	25,21	448,8
5	315	25,21	268,9
6	299	16,97	268,9
7	299	16,97	241,2
8	285	11,42	241,2
9	307	16,97	434,6

Table 5. State points of the cooling process with R410A

The actual compression that takes place in the compressor is not isentropic but polytropic, which results in an additional increase in temperature of the vapor at the compressor outlet. As an example, in order to determine the parameters of actual state 2, opposed to ideal state (noted as 2i in Table 5.) [10], compressor efficiency of 90 % is used. Using the following expression, with enthalpies at 1 and 2i and compressor efficiency as known values, the actual enthalpy at state point 2 can be calculated:

$$\eta = \frac{h_{2i} - h_1}{h_2 - h_1} \quad (1)$$

The mass flow through the evaporator is noted as m_{evap} and represents the mass flow circulating on the low-pressure side. The mass flow that passes through the condenser and circulates on the high-pressure side is noted by m_{cond}. Vapor flow rate from the flash chamber is noted as m_3, and following mass flow balances apply:

$$m_{evap} = m_7 = m_8 = m_1 = m_2 \quad (2)$$

$$m_{cond} = m_9 = m_4 = m_5 = m_6 \quad (3)$$

The mass rate balance for direct contact heat exchanger encounters the mixing of the vapor mass flow from evaporator and compressor 1 (m_{evap}) and the mass flow of vapor from the flash chamber (m_3) as follows:

$$m_{evap} + m_3 = m_{cond} \quad (4)$$

The mass fraction of water vapor for state 6 is x_6=0,15, so $m_3 = 0{,}15 \cdot m_{cond}$. Therefore following equation can be derived from the previous equations:

$$m_{evap} = (1 - 0{,}15) \cdot m_{cond} \quad (5)$$

To determine parameters for state 9, along with previous mass balance equations, the energy balance for direct contact heat exchanger is set as:

$$m_{cond} h_9 = m_{evap} h_2 + m_3 h_3 \quad (6)$$

where:
m is mass flow rate [kg/s]
h is enthalpy [kJ/kg].

The specific cooling load (specific cooling load of the evaporator) is the following:

$$q_{evap} = \frac{m_{evap} \cdot (h_1 - h_8)}{m_{cond}} = (1 - x_6) \cdot (h_1 - h_8) = 155{,}4\ [kJ/kg] \quad (7)$$

The specific compressor power is calculated as:

$$w_{tot} = w_1 + w_2 = (1 - x_6)(h_2 - h_1) + (h_4 - h_9) = 24{,}4\ [kJ/kg] \tag{8}$$

Specific heat transferred to the environment through the condenser is calculated as:

$$q_{cond} = h_4 - h_5 = q_{evap} + w_{tot} = 179{,}9\ [kJ/kg] \tag{9}$$

For a theoretical cooling load per one cooling unit of 10,96 kW, particular mass flow rates can be calculated, and the total compressor power is 1,72 kW. Using the calculated data, the Energy Efficiency Ratio (EER) is calculated as:

$$EER = \frac{q_i}{w_u} = 6{,}36 \tag{10}$$

4. Refrigerant replacement

The refrigerant currently used is R410A. It is a mixture of refrigerants R125/R32 (50%/50%) with a negligible slip temperature of 0,1 °C at atmospheric pressure. The R454B refrigerant was selected as a refrigerant suitable for replacement of R410A. R454B has a 78 % lower GWP compared to R410A (Table 6). The most important parameters of both refrigerants are presented in Table 6.

Parameter	**R410A**	**R454B**
Composition (%)	R32/R125 (50/50 %)	R32/R1234yf (67/7/26 %)
Molecular mass (kg/kmol)	72,6	62,6
Critical temperature (°C)	70,17	78,1
Critical pressure (bar)	47,7	52,67
Boiling point at atmospheric pressure (°C)	-51,[illegible]	-50
Slip temperature	0,1	1,5
ODP	0	0
GWP	**2088**	**467**
ASHRAE Classification Group	A1	A2L

Table 6. Refrigerant parameters R410A and R454B [11]

To compare the system parameters using the two refrigerants, it is necessary to calculate the system parameters with the same input data and methodology as presented in the previous chapter and using the log*p*-*h* diagram of refrigerant R454B. The temperatures of the cooled space, the ambient temperatures and the required cooling load are adopted as input data. R454B is characterized by a sliding temperature of 1,5 K. Therefore, the evaporation and condensing temperatures are adopted as a mean temperature value. The input data are: evaporation temperature: $T_{evap} = 285\ K$, condensation temperature: $T_{cond} = 315\ K$, evaporation pressure: $p_{evap} = 10{,}8\ bar$, condensation pressure: $p_{cond} = 23{,}64\ bar$ and compressor efficiency $\eta = 0{,}9$. All relevant system parameters for both refrigerants are shown in Table 7.

Refrigerant	**GWP**	$\frac{p_{cond}}{p_{evap}}$	q_{evap} $[kJ/kg]$	w_{tot} $[kJ/kg]$	q_{cond} $[kJ/kg]$	**t_4 [°C]**
R410A	2088	1,486	155,4	24,4	179,9	56,85
R454B	467	1,477	192,1	23,2	215,4	57,85

Table 7. Comparison of cooling fluids

The pressure ratio for the R454B, compared to the R410A system, changed by a very small percentage (0,6 %). The temperature in the second compressor did not increase significantly. Specific cooling capacity increased, and as a result, mass flow rate decreased, which is beneficial to the environment [12], [13]. The total specific work of the compressor for the R454B refrigerant system decreased by 4,78%. The cooling loads for both refrigerants are the same, but the R454B system has a smaller compressor power, as shown in Table 8. Taking into account that four cooling units in the Data Center server room are installed, with additional four units in other spaces, all with substantial annual working hours, replacement of the refrigerant will ensure the decrease of the electrical energy consumption by 23,5 %. EER for the R454B, for same cooling load is higher than for R410A, indicating better performance.

Refrigerant	Cooling load [kW]	Compressor power [kW]	EER
R410A	10,96	1,91	6,63
R454B	10,96	1,46	8,27

Table 8. The cooling load on the evaporator, compressor power, and EER for both refrigerants

From the analysis presented, it can be concluded that refrigerant R454B offers better working parameters than R410A, with a substantial reduction in GWP factor and a smaller negative influence on the environment without any system modification.

5. Conclusions

Many refrigerants used in vapor-compression cooling systems induce negative impact on the environment due to their high GWP and an ODP. Data from the case study are used to present the environmental benefits and improvement of system parameters resulting from refrigerant replacement. For the case study, an analysis of the cooling system of Data Center is presented with significantly high cooling loads imposed from installed electronic devices. Computer equipment with a power of 48 kW is installed in the Server Room of the Data Center, which is in operation 24 hours a day throughout the year.

A thermodynamic calculation and analysis of the cooling system of the Data Center were presented for the currently used refrigerant R410A. Although it has been used for a long time as a replacement for R22, R410A, with a GWP factor of 2.088, induces a significant negative impact on the environment. Therefore, replacement of R410A with a refrigerant with significantly lower GWP, R545B, is analysed. System parameters are compared for R410A and the R545B and results have shown that R545B offers better system parameters, lower compressor power, lower refrigerant mass flow rates, and higher EER. The analysis showed that the replacement of the refrigerant is technically feasible, and it will result in improved system parameters, reduction of energy consumption, and reduction of negative environmental impact of the system.

Further research will include the analysis of system parameters for other refrigerants to find the optimal solution. Also, installation of central cooling system should be explored, with local and central regulation. This will be investigated as an option to ensure the further reduction of system energy consumption.

6. References

[1] B. Y. J. M. Calm and G. C. Hourahan. (2001). “Refrigerant data summary,” Eng. Syst., vol. 18. No. 11, pp. 74-88
[2] J. M. Calm. (2002). “Emissions and environmental impacts from air-conditioning and refrigeration systems,” Int. J. Refrig., vol. 25, no. 3, pp. 293–305, doi: 10.1016/S0140-7007(01)00067-6
[3] Risto Ciconkov. (2018). “Refrigerants: There is still no vision for sustainable solutions,” Int. J. Refrig., vol. 86, pp. 441–448
[4] A. Sočev. (2009). “Diploma thesis; Novelty in the field of cooling technique” University of Zagreb, Croatia
[5] D. E. Mitu and F. S. Memet. (2011). “Considerations on adopting R 404A instead of R22 on reefers,” Ann. DAAAM Proc. Int. DAAAM Symp., vol. 22, no. 1, pp. 661–662, doi: 10.2507/22nd.daaam.proceedings.324
[6] A. G. Devecioğlu. (2017). “Seasonal performance assessment of refrigerants with low GWP as substitutes for R410A in heat pump air conditioning devices,” Appl. Therm. Eng., vol. 125, pp. 401–411
[7] Sethi and S. F. Y. Motta. (2016). “Low GWP Refrigerants for Air-conditioning and Chiller Applications,” Int. Compress. Eng. Refrig. Air Cond. High Perform. Build. Conf., vol. 2, no. 2013, pp. 1–8
[8] Impuls ing d.o.o., “IntegraCAD.” https://integracad.com/
[9] VDI-Standard. (2015). ‘VDI 2078 - Calculation of thermal loads and room temperatures (design cooling load and annual simulation).’ B. Verlag
[10] C. L. Townsend and J. M. Varnum. (1986). Fundamentals of engineering thermodynamics. John Wiley & Sons, Inc.
[11] B. Shen and M. R. Ally. (2021). “Comparative performance of low global warming potential (Gwp) refrigerants as replacement for r-410a in a regular 2-speed heat pump for sustainable cooling,” Sustain., vol. 13, no. 15, doi: 10.3390/su13158199
[12] C. Guzzardi, M. Azzolin, and S. Lazzarato. (2021). “Effect Of the Refrigerant Charge On The System Performance And Mass Distribution In Air-To-Water Heat Pumps and mass distribution in air-to-water systems,”
[13] M. Rusko, I. Pavlova, J. Vanova, and R. Kralikova. (2017). “Connectivity of quality management systems and environmental management systems,” Ann. DAAAM Proc. Int. DAAAM Symp., pp. 1213–1220, doi: 10.2507/28th.daaam.proceedings.169