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Theoretical aspects regarding energy efficiency in foods refrigeration and freezing

Aspecte teoretice privind eficienta energetica in refrigerarea si congelarea alimentelor

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Abstract

This paper presents a technical study on energy consumption and performance of a refrigeration system used for food products refrigeration and congelation. The authors compared the two-stage refrigeration system with the cascade refrigeration system. The analysis was based on the thermodynamic cycles corresponding to each one of the proposed solutions. For the booster system several refrigerants were considered in the analysis for the upper loop, respectively R717, R404A, R407C and R417A. Based on the total energy consumption of the installation (compressor, fans, recirculation pumps), the overall performance coefficient of the installation was determined. The study showed that the lowest electrical energy consumption corresponds to the cascade refrigeration system with R717-R744 and the two-stage compression refrigeration system with R717. The difference between the 2 optimal variants is only 4.6%. Therefore, it is recommended that the choice of the final scheme to be made on the basis of an LCC (Life cycle cost) analyze, which takes into account the refrigerant charge, the initial investment cost, the operating costs and the electricity cost.

Keywords: ammonia, carbon dioxide, power consumption, coefficient of performance

1. Introduction

Refrigeration systems with mechanical vapor compression having two compression stages and two vaporization temperatures are used in food products freezing and refrigeration processes. The main reasons for adopting the refrigeration system mentioned above are related to energy savings, due to the decrease in the discharge temperature of refrigerant vapors and the possibility of using cold, at the temperature level corresponding to the open intercooler. The refrigerant used in refrigeration installations with mechanical vapor compression, with two stages and two vaporization temperatures can be ammonia or a type of freon. Refrigeration installations generate, during their operation, CO_2 emissions due to refrigerant leaks in the atmosphere attributed to equipment performance (direct emissions), but also mainly due to their energy consumption (indirect emissions). Thus, they contribute significantly to both direct and indirect greenhouse gas emissions. Greenhouse gas emissions can occur directly through the leakage of refrigerants with a high global warming potential (GWP), which can account for up to 30% of the system load per year [1]. Therefore, there is a global concern about the use of refrigeration equipment with high energy efficiency as well as with lower GWP, which could halve the CO_2 emissions [2].

Choosing one appropriate refrigerant for a particular application, which must comply with regulatory policies to reduce greenhouse gas emissions, seems quite a challenge. When considering refrigerant alternatives for future decision makers, the public and manufacturers must select refrigerants with the best balance between:

- Safety for consumers and service technicians (flammability, toxicity and high pressure)
- Reducing CO_2 emissions by increasing the equipment energy efficiency
- Environmental concerns about reducing ozone depleting potential (ODP).

Indirect emissions are also significant, as these systems are large consumers of electricity and are reported to consume about 4 $MtCO_2e$ per year, where CO_2e is the equivalent of carbon dioxide [3]. In recent years, natural refrigerants have been proposed as an environmentally friendly solution for the refrigeration industry, due to the inevitable future elimination of HFCs [4]. Refrigerants like ammonia, hydrocarbons, carbon dioxide (R744) do not contribute to ozone depletion and have a low impact on global warming (low GWP), so they offer a long-term solution, suitable for refrigeration/ freezing applications [5].

2. Methodology

The technical economic study was carried out for a refrigeration installation, which provides the refrigeration load of 100kW and the freezing load of 75 kW. The vaporization temperature for refrigeration is -15°C respectively -40°C for freezing.
For the cascade type refrigeration system the following pairs of refrigerants were evaluated: CO_2 - NH_3; CO_2 - R404A; CO_2 - R407C; CO_2 - R417A. The scheme of the cascade refrigeration plant is presented in Figure 1.

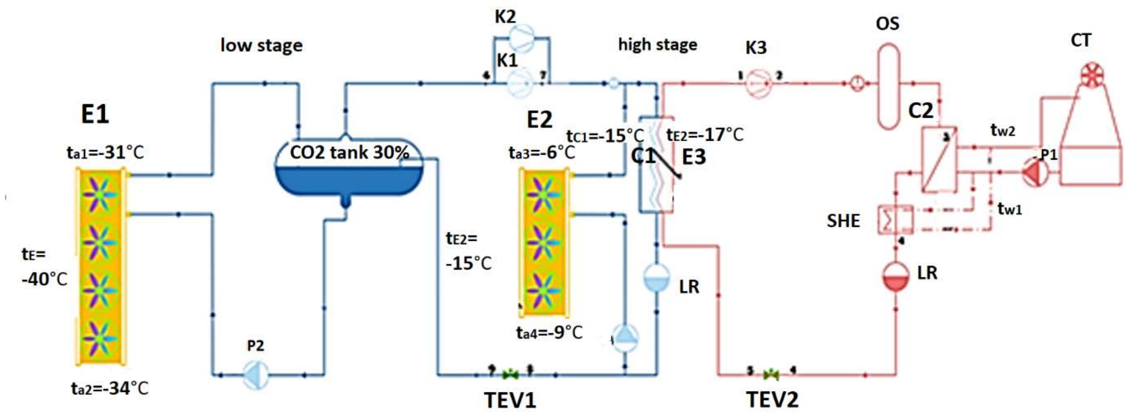


Figure 1. Cascade refrigeration installation, with two vaporization temperatures

The second option consists in a mechanical vapor compression plant having two compression stages, an intermediate open intercooler and working with two vaporization temperatures. The corresponding scheme is presented in Figure 2 [6].

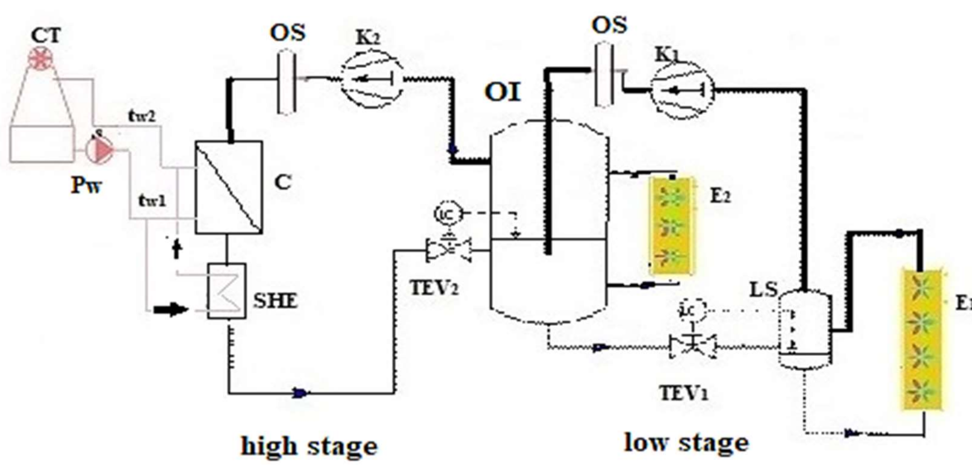


Figure 2. Refrigeration plant in two stages, with open intercooler and two vaporization temperatures

Thermodynamic cycles were plotted for each pair of agents: R744 - R717; R744 - R404A / R407C / R417A according to the input data from Table 1, using the Coolpak program [7].

Tabel 1. Input data for cascade refrigeration system

Refrigerant pair	R744-R717	R744 – R404A/ R407C/ R417A
tc [°C]	30	42
t_{01} [°C]	-40	-40
t_{02} [°C]	-15	-17
Overheating in the evaporator [°C]	-	5
Overheating in the internal heat exchanger [°C]	-	12

Condenser subcooling [°C]	5	5
Isentropic efficiency [-]	0.7	0.7
$\Phi_{01\ low\ stage,}$ [kW]	75	
$\Phi_{02CO2\ high\ stage}$ [kW]	100	
$\Phi_{03condenser/evaporator}$[kW]	**186.15**	

Thermal load of the low stage condenser / high stage evaporator ($\Phi_{03condenser/evaporator}$) was determined from the following equations:

$$\Phi_{01CO2low\ stage} = 75\ kW = \dot{m}_1 \cdot (h_1 - h_4) \ \Rightarrow \ \dot{m}_1\ at\ t_0 = -40°\text{C} \quad (1)$$

$$\Phi_{02CO2low\ stage} = 100\ kW = \dot{m}_2 \cdot (h_2 - h_3) \ \Rightarrow \ \dot{m}_2\ at\ t_0 = -15°\text{C} \quad (2)$$

$$\Phi_{03condenser/evaporator} = \Phi_{c1} = \Phi_{02CO2low\ stage} + \dot{m}_1 \cdot (h_2 - h_3) \quad (3)$$

Based on the thermodynamic cycles, the electrical energy consumption for compressor operation was calculated, as well as the performance coefficient of the installation, in each constructive variant: cascade with two refrigerants and with two compression stages with two vaporization temperatures. For an extended analysis, in addition to the electricity consumption necessary to operate the compressor other types of consumers should be taken into account:
- fans from air-cooled condensers;
- fans from air cooling batteries (evaporators);
- fans from the cooling tower (in the case of the ammonia condenser);
- the liquid refrigerant circulation pumps of the coolant in the cooling tower circuit.

The equipment and components of the refrigeration systems were chosen based on the thermal loads required by the evaporators and condensers, in each constructive variant while the electrical energy consumption was extracted from the technical sheets. The total energy consumption resulted by summing up all the consumptions related to the equipment components of the respective refrigeration installation. The overall efficiency of the refrigeration system was determined as the ratio between the total refrigeration power (refrigeration circuit + freezing circuit) and the total electrical power.

3. Results

3.1. Booster system

The comparative analysis was performed in terms of electrical energy consumption, performance coefficient, effect on the environment (ozone depletion - ODP and global warming - GWP). The values of the parameters and quantities characteristic of the thermodynamic cycles, when operating in the cascade variant, as well as the values of the calculated quantities are included in Table 2.

Table 2. Parameters and quantities for the cascade refrigeration system

Refrigerant / Parameter	R744	R717	R417A	R407C	R404A
t_0 [˚C]	-40	-17	-17	-17	-17
p_0[bar]	10	2.17	2.15	2.65	3.36
tc [˚C]	-15	30	42	42	42
p_c [bar]	22.9	11.67	14.21	17.32	19.04
Compression ratio low stage [-]	2.29	-	-	-	-
Compression ratio high stage [-]	-	5.37	6.61	6.54	5.67
v_{asp} [m^3/kg]	0.0381	0.5507	0.0928	0.0887	0.0631
V_{asp} [m^3/h]	37	329.1	495.1	389.9	365.1
q_0 [kJ/kg]	269.4	1124.7	125.6	152.5	115.87
q_C [kJ/kg]	319.09	1451.3	181.75	220.18	169.94
l_k [kJ/kg]	49.67	350.14	56.12	67.66	54.06
$\dot{m}_{AF}$ [kg/s]	0.270	0.166	1.482	1.221	1.607
Φ_0 [kW]	75	186.15	186.15	186.15	186.15
Φ_C[kW]	186.15	240.22	269.30	268.75	273.02
ODP [-]	0	0	0	0	0
GWP [-]*	1	0	2117	1624	3943

**According to AR5 values [8]*

By analyzing the data presented in Table 1, it can be noticed that the highest values for condensing pressure in the high stage corresponds to R404A. This aspect leads to the conclusion that the energy consumption on this circuit will have the highest value, fact sustained by the calculated mechanical work. Regarding the refrigerant mass flow it can be observed that it has the highest value for the high stage circuit when operating with R404A. The high flow rates in circulation determine large dimensions of the component equipment and increased emissions in the case of damages. The volume flow rate aspirated by the compressor on the high stage circuit, with implications of the compressor size, has the highest value for R417A. The pressure of the low stage for R744 is higher than atmospheric pressure, respectively 10 bar. So is no chance to entry of air from low side leakage and the operating problems are related.

The electrical energy consumption of the R744 - R717 / R417A / R407C / R404A cascade system is included in Tables 3, 4 and 5.

Table 3. Electric power consumption on the R744 circuit (low stage)

Refrigeration circuit	Evaporator fan (Model: SOLO80 384F 3 x Ø 800 / 6PH) [kW]	3.6
	Liquid CO_2 pump, [kW]	0.054
Congelation circuit	Evaporator fan (Model: SOLO60 484E 4 x Ø 630 / 4PH) [kW]	3.2
	Liquid CO_2 pump [kW]	0.074

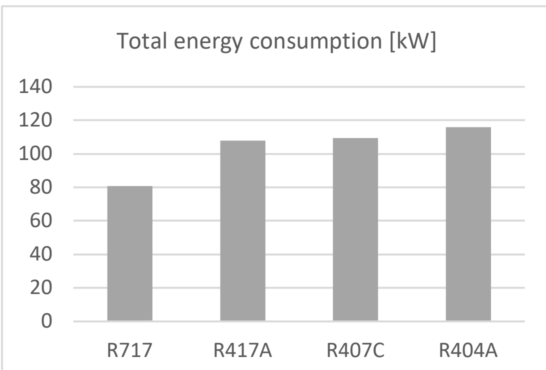
Table 4. Electric power consumption on the R717 circuit (High Stage)

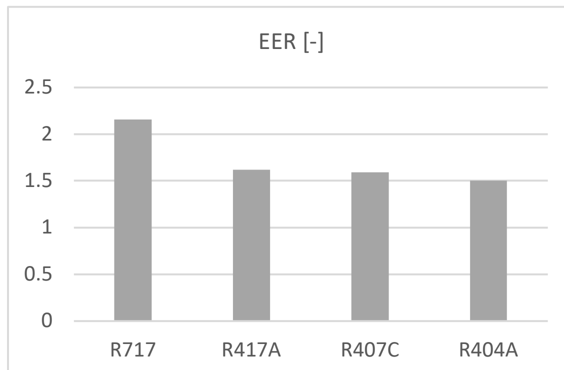
Water-cooled condenser and cooling tower, [kW]	Fans	2.2
	Recirculating pump condenser-cooling tower (m_{rec}=11m^3/h)	0.254
Compressor, [kW]		57.95

Table 5. Electric power consumption on R417A / R407C / R404A circuit (High Stage)

	R417A	R407C	R404A
Compressor, [kW]	83.15	82.58	86.85
Fans – air-cooled condenser, [kW]	4.4	6.6	8.8

From Tables 3, 4 and 5 it can be observed that the major share of energy consumption is at the compressor, regardless of the constructive system considered.





3a. 3b.

Figure 3. Total energy consumption and EER values output for different constructive solutions

From Figure 3 it can be concluded that in the case of the refrigeration installation in the cascade, with ammonia in the high stage, the lowest electrical energy consumption is registered and the performance coefficient, for the entire installation, also has the highest value. For the case of the other 3 refrigerants analyzed, the energy consumption registers increase between $33.6 \div 43.6\%$, while the global performance coefficient decreases. This is explained by the fact that the refrigeration load at the consumer remains the same and the energy consumption increases on the high stage circuit to obtain the same useful effect at the consumer.

3.2. 2-stage refrigeration system, with closed intercooler and 2 vaporization temperatures

The values of the parameters and quantities characteristic of the thermodynamic cycles as well as the calculated quantities are included in Table 6.

Table 6. Characteristic parameters for R717 and R417A systems

Refrigerant / Parameter	R717	R417A
t_{01} [˚C]	-39	-40
t_{02} [˚C]	-15	15
p_{01} [bar]	0.715	1
p_{02} [bar]	2.36	2.75
Compression ratio low stage [-]	3.3	2.75
Compression ratio high stage [-]	4.95	7.2
t_C [˚C]	30	42
p_C [bar]	11.702	20
v_{asp} [m^3/kg]	1.66	0.23
m_{LS} [kg/s]	0.068	0.38
m_{HS} [kg/s]	0.18	1.98
q_C [kJ/kg]	1442.9	150.7
$l_{k,LS}$+$lk,_{HS}$ [kJ/kg]	556.4	109.0
$P_{k,LS}$+$P_{K,HS}$ [kW]	76.77	142.69
Φ_0 [kW]	286.15	286.15
Φ_C [kW]	264.8	299.6
EER [-]	2.28	1.22
ODP [-]	0	0
GWP [-]*	0	1950

**According to AR5 values [8]*

The pressure of the low stage for R717 is lower than atmospheric pressure, respectively 0.715 bar. So is chance to entry the air from low side and is necessary to use automatic air purger with control (instrument, valve, pipes, thermal insulation) to resolve this problem of entry of non-condensable air in the system.

The R744 has a much lower vapour specific volume at low temperature (0.0381 m^3/kg) compared R717 (1.66 m^3/kg). This is approximately 44% less at a saturated vapour of -40 ˚C.

Greater vapour volume flow rate requirement for low stage means larger compressor for R717 that is required. For R744 the compressor size for low stage is drastically reduced from 406.4 m^3/h to 37m^3/h. Thus, the compressor size for R744 low stage side is smaller as compared to the low stage ammonia. The suction line size is smaller (smaller suction valve, strainer, fitting etc.) and the thermal insulation requirement will be also less.

The compression ratio required for low stage is much lower for R744; it's approximately 31% less then low stage ammonia.

Electrical energy consumption related to equipment is included in Table 7.

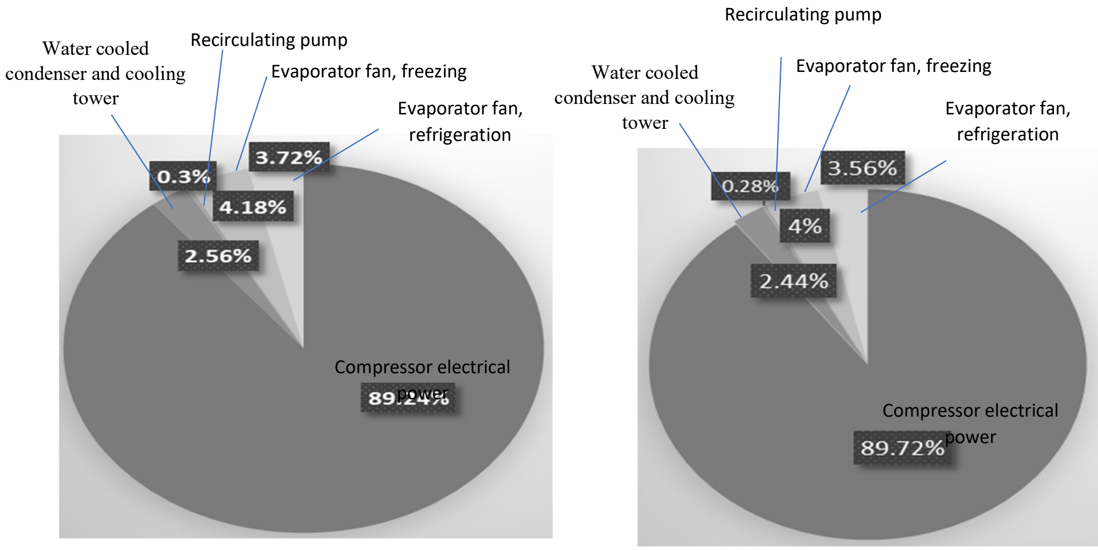
Table 7. Electrical energy consumption

Equipment type	R717	R417A
Compressor low and high stage [kW]	76.77	142.69
Water cooled condenser and cooling tower [kW]	2.2	-
Air cooled condenser fan [kW]	-	4.4
Recirculating pump condenser-cooling tower with a flow of 11m3/h [kW]	0.254	-
Evaporator fan, freezing circuit [kW]	3.6	3.6
Evaporator fan, refrigeration circuit [kW]	3.2	3.2
Total electrical energy consumption [kW]	86.024	153.88
EER [-]	2.03	1.137

From Table 6 it can be seen that the lowest electrical energy consumption corresponds to R717 for which the performance coefficient also has the highest value. By using R417A as a refrigerant, energy consumption increased by 78.9%, while the overall coefficient of performance decreased by 54%.

4. Comparative analysis

In the following, a comparative analysis will be performed between the two solutions that have the highest efficiency in each case. Thus, for the cascade cooling system, the pair of carbon dioxide - ammonia was chosen and for the installation with two refrigeration stages, ammonia was chosen as the refrigerant, which in both situations obtained the highest performances in terms of EER and the lowest electrical energy consumption.



4a. 4b.

Figure 4. Share of electrical power consumed in the refrigeration system; 4a. R717 4b. R744-R717

From Figure 4 and Table 8 it can be seen that both types of installation have a very similar electrical energy consumption with a slightly higher value in the case of the booster type system. The largest contribution to energy consumption is made by the compressor in each situation, with a percentage of about 90% of the total energy consumption.

Table 8. Parameters defining energy efficiency

Refrigerant	R717	R744-R717
Total electrical energy consumption [kW]	86.024	90
EER [-]	2.03	1.94

Adopting one of the options can be influenced not only by energy consumption but also by investment and maintenance costs.

5. Conclusions

The technical analysis performed highlights the following aspects:

- Although the desired useful effect (cooling power on refrigeration and freezing) is the same, the energy consumption is different, even in the case of the same constructive variant of refrigeration system. As the analysis of thermodynamic cycles shows, the characteristic parameters depend on the refrigerant.

- For the cascade refrigeration system, the refrigerant from the high stage, which meets the criteria regarding the lowest electrical energy consumption, the best coefficient of performance, zero ozone depletion effect, as well as zero effect on global warming, is ammonia.

- For the refrigeration system with two compression stages and two vaporization temperatures, the optimal variant from the point of view of the consumed electrical energy is the one with ammonia.

- The implementation of each one of the analyzed refrigeration systems has advantages in terms of environmental impact. Refrigerants are natural, without the potential to destroy the ozone layer and with minimal impact on global warming.

- the shaft power at compressors (low stage + high stage) represents about 90% from total value of electrical consumption. The fans and pumps give a smaller value, respectively about 10%.

- The difference regarding the electrical energy consumption between the 2 optimal variants is small, around 4.6%. Therefore, it is recommended that the choice of the final variant to be made on the basis of an LCC (Life cycle cost) analyze, which takes into account the refrigerant charging, the initial investment cost, the operating costs and the electricity cost. CO2 is approximately 37% cheaper than ammonia. Thus, there will be additional benefit in future cost saving.

Nomenclature

l – specific mechanical power consumption by compressor [kJ/kg]	t – temperature [˚C]
m – refrigerant mass flow rate [kg/s]	v – specific volume [m^3/kg]
q – specific thermal power [kJ/kg]	
Φ - thermal power [kW]	
p – pressure[bar]	
P – Compressor electrical power [kW]	

V –volume flow [m^3/h]

EER – coefficient of performance [-]

GWP – warming global potential [-]

ODP – ozon depletation potential [-]

subscripts

0 – evaporation

C – condensation

K - compressor

LS – low stage temperature or freezing

HS – high stage temperature or cooling

AF – refrigerant

suc – suction

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