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COMPARISON BETWEEN DEFROSTING METHODS USING DIFFERENT REFRIGERANTS

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In this study, the performance analysis of a refrigeration system operating with different refrigerants was conducted for three defrosting methods (air, electric heating, and hot gas) within an existing refrigeration system in the laboratory of Engineering Thermodynamics, Department of Thermotechnics, Engines, Thermal and Refrigerating Equipment, Faculty of Mechanical and Mechatronic Engineering, National University of Science and Technology POLITEHNICA Bucharest, Romania. Thermodynamic analyses were conducted on refrigerants: R290, R134a, R600a, R600, R404A, R32, R1234yf, and R1234ze(E) over a 24-hour period for refrigeration, but also for freezing. The results indicated that the air defrost method demonstrated higher defrosting efficiency for most refrigerants, except for R600 and R600a. In the case of the electric heating method, COP remained low regardless of the refrigerant used. This study observed, for instance, for refrigeration, that the refrigerant R290 has a COP value of 4.873 for air defrosting, 4.463 for resistance defrosting, and 4.815 for hot gas defrosting method. The same hierarchy of COP is observed for all analyzed refrigerants for freezing case, as example being R290 which has a COP value of 2.614 for electric heating defrosting and 2.879 for hot gas defrosting method.

Keywords: air defrost, electric heating defrost, hot gas defrost, coefficient of performance, refrigeration, freezing

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1. Introduction

Vapor Compression Refrigeration Systems (VCRS) are extensive in the field of artificial cooling, constituting approximately 15% of the world's electricity consumption and contributing to around 10% of global greenhouse gas emissions. Projections indicate a tenfold increase in cooling demand by 2050, emphasizing the urgent need to enhance the efficiency of VCRS [1]. For the vapor Compression Refrigeration Systems, the frost formation that occurs on the evaporator tubes is the most detrimental and major issue [2]. The thermal resistance between the air and refrigerant is heightened by the frost layer, leading to a decline of the cooling capacity. Another reason for decrease in cooling capacity is a reduced air-side volume flow. This reduction is attributed to the decreased hydraulic diameter of the flow channel, maintaining constant fan power [3,4]. As a result, both the cooling capacity of the refrigeration system and the coefficient of performance (COP) experience a reduction [5,6].

There are active and passive methods of defrosting with and without power consumption. Several active defrost methods have been reported, such as hot gas bypass, electric heating, desiccant dehumidifier, reverse cycle, electrohydraulic, oscillation, and ultrasonic vibration [7]. In paper [8], a hot gas bypass defrost method is used to delay the formation and spread of frost for an air source heat pump. The results from [9] indicated that, compared to the electric heating method, the hot gas method was 7.15% more efficient in terms of defrosting efficiency. Moreover, the R290 refrigerant demonstrated a 5.61% higher efficiency than other refrigerants. In contrast to electric heating defrosting (EHD), hot gas defrosting (HGD) demonstrates the capability to eliminate the accumulated frost approximately 1.5 times faster. Moreover, as the evaporator undergoes internal heating, the excess heat transmitted to the display case is minimized compared to electric defrost [10]. Approximately 1% or more of the heat generated by the electric defrost heating goes into melting the frost while the remaining excess heat is transferred to the air within the display case [11].

2. Theoretical analysis

In this study, the effects of different defrosting methods (air, electric heating and hot gas) for solving the frost issue were investigated theoretically. The COP has been evaluated, using different refrigerants (R134a, R32, R404A, R1234yf, R1234ze(E), R600, R600a, R290) for two cases: refrigeration with evaporation temperature t_0=-10°C and freezing with t_0=-28°C, being mentioned that there is no air defrosting method for freezing. In Fig. 1 is illustrated the vapor compression refrigeration system existing within the laboratory of Engineering Thermodynamics. It represents the simplest refrigeration setup, employing air for defrosting. The main components include the evaporator EV, condenser Cd, compressor Cp, throttle valve TV, liquid separator LS, liquid receiver LR and fans F_1 and F_2. When the system stops or is in pump-down mode, the evaporator fans continue to operate, compelling the system to undergo defrosting.

Fig. 2 illustrates the schematic of the vapor compression cycle with mechanical vapor compression and electric defrosting. In the context of electric heating defrosting, the usual approach involves applying heat to the surface of an outdoor coil to melt off frost. As illustrated in Fig. 3, the superheated refrigerant vapor, discharged from the compressor, is directed into an evaporator (outdoor coil), bypassing both a condenser and an expansion device. This setup enables high-pressure, high-temperature refrigerant gas from the compressor discharge to flow into the frosted coil. As the hot refrigerant gas traverses the coil, it undergoes condensation, releasing its latent heat. This process warms the heat exchanger and facilitates the melting of the frost [12].

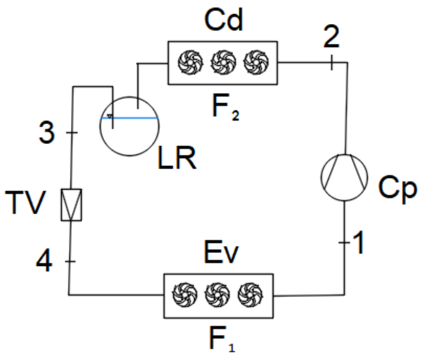

Fig. 1. Air defrost method in mechanical vapor compression refrigeration cycle

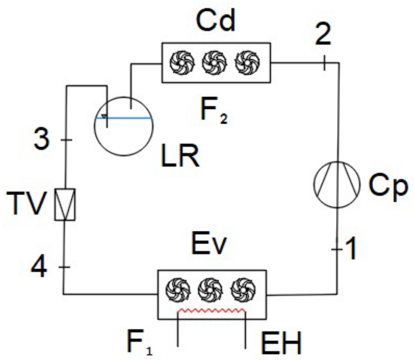

Fig. 2. Electric heating defrost method in mechanical vapor compression refrigeration cycle

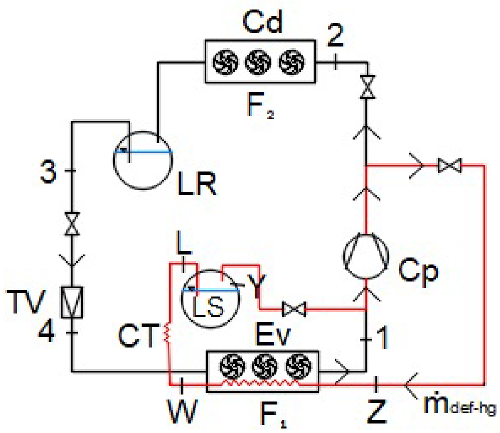

Fig. 3. Hot gas defrost method in mechanical vapor compression refrigeration cycle

The difference between fig.1 and fig.2 is represented by the presence of the electric resistance in fig. 2, which is powered by an electric current. From a hydraulic standpoint, differences are observed only in the case of figure 3, where an additional circuit is required for operation, thus increasing the complexity of the scheme.

As for advantages and disadvantages, air defrosting is by far the most energy-efficient due to the operation of a simple fan, but it is the least suitable in terms of defrosting time. In the case of EHD, it is characterized by simplicity in terms of construction but has a high electricity consumption and disperses heat into the cooled space. HGD presents the advantage of fast defrosting, with heat transfer occurring from the inside of the tube to the outside without consequences for the product in the cooled space, but it requires a complex hydraulic scheme and a corresponding automation circuit.

Fig. 4 shows the evaporator of the refrigeration system under investigation. It is obvious that the evaporator is clogged with ice, necessitating a defrosting process.

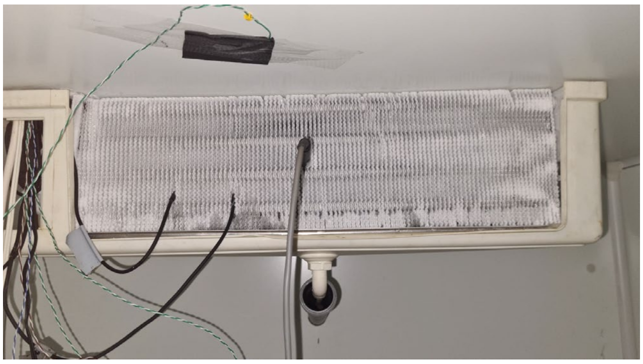

Fig. 4. Evaporator clogged with 700 g of ice

In Fig. 5, the bypass cycle within the hot gas defrosting cycle is presented for the refrigeration system with refrigerant R290. Compression occurs in the Y-Z process, followed by the condensation of the refrigerant (Z-W) as it passes through the evaporator, resulting in defrosting. The laminar process W-L occurs in capillary tube (CT), followed by the separation of the R290 liquid refrigerant in LS.

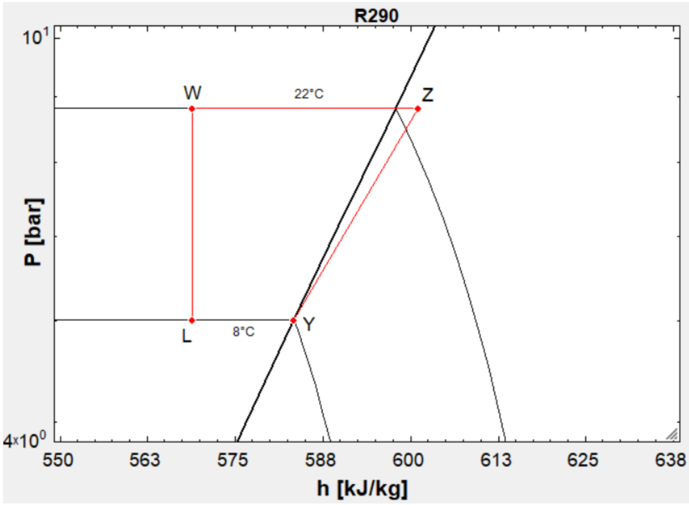

Fig. 5. Hot gas defrost method by-pass cycle

The system was designed to operate for 18 hours out of 24, with the system at rest for the remaining 6 hours

The following assumptions were made in modelling the defrost method in mechanical vapor compression refrigeration cycle:

- the total time is the sum of operating time in the cooling mode added to the thermostat-controlled time, with the addition of defrosting time;
- the total defrosting time for each type of defrosting is the same, although individual defrosting time may vary depending on the application;
- the temperature of the refrigerant in the supplementary circuit used for hot gas defrosting is the same for both freezing and refrigeration;
- it was considered a theoretical cycle with superheating and subcooling;
- the system's compressor is a hermetic type, having S=19,6 mm, D=34,9 mm, dead space coefficient ε_0=2.5%, and n_r=3000 rot/min as characteristics;
- the isentropic compression efficiency is assumed to be 1 which means that the compression process is adiabatic and reversible;
- the energy balance on the evaporator during defrosting is made under the assumption that the entire heat quantity obtained through the defrosting method is entirely absorbed by the subcooled ice;
- it is assumed that the ice deposited on evaporator is subcooled to an average temperature of -5°C, given that the evaporation temperature is -10°C, the value of -5°C being the mid value between evaporating temperature and the temperature inside of the cooled room which is about 0°C in case of refrigeration;

- for freezing, the ice temperature is considered to be -14°C, as an average between the evaporation temperature of -28°C and the 0°C temperature, which is the stage when ice starts to form;
- for the studied refrigeration system, the maximum quantity of ice deposited on the evaporator was 700 g, being experimentally determined and present in Fig. 4;
- defrosting times are established in commercial and industrial applications, obtained experimentally and according to bibliography [8];

The equipment was used to analyze the three types of defrosting described in figures 1, 2, 3, in terms of COP, considering the following refrigerants: R290, R134a, R600a, R600, R404A, R32, R1234yf, and R1234ze(E).

The analysis was conducted utilizing the Engineering Equation Solver software [13]. The mathematical model was constructed based on scientific articles [9,14,15]. Subsequently, the total electric power demand $\dot{E}_{cons}$, as expressed in Equations (1), (2), and (3), was calculated for air, resistance, and hot gas defrosting, respectively:

$$\dot{E}_{cons} = \frac{18}{24} \cdot (P_{cp} + P_{F_1} + P_{F_2}) + \frac{3}{24} \cdot P_{F_1} \quad (1)$$

$$\dot{E}_{cons} = \frac{18}{24} \cdot (P_{cp} + P_{F_1} + P_{F_2}) + \frac{2}{24} \cdot P_{\mathrm{Re}s} \quad (2)$$

$$\dot{E}_{cons} = \frac{18}{24} \cdot (P_{cp} + P_{F_1} + P_{F_2}) + \frac{1}{24} \cdot P_{Cp_l} \quad (3)$$

where:

P_{cp} is compressor power input;

P_{F_1} is power input of the evaporator fan ;

P_{F_2} is power input of the fan cooling the condenser;

$P_{\mathrm{Re}s}$ is power input for the electric resistance;

P_{Cp_l} is power input of the compressor used in the bypass loop;

Regarding time ratios which are present in eq. (1), (2) and (3), explanations are given below:

- the study is conducted on a 24 hour period of time;
- the VCRS system is working 18 hours out of 24 hours, the difference of 6 hours being the time of standby when the need for cold in the room was achieved;
- the total defrosting time that occurs during a 24 hour evaluation period of the system in case of air defrost method is 3 hours;
- the total defrosting time that occurs during a 24-hour evaluation period of the system in case of electric heating method is 2 hours;
- the total defrosting time in hours that occurs during a 24-hour evaluation period of the system in case of hot gas defrost method is 1 hour;
- total defrost time periods for all cases of defrost were taken accordingly to [9] and also experimentally tested;

The coefficient of performance (COP) of the refrigeration cycle with and without defrosting are:

$$COP_c = \frac{\dot{Q}_0}{P_{cp}} \quad [-] \tag{4}$$

$$COP_{with\,defrost} = \frac{\dot{Q}_0}{\dot{E}_{cons}} \quad [-] \tag{5}$$

where:

$\dot{Q}_0$ is cooling capacity;

The equation system used to obtain the liquid refrigerant mass (m_L) is:

$$m_{refr} = m_{\deg\_g} \cdot \tau_g \tag{6}$$

$$m_L = m_{refr} \cdot (1 - x_L) \tag{7}$$

where:

m_{refr} is the mass of refrigerant in the HGD loop;

m_{deg_g} is the flow rate of the refrigerant for the HGD loop;

x_L is the loop refrigerant vapor title before entering the LS;

τ_g is the individual time in seconds for HGD defrost which is 15 minutes in this case;

Technical information is given in Table 1 and 2.

Table 1

Main data of refrigeration system

Hermetic Compressor AE 4460 Z				
1	Evaporation temperature	t0	-10	°C
2	Condensation temperature:	tc	40	°C
3	Cylinder diameter:	D	0.03439	m
4	Piston stroke:	S	0.0192	m
5	Number of cylinders:	i	4	-
6	Compressor speed:	nr	3000	rot/min
7	Dead space volume:	ε_0	0.025	%
8	Superheat:	Δtsh	11	°C
9	Subcooling:	Δtsc	5	°C
10	Evaporator fan power	F_1	0.035	kW
11	Condenser fan power	F_2	0.025	kW
Characteristics of Electric Heating Defrosting				
1	Electric resistance power	P_{res}	460	W
Characteristics of Hot Gas Defrosting				
1	Evaporating loop temperature	t_{og}	8	°C
2	Condensing loop temperature	t_{cg}	22	°C
3	Ice mass deposited on the evaporator	m_{ice}	0.7	kg
4	Latent heat of ice	LE	333.6	kJ/kg
5	Average ice temperature	T_ice_g	-5	°C
6	Specific heat of ice	cp_{ice}	2.1	kJ/(kg K)

Table 2

Specific data of freezing system

Hermetic Compressor AE 4460 Z				
1	Evaporation temperature	t0	-28	°C
2	Average ice temperature	T_ice_g	-14	°C

The theoretical analysis has been carried on the following conditions:

- all parameters from table 1 and 2 are kept constant;
- all parameters from table 1 were used for the freezing study except evaporation temperature and average ice temperature which can be seen in table 2;
- the variables used were defrosting times and thermodynamic characteristics of the various refrigerants used;

3. Results and discussion

Figure 6 shows the Coefficient of Performance (COP) calculated with eq. (5) for the air defrosting method using various refrigerants. Under these operating conditions, R32 exhibits the highest COP, while R600 displays the lowest. For the remaining refrigerants the highest COP is obtained for R290 followed by R404A, R134a, R1234yf, R1234ze(E) and R600a.

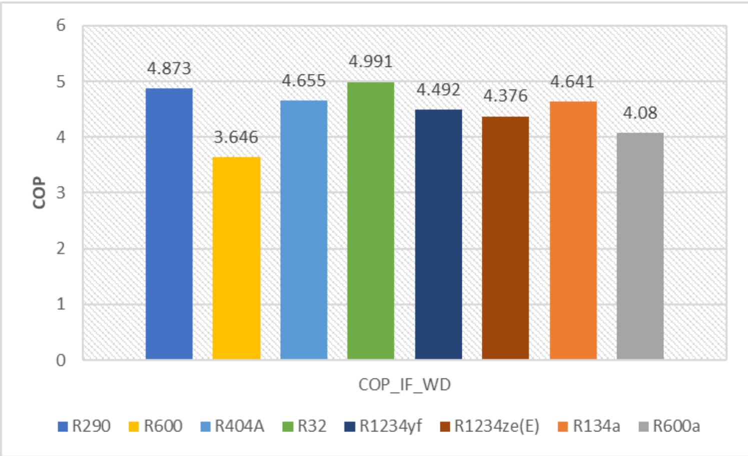

Fig. 6. COP for air defrost method

In Fig. 7, corresponding to the electric heating defrosting method, it is noticed that R32 exhibits the highest COP, followed by R290. The lowest COP is observed for the refrigerant R600. From Fig.7 can be noticed that the hierarchy of the COP values is the same as in the case of air defrost method.

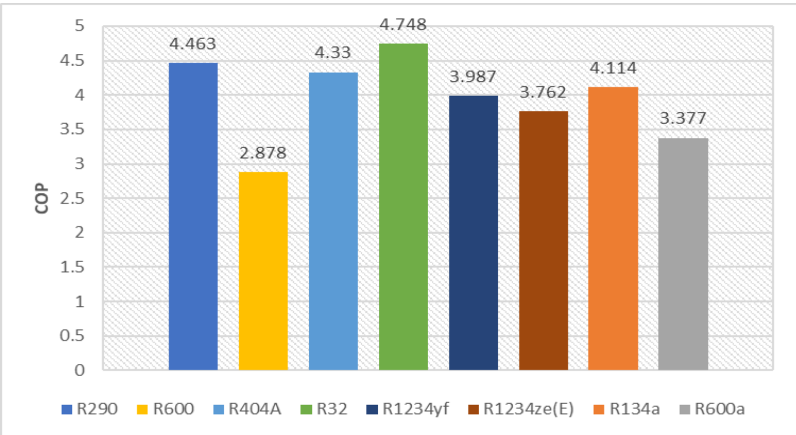

Fig. 7. COP for electric defrost method

In Fig. 8, for hot gas defrosting, it can be observed that the same hierarchy is maintained for the refrigerants used, with R32 having the highest COP, followed by R290. Compared to air and electric heating defrost methods, in the present case R134a has a higher COP than R404A.

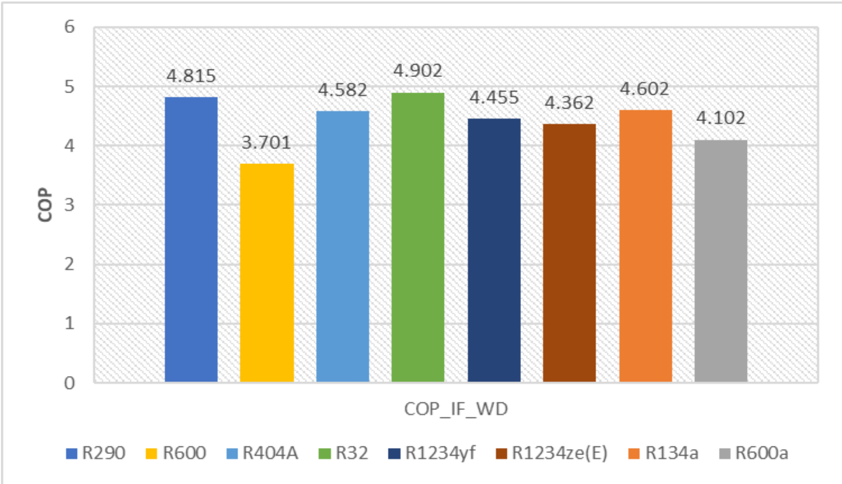

Fig. 8. COP for hot gas defrost method

Regarding the cycle COP determined using eq. (4), as shown in Fig. 9, it is observed that R600 has the highest value, while the lowest value is exhibited by R404A.

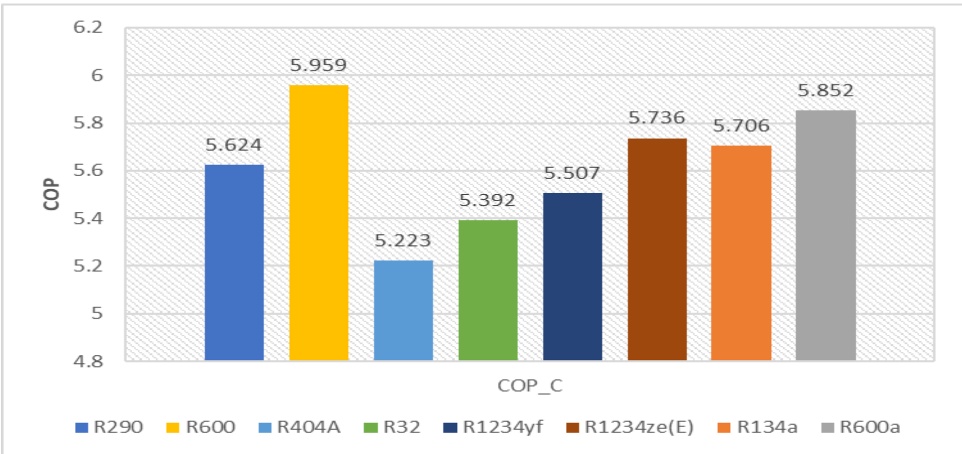

Fig. 9. No defrost cycle COP

The second highest value is obtained for R600a followed by R134ze(E), R134a, R290, R1234yf and R32.

Fig. 10 presents a comparison between the three defrosting methods, where it can be observed that the highest COP is achieved by the refrigerant R32 in air defrosting, followed by COP in hot gas defrosting, and the lowest value is observed in electric heating defrosting. The same hierarchy is maintained concerning the defrosting method, except for refrigerants R600 and R600a, where hot gas defrosting yields a better COP than air defrosting due to the low compression energy consumption and the ratio between defrosting times. From Fig. 10 can be noticed that for all considered refrigerants the lowest COP value is obtained for the electric heating defrost method. It is interesting to point out that in case of R600 the cycle COP is the highest among the considered refrigerants while its COP with defrosting for all methods is the lowest one.

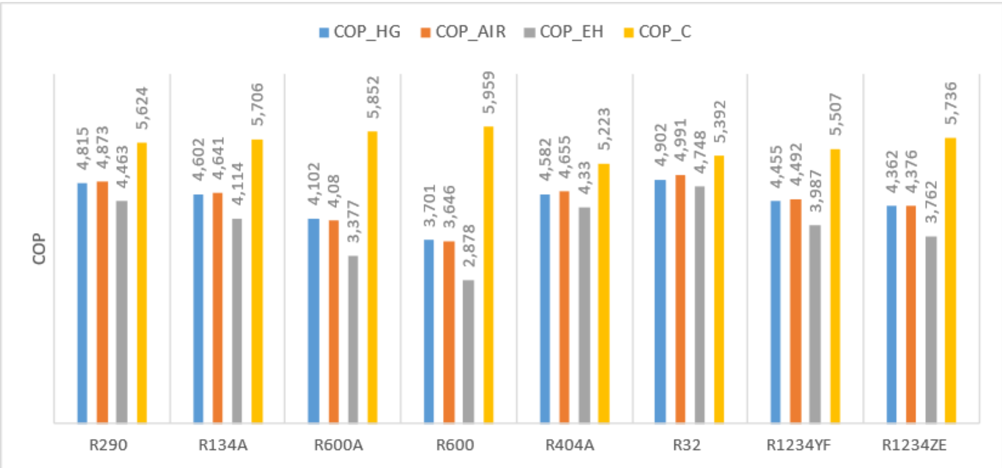

Fig. 10. Comparative COP - Air defrosting, Electric Heating defrosting, Hot gas defrosting, and Cycle COP

Next, the same study is conducted for a vapor compression refrigeration system used for freezing, with the evaporating temperature set at t_0 =−28°C. According to the analysis, the obtained results are as follows, with the mention that defrosting with air is no longer feasible.

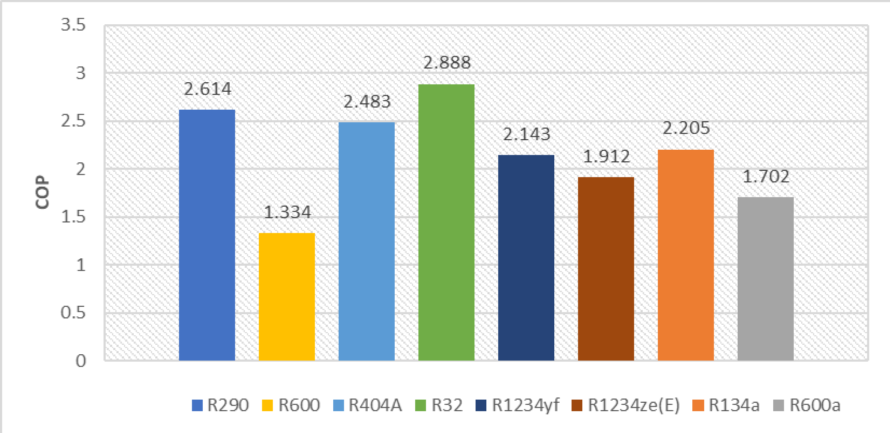

Fig. 11. COP for electric defrost method

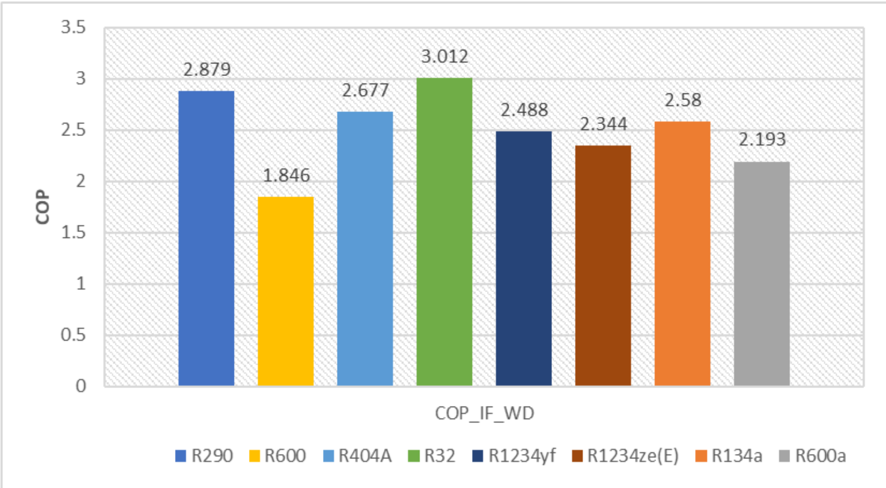

Fig. 12. COP for hot gas defrost method

In Fig.11 and Fig.12, the COP for the two defrosting methods is presented for various refrigerants. It is observed that the hierarchy does not change compared to the ones presented above, but the COP values are considerably lower in the case of freezing compared to refrigeration.

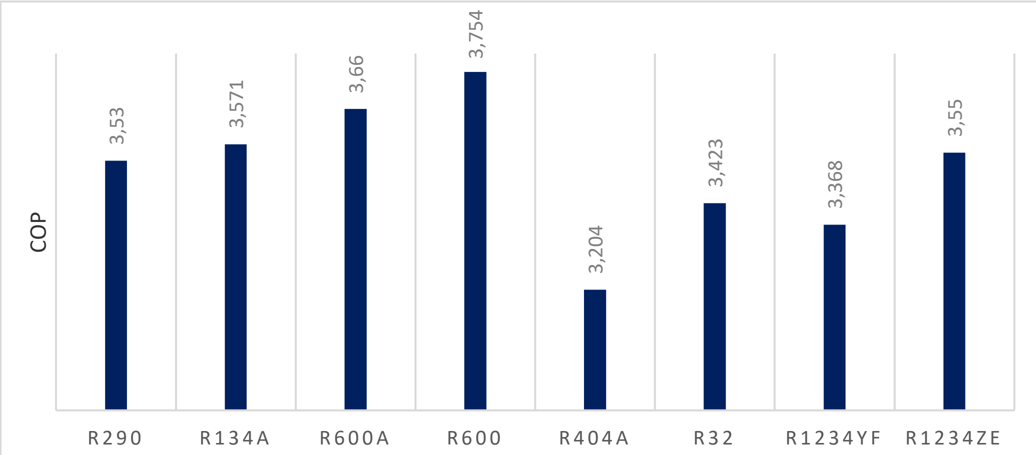

Fig. 13. COP cycle

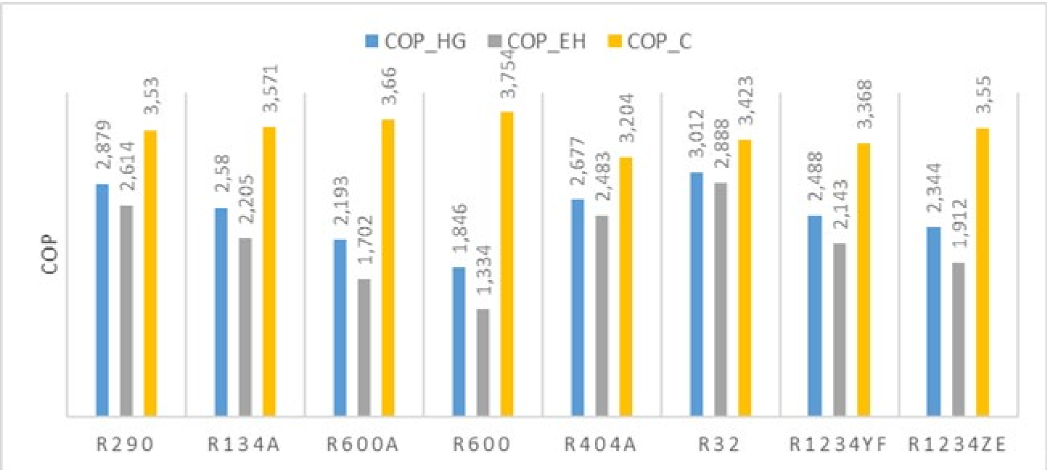

Fig. 14. COP for air defrosting, electric heating defrosting, hot gas defrosting, and cycle defrosting

Fig. 13 and Fig.14 show the COP cycle, providing a recapitulation of the three methods, and the same conclusion is reached, indicating that hot gas defrosting is more efficient than electric heating defrosting for all the refrigerants used.

Continuing, a study was conducted on the bypass cycle (Fig. 5) within the hot gas defrosting cycle, where the variation of the liquid mass at the liquid separator inlet was monitored based on the mass of ice deposited on the system's evaporator. The amount of refrigerant resulting from the defrosting process must be stored in liquid state in LS to avoid hydraulic shock in the compressor.

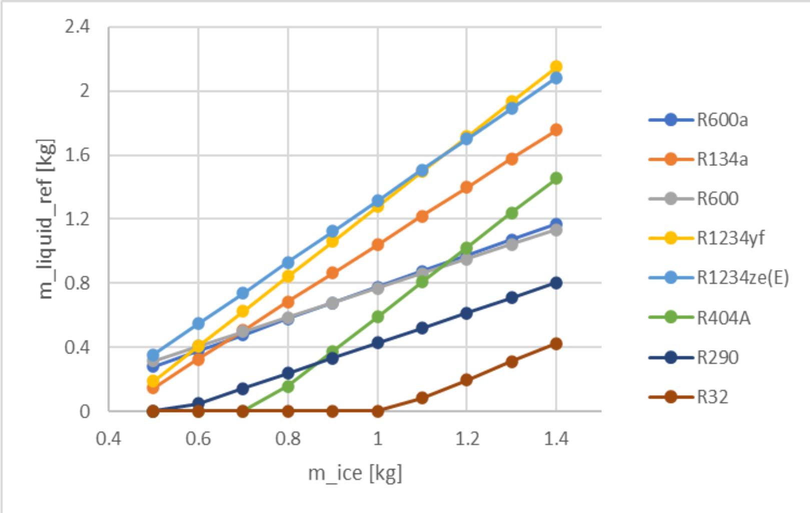

Fig. 15. Variation of liquid refrigerant mass as a function of ice quantity

Fig. 15 shows that for all refrigerants, the increase in the amount of ice deposited on the evaporator leads to an increase in the liquid quantity at the entrance to LS. Additionally, it is highlighted that R404A and R32 begin condensation after melting a large amount of ice, specifically, more than 0.7 kg for R404a and 1 kg for R32.

4. Conclusions

As expected, defrosting alters the cycle COP being lower when defrosting is present, regardless of the defrosting method, compared to the cycle without defrosting. The coefficient of performance for air defrosting is the highest, followed by hot gas defrosting, and, finally, electric heating defrosting.

As anticipated, defrosting modifies the coefficient of performance, leading to a depreciation of the cycle COP, which is lower when defrosting is present, regardless of the defrosting method and refrigerant used.

In the case of air defrosting, the COP is higher, but it has the disadvantage of not completely defrosting the entire ice quantity, leading to increased humidity in the cooled space. The least advantageous defrosting method is the electric heating method.

Both the refrigerant and the defrosting method can modify the overall optimum coefficient of performance provided by the cycle.

It is observed that for refrigerants R600 and R600a, COP, accounting for defrosting, is better in the case of hot gas defrosting than with air defrosting. This is due to the low energy consumption achieved by the compressor and the ratio between defrosting times for air and hot gas.

However, for freezing, air defrosting is no longer possible. It is observed that hot gas defrosting is the most efficient compared to electric heating defrosting, having the highest COP for R32, followed by R290, with the lowest value obtained for R600.

In the freezing case, it is observed that the efficiency hierarchy is maintained, with the specification that COP values are proportionally smaller compared to the refrigeration case.

In the case of the hot gas defrost method, in the bypass cycle for all refrigerants, the increase in the amount of ice deposited on the evaporator leads to an increase in the liquid quantity at the entrance to LS.

R E F E R E N C E S

[1]. *Xiaohui She, Lin Cong, Binjian Nie, Guanghui Leng, Hao Peng, Yi Chen, Xiaosong Zhang, Tao Wen, Hongxing Yang, Yimo Luo*, Energy-efficient and economic technologies for air conditioning with vapor compression refrigeration: A comprehensive review, Applied Energy, Volume 232,2018, Pages 157-186, ISSN 0306-2619.

[2]. *Mohammed Amer, Chi-Chuan Wang*, Review of defrosting methods, Renewable and Sustainable Energy Reviews, Volume 73,2017, Pages 53-74, ISSN 1364-0321

[3] *R. Le Gall, J.M. Grillot, C. Jallut*, Modelling of frost growth and densification, International Journal of Heat and Mass Transfer 40 (13) (Sep. 1997) 3177–3187.

[4] *D.L. da Silva, C.J.L. Hermes, C. Melo*, First-principles modeling of frost accumulation on fan-supplied tube-fin evaporators, Applied Thermal Engineering vol. 31, no. 14–15, Art. no (Oct. 2011) 14–15,.2011.04.029.

[5] *X.-M. Guo, Y.-G. Chen, W.-H. Wang, C.-Z. Chen*, Experimental study on frost growth and dynamic performance of air source heat pump system, Applied Thermal Engineering vol. 28, no. 17–18, Art. no (Dec. 2008) 17–18.

[6] *W. Wang, S. Zhang, Z. Li, Y. Sun, S. Deng, X. Wu*, Determination of the optimal defrosting initiating time point for an ASHP unit based on the minimum loss coefficient in the nominal output heating energy, Energy 191 (Jan. 2020), 116505.

[7] *Patil, M. S., J. H. Seo, and M. Y. Lee*, Heat transfer characteristics of the heat exchangers for refrigeration, air conditioning and heat pump systems under frosting, defrosting and dry/wet conditions-A review, Applied Thermal Engineering 113: 1071–87.2016.11.107.

[8] *Ju-Suk Byun, Jinho Leeb, Chang-Duk Jeon*, Frost retardation of an air-source heat pump by the hot gas bypass method, International Journal of Refrigeration 31 (2008) 328–334.

[9] *Meltem Koşan, Erhan Arslan, Süleyman Erten, Fatma Nur Erdoğmuş & Mustafa Aktaş*, Determination of defrost efficiency and energy efficiency index value using different defrost methods and refrigerants: An experimental study, Science and Technology for the Built Environment, 28:8, 1012-1023.

[10] *Rainwater J. H.*, Five Defrost Methods for Commercial Refrigeration, ASHRAE Journal 51, no. 3 (2009) :38-51.

[11] *Kashif Nawaz, Ahmed Elatar, Brian Fricke*, A Critical Literature Review of Defrost Technologies for Heat Pumps and Refrigeration Systems, Oak Ridge National Laboratory, 2018.
[12] *Hoffenbecker N., Klein S. A., Reindl D. T.*, Hot gas defrost model development and validation, International Journal of Refrigeration 28, no. 4 (2005): 605-615.
[13] *** Engineering Equation Solver Academic Professional, V.10.664-3D #4487, Faculty of Mechanical Engineering, University Politehnica of Bucharest, 2022.
[14] *Gh. Popescu, S. Porneala, E. Vasilescu, V. Apostol*, s. al., Echipamente și instalații frigorifice, Edit. Printech, pp. 135 – 140, 200.
[15] *Pop H, Apostol V, Alqaisy S J, Hmood K S, Al Douri J And Badescu V* 2021, Mass flow rate evaluation of a hermetic compressor from a small scale vapour compression refrigeration system, UPB Scientific Bulletin, Series D: Mechanical Engineering 83 pp 1454-2358.