IMPROVING PERFORMANCE OF COLD ROOM REFRIGERATION SYSTEM BY DESUPERHEATING ENERGY RECOVERY USING PCMs
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ÎMBUNĂTĂȚIREA PERFORMANȚEI UNUI SISTEM FRIGORIFIC (IFV) CE ECHIPEAZA O CAMERA FRIGORIFICA, PRIN RECUPERAREA ENERGIEI DIN PROCESUL DE DESUPRAINCALZIRE CU AJUTORUL PCM-urilor

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DOI: https://doi.org/10.35633/inmateh-70-53

Keywords: *vapour compression refrigeration, phase change material, evaporator, defrosting, thermal energy storage*

ABSTRACT

The paper aims to investigate how to improve the performance of a refrigeration system (Rs) that equips a cold room, by incorporating phase change materials (Phase Change Materials - PCMs) in these systems, a study that has not yet been extended experimentally. The study is carried out on a cold room within the National University of Science and Technology Politehnica Bucharest - Faculty of Mechanical and Mechatronics Engineering, Department of Thermodynamics, Engines, Thermal and Refrigeration Equipment.

This room is equipped with a refrigeration system with mechanical vapour compression (VCRs), which uses R404A as refrigerant. Mechanical vapour compression refrigeration system (VCRs) with an evaporation temperature below 0°C causes ice to form on the evaporator leading to reduced performance. Currently, the widely used methods for defrosting are the standard methods, the most used being the electric one, which of course consumes energy. This paper aims to evaluate the availability of heat that could be used in the defrosting process by means of PCMs. The study was made using the Engineering Equation Solver software, several types of PCMs and also different refrigerants (R600a, R600, R1234yf, R1234ze, R152a, R290, R32) and in this way it was intended to identify the right agent to be used for a particular type of PCM.

REZUMAT

Lucrarea investighează modul de îmbunătățire a performanței unei instalații frigorifice (IFV) ce echipează o camera frigorifica, prin încorporarea materialelor cu schimbare de fază (Phase Change Materials - PCM-uri) în aceste sisteme, studiu care nu a fost încă extins experimental. Studiul se realizează pe o cameră frigorifică din cadrul Universității Naționale de Știință și Tehnologie Politehnica București – Facultatea de Inginerie Mecanică si Mecatronica, Departamentul de Termotehnica, Motoare, Echipamente Termice și Frigorifice. Această camera este echipată cu o instalație frigorifică cu comprimare mecanică de vapori (IFV), ce folosește ca agent frigorific R404A. Sistemul frigorific cu comprimare mecanică de vapori (IFV), cu o temperatura de vaporizare mai mică de 0°C, determină depunerea de gheață la vaporizator care conduce la reducerea performanței acestuia. În prezent, metodele utilizate pe scară largă pentru degivrare sunt metodele standard, cea mai utilizata fiind cea electrica, care consuma bineînțeles energie. Lucrarea își propune să evalueze disponibilitatea de căldură ce ar putea fi utilizată în procesul de degivrare cu ajutorul PCM-urilor. Studiul s-a făcut cu ajutorul software-ului Engineering Equation Solver, folosind mai multe tipuri de PCM-uri și de asemenea diferiți agenți frigorifici (R600a, R600, R1234yf, R1234ze, R152a, R290, R32) și in acest mod se dorește a se identifica agentul potrivita fi utilizat pentru un anumit tip de PCM.

INTRODUCTION

In order to provide the consumer with quality products, food systems must use rapid cooling and cold storage technology. Over the past thirty years, the number of farms has increased, so energy efficient cold storage units have been needed. Cold storage is essential for vegetable farmers to preserve product quality.

Cold storage is an essential component in the food supply chain. Without rapid cooling and proper storage conditions, products deteriorate quickly. Nutritional losses and even damage to entire crops can occur. Initial rapid cooling to extract latent field heat extends shelf life and maintains product quality *(Kraemer et al., 2020)*.

Artificial cold is used in the food industry, for cooling and freezing food products, using temperatures up to -40°C, and for freeze-drying processes, drying products by freezing and sublimating ice in vacuum are carried out using temperatures from -40° C to -80°C.

There are several methods of cold processing of food products, among which the following were mentioned: refrigeration, i.e. rapid cooling to temperatures of 0...5°C, is a method aimed at rapid cooling of food products to final temperatures above the freezing point and freezing, i.e. cooling to the final temperature of -18... -25°C, with water hardening of the products in a proportion of over 95%; it is a method by which the food product is cooled to a final temperature well below the freezing point.

According to the above, there are two types of cold rooms, namely: refrigeration and freezing.

Refrigeration cold rooms are generally intended for the storage of medicines, wine, food, flowers, etc. The thickness of the panels used in their construction is between 60 mm and 100 mm. The temperature obtained inside will be maintained between +14°C and -25°C, depending on the customer's wishes.

Freezing cold rooms are intended, in general, for freezing products (meat, fish, etc.). This time, the thickness of the panels used will be greater, namely between 80 mm and 120 mm. The temperature obtained will be maintained between -25°C and will reach up to -40°C. The cooling and freezing time of the products can vary between 2 and 24 hours *(Horbaniuc B., 2006).*

If the refrigeration system () that equips the cold room operates at an evaporation temperature below 0^{o}C, ice is deposited on the evaporator and defrosting is required. Defrosting the evaporators is a necessary operation in the case of refrigeration systems used to freeze food products because the ice or snow that is deposited on the heat transfer surface of the batteries acts as a thermal insulator and thus reduces the free area for air circulation and reduces the performance of the system *(Qu et al., 2012)*.

Several classic defrosting procedures can be applied: *hot air defrosting* is used in rooms with positive temperatures or in the case of heat pump evaporators; *electric defrosting* process is used in rooms with negative temperatures; *reverse-cycle defrosting* can be used if the evaporator and the condenser are made up of pipes equipped with fins, by reversing the cycle, the evaporator becomes a condenser, and the condenser becomes an evaporator; *hot gas defrosting* – a process in which the evaporator is fed with hot vapours coming directly from the cooling system of the compressor while the rest of the installation works normally; *water defrosting* consists of spraying with water the evaporator loaded with ice *(Al Douri et al., 2021)*.

In current research, a new defrosting method using PCMs (Phase Change Materials) is noted. PCMs are materials that can absorb and release large amounts of energy when they change from one phase to another, such as from solid to liquid or vice versa. The PCMs have high thermal energy storage capacity and have the ability to release and absorb a large amount of energy at a constant temperature *(Regin et al., 2008).*

Also, there are several different ways to improve the efficiency of refrigeration system by using phase change materials like, advanced insulation, improve heat exchangers, and defrost mechanisms.

In 2018, researchers studied experimentally the effect of adding water as PCMs in the evaporator for the domestic refrigeration system, the experimental results showed that using three fins of PCM would reduce the energy consumption of the compressor by 17.4% per day *(Zarajabad at al., 2018).*

Other researchers investigated the effect of adding a slab with 5mm thickness eutectic aqueous solution as a PCM on the back between the evaporator and the insulation on the energy efficiency of the refrigerator, resulting in improved conduction heat transfer from the evaporator to the PCM and an increase in the coefficient of performance by 5-15%, and a decrease in the off and on number of the compressor which leads to the stability temperature in the room of the refrigerator *(Azzouz et al., 2008)*.

In another paper, the authors studied the enhance of a household refrigerator using PCMs with nanoparticle for increasing the thermal conductivity at the condenser, the results show that the consumption of energy was decreased by 13.06% and around 18% by using PCMs with nanoparticle *(Kumar et al.,2020).* Also, researchers investigated the effect of adding a slab of 5mm thickness from PCM to the evaporator and compared it to the evaporator without PCM. The results show an increase in the coefficient of performance of 10-30% compared to the evaporator without PCM *(Azzouz et al., 2009).*

The modern household refrigerator was studied by incorporating PCM into the structure of heat storage condensers, the results show a decrease in condensation temperature and a rise in evaporator temperature, resulting in a 12% increase in energy efficiency *(Cheng et al, 2011).*

Khan at al., (2015), investigated the effect of adding PCM behind the evaporator coil on the compressor on-off cycle for household refrigeration systems, and the results show that the number of compressor on-off cycles is about 3-5 times lower than that of the system without PCM, and the average compressor running time is reduced by 5-30% with PCM compared to without PCM.

Other researchers used four different types of PCM in the evaporator for two different refrigerator models to demonstrate the effect of adding PCM in the refrigeration system. The results show that for all PCMs, the temperature of the evaporator and condenser was increased by 2ºC to 4ºC, the off-on time of the compressor was improved, for refrigerator 1 using 1.8 kg of PCM resulted in an 8.8% energy savings, and for refrigerator 2 using 0.95 kg of PCM resulted in a 9.4% energy savings *(Yusufoglu et al., 2015)*.

Rahman et al., (2013), investigated the effect of adding PCM to the evaporator of a household refrigeration system and compared the systems with and without PCM. The results show that the system with PCM increases the COP (coefficient of performance) by 55-60% over the non-PCM and that in both cases, with and without PCM, the COP increases as the thermal load decreases and decreases as the thermal load increases.

The effect of adding PCM in the evaporator and paraffin as PCM in the condenser was then investigated for three types of household energy storage refrigeration systems: CSE refrigerator, DES refrigerator, and HSC refrigerator, and found that the DES refrigerator has the best economy energy, performance of up to 32%, which is higher than the total (28%) of the other two types of household refrigeration systems with energy storage *(Cheng et al., 2017)*.

In another article, it was studied the effect of adding a heat exchanger containing N-Octadecane as PCM before and after the condenser to compare the COP of the refrigerator with and without PCM, and the results show that using PCM in the household refrigeration cycle improves the convection process and results in a 9.58% increase in the household's performance coefficient *(Bakhshipour et al., 2017)*.

Other researchers analysed the experimental effect of adding a PCM heat exchanger in the evaporator to improve the efficiency of residential refrigeration systems; the results show that power consumption is decreased by 12% and COP is raised by 8% when compared to the refrigerator without PCM *(Elarem et al., 2017)*. Other authors investigated the effect of installing a PCM at three positions in the refrigeration system: before and after the compressor and after the condenser; the results show the efficiency improved by 6-8% *(Wang et al., 2007)*.

In another study, the researchers evaluated the performance of adding PCM to the frost-free household refrigeration system and compare it to the system without PCM; the results show that the energy consumption of the household refrigeration with PCM decreased by 18.6% and the compressor on-off time decreased by 13.6% compared with household refrigeration without PCM *(Liu et al., 2017)*.

In another paper, the authors studied experimentally the adding of PCM into the wall of a household refrigeration system; the experiments showed that the temperature of the air inside remained constant for 7h at –8◦C, resulting a decrease in the energy consumption by 30% to 54% *(Gin et al., 2011).*

In a new research paper, the effect of additional PCM in the condenser of the domestic refrigeration system was investigated experimentally, and the results showed that the energy consumption was reduced by 15%, and the COP of the refrigerator improved by 28% when compared to the system without PCM *(Dandotiya et al., 2017)*.

MATERIALS AND METHODS

System description

The cold room on which the study is carried out is a container mounted inside the CG 004 room, within the National University of Science and Technology Politehnica Bucharest - Faculty of Mechanical and Mechatronics Engineering, Department of Thermodynamics, Engines, Thermal and Refrigeration Equipment, this room having the role of keeping various food products at refrigeration or freezing temperatures.

The characteristics of the cold room are presented in Table 1. The cold room is complete and is made up of high-density heat-insulating panels and is equipped with a refrigerating unit with high energy efficiency, automation panel, door, and other accessories necessary for the proper functioning.

Table 1

Cold room characteristics

Dimensions	Length	Width	Height
External dimensions [m]	1.43	1.43	1.43
Internal dimensions [m]	1.2	1.2	1.2
Thickness of the walls and floor [m]		0.115	
Useful volume [m^3]		1.728	

Fig. 1 - Overview image of the experimental setup

The system (VCRs), in addition to the compressor, condenser, lamination valve and evaporator, also includes a heat exchanger (PCM-refrigerant discharged by the compressor), thermal energy storage through phase change. This thermal energy could be used externally for domestic water heating or within the scheme (inside) for evaporator defrosting. During defrosting, this thermal energy can be calculated (evaluated) because the equivalent of ice deposited on the evaporator (measured experimentally) that can be melted with this thermal energy is known. The installation works for 4 hours and during this time an amount of ice is collected, which is to be melted using an amount of PCM, then in 20 minutes the defrosting takes place. One of the major advantages of using PCMs in VCRs is their ability to reduce power consumption. Thus, energy consumption can be reduced if PCMs are used for defrosting. The potential use of PCMs in increasing the energy savings and COP of VCRs has also been highlighted in various scientific papers.

In the experiment there are five kinds of PCMs: RT 54 HC; SP 50; RT 44 HC; RT 35 HC and SP 31.

The properties of the PCMs used are presented in Table 2.

Table 2

PCMs properties

Property	SP 31	RT 35 HC	RT 44 HC	RT 54 HC	SP 50
Melting temperature [ºC]	31-33	34-36	41-44	53-54	50-51
Solidification temperature [ºC]	28-30	36-34	44-40	54-53	47-48
Heat storage capacity [kJ/kg]	210	240	250	200	220
Specific heat capacity [kJ/(kg·K)]	2	2	2	2	2
Density solid (at 20°C) [kg/m^3]	1.35	0.88	41-44	0.85	1.4
Density liquid (at 60°C) [kg/m^3]	1.3	0.77	44-40	0.8	1.3
Heat conductivity [W/(m·K)]	0.5	0.2	0.2	0.2	0.6

Sources: *https://www.rubitherm.eu/en/productcategory/organische-pcm-rt*
https://www.rubitherm.eu/en/productcategory/anorganische-pcm-sp

VCRS characteristics

The diagram and operating cycle of the refrigeration system are presented in Fig. 2 (a) and (b) respectively.

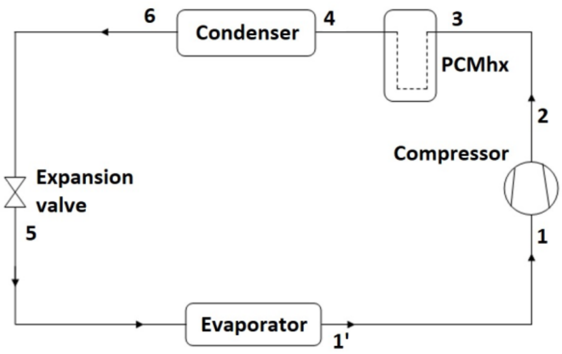

Fig. 2 - Schematic view of the refrigeration system with PCM

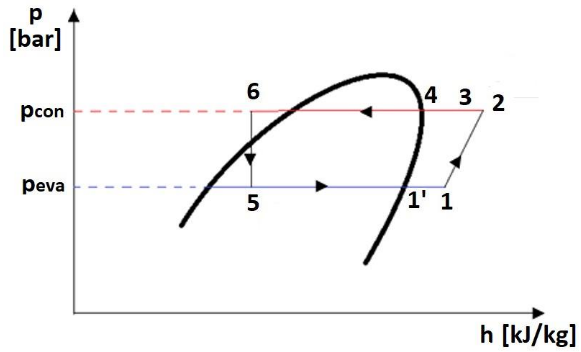

Fig. 3 - Thermodynamic cycle of the VCRS

Mathematical model

The evaporative pressure $p_{eva.}$ [bar], the condensing pressure $p_{con.}$[bar], overheating degree Δt_{sh} [°C] are determined experimentally. With these values, the following thermodynamic states of the refrigerant can be determined, in connection with Fig.3.

$$\begin{aligned}
&State\ 1' \rightarrow p_{eva.}\ \Omega\ x=1 \rightarrow t_{1'};\ h_{1'};\ v_{1'};\ s_{1'}\\
&State\ 1 \rightarrow p_{eva}\ \Omega\ (t_1=t_{1'}+\Delta t_{sh}) \rightarrow h_1;\ v_1;\ s_1\\
&State\ 2 \rightarrow p_{con}\ \Omega\ (s_1=s_2) \rightarrow t_2;\ h_2;\ v_2\\
&State\ 3 \rightarrow p_{con}\ \Omega\ (t_3=t_4+5) \rightarrow h_3;\ v_3;\ s_3\\
&State\ 4 \rightarrow p_{con}\ \Omega\ x=1 \rightarrow t_4;\ h_4;\ v_4;\ s_4\\
&State\ 6 \rightarrow p_{con}\ \Omega\ x=0 \rightarrow t_6;\ h_6;\ v_6;\ s_6\\
&State\ 5 \rightarrow p_{eva}\ \Omega\ (h_5=h_6) \rightarrow t_5;\ v_5;\ s_5
\end{aligned} \quad (1)$$

where:

p_{eva} is the evaporator pressure [bar]; x is the quality of refrigerant [-]; t is the temperature [°C]; h is the specific enthalpy [kJ/ kg]; s is the specific entropy [kJ/ (kg·K)]; v is the specific volume [m³/ kg].

The heat flux recovered with the PCM, $\dot{Q}_{recovery}$ is determined with the relation:

$$\dot{Q}_{recovery} = \dot{m} \cdot \left(h_2 - h_3\right) \quad (2)$$

where: $\dot{m}$ is the refrigerant flow rate [kg/s];

h_2 - the enthalpy of the refrigerant on state 2 [kJ/kg];

h_3 - the enthalpy of the refrigerant on state 3 [kJ/kg].

The heat required to melt the amount of PCM in four hours of operation, $\dot{Q}_{2-3}$ [W] is:

$$\dot{Q}_{2-3} = m_{PCM} \cdot \frac{\lambda_{PCM}}{\tau_{melting}} \quad (3)$$

where: m_{PCM} [kg] is the PCM mass required and results from an energy balance with the experimental measurement of the amount of ice deposited during the four hours of system operation, between two consecutive defrosts; λ_{PCM} [kJ/kg] the heat storage capacity, and $\tau_{melting}$ is the melting time [s].

In order to melt the respective PCM in 4 hours, the condition must be imposed that the heat flow recovered with the help of the PCM is equal to the heat flow required for melting the PCM, i.e. $\dot{Q}_{recovery} = \dot{Q}_{2-3}$. If $\dot{Q}_{recovery} > \dot{Q}_{2-3}$ the melting time of the PCM decreases.

Based on the mathematical model presented before, a program has been developed in Engineering Equation Solver software.

RESULTS

Following the numerical simulation for each type of PCM, but also for all refrigerants used, the results obtained are presented in Tables 3 and 4.

- For PCM type SP 31 the conditions that must be met and check are:
  1) The temperatures must be: t_3 > t_4 (condition met)
     Temperature t_3=t_4 + 5
     So, t_3=46.58 °C
  2) t_3 > $t_{melting}$ (condition met)
     $t_{melting}$ =33 °C for SP 31

The values for the melting temperature of the PCM, $t_{melting}$, are shown in Table 2, line 1.

Table 3

The parameters of the VCR system for PCM - SP 31

Den. no.	Property	t_2 [°C]	t_3 [°C]	t_4 [°C]	$\dot{m}$ [kg/s]	$\dot{Q}_{recovery}$ [kW]	m_{PCM} [kg]
1.	R 404 A	60.12	46,58	41.58	0.0087	0.1538	3.147
2.	R 600 a	49.63	46.58	41.58	0.00109	0.0065	3.147
3.	R600	50.94	46.58	41.58	0.00063	0.0054	3.147
4.	R1234yf	48.82	46.58	41.58	0.0047	0.01232	3.147
5.	R1234ze	50.73	46.58	41.58	0.00284	0.0126	3.147
6.	R 152 a	77.97	46.58	41.58	0.00207	0.08913	3.147
7.	R 290	61.91	46.58	41.58	0.00324	0.1105	3.147
8.	R 32	116.8	46.58	41.58	0.00629	0.5919	3.147
9.	R450a	56.38	46.58	41.58	0.03178	0.03315	3.147

- For PCM type RT 35 HC the conditions that must be met and check are:
  1) The temperatures must: t_3 > t_4 (condition met)
     Temperature t_3=t_4 + 5
     So, t_3=46.58 °C
  2) t_3 > $t_{melting}$ (condition met)
     $t_{melting}$ =36 °C for RT 35 HC

Table 4

The parameters of the VCRS system for PCM - RT 35 HC

Den. no.	Property	t_2 [°C]	t_3 [°C]	t_4 [°C]	$\dot{m}$ [kg/s]	$\dot{Q}_{recovery}$ [kW]	m_{PCM} [kg]
1	R 404 a	60.12	46.58	41.58	0.0087	0.1538	2.754
2	R 600 a	49.63	46.58	41.58	0.00109	0.0065	2.754
3	R600	50.94	46.58	41.58	0.00063	0.0054	2.754
4	R1234yf	48.82	46.58	41.58	0.0047	0.01232	2.754
5	R1234ze	50.73	46.58	41.58	0.00284	0.0126	2.754
6	R 152 a	77.97	46.58	41.58	0.00207	0.08913	2.754
7	R 290	61.91	46.58	41.58	0.00324	0.1105	2.754
8	R 32	116.8	46.58	41.58	0.00629	0.5919	2.754
9	R450a	56.38	46.58	41.58	0.03178	0.03315	2.754

- For PCM type RT 44 HC the conditions that must be met and check are:
    1) The temperatures must: t_3 > t_4 (condition met)
       Temperature t_3=t_4 + 5
       So, t_3=46.58°C
    2) t_3 >$t_{melting}$ (condition not met)
       $t_{melting}$ =44°C for RT 44 HC

It can be seen that the second condition is not met, being at the limit, so this PCM-type paraffin cannot be used in this case. Proceeding in the same way, it is observed that for the other two types of PCM: RT 54 HC and SP 50, the 2nd condition is not met. So, the types of PCM: RT 44 HC, RT 54 HC and SP 50 cannot be used in the PCM heat exchanger**.**

CONCLUSIONS

In this paper, the possibility of improving the performance of a cold room refrigeration system by desuperheating energy recovery using Phase Change Materials has been investigated. One of the most accessible and widely used methods of defrosting is electric defrosting. The performance of a refrigeration system can be improved if the electric defrosting process could be replaced with an PCM based defrosting system. In order to evaluate the heat required for melting the ice accumulated on the evaporator during operation, an experimental setup based on a vapor compression refrigeration operating system with R404A, and a cold room has been used. After evaluating the heat required for defrosting a thermodynamic study has been carried out for refrigerants R404A, R600a, R600, R1234yf, R1234ze, R152a, R290 and R32 considering the SP 31, RT 35 HC, RT 44 HC, RT 54 HC and SP 50 PCMs. The aim of the thermodynamic study is to evaluate if the heat available in the desuperheating process corresponding to each refrigerant can be used in the process of PCM melting. Not all studied PCMs are suitable for a PCM based defrosting system.

The main results point out that:

- for the refrigerant R404A, an amount of thermal energy from the desuperheating process of 0.1538 kW could be stored for a mass of 3.147 kg of PCM - SP 31 and for PCM - RT 35 HC, the same amount was stored for a significantly smaller mass of 2.754 kg of PCM.

- among the refrigerants analysed, for the same mass of PCM, the R32 refrigerant has the highest available thermal energy recovered from the desuperheating process.

- for the PCMs: RT 54 HC; SP 50 and RT 44 HC the analysed agents do not lead to temperature values in state 3 lower than the melting temperature of the PCM (t_3 > $t_{melting}$), the condition imposed for the required mass of PCM to melt, so they cannot be used in the present case studied.

- for the refrigerants R600, R600a, R1234yf, R1234ze, R450a, regardless of the type of PCM used, their use is not recommended in the analysed case, because the heat flow recovered with the help of the PCMs does not cover the heat flow necessary to melt the PCM.

Future work will involve experimental development of PCM based defrosting system that could improve the efficiency of vapor compression refrigeration systems.

ACKNOWLEDGEMENTS

This work has been funded by the European Social Fund from the Sectorial Operational Programme Human Capital 2014-2020, through the Financial Agreement with the title "Training of PhD students and postdoctoral researchers in order to acquire applied research skills - SMART". Contract no.13530/16.06.2022 - SMIS code:153734.

REFERENCES

[1] Azzouz K., Leducq D., Gobin D., (2008), Performance enhancement of a household refrigerator by addition of latent heat storage, *Int. J. Refrig.*, vol. 31, no. 5, pp. 892–901.

[2] Azzouz K., Leducq D., Gobin D. , (2009), Enhancing the performance of household refrigerators with latent heat storage: An experimental investigation, *Int. J. Refrig.*, vol. 32, no. 7, pp. 1634–1644.

[3] Al Douri, J., Hmood, K., Apostol, V., Pop, H., Alqaisy, S., Ibrean, B., (2021), Review regarding defrosting methods for refrigeration and heat pump systems, *TE-RE-RD*, Romania.

[4] Bakhshipour S., Valipour, M.S., Pahamli Y., (2017), Parametric analysis of domestic refrigerators using PCM heat exchanger, *Int. J. Refrig.*, vol. 83, pp. 1–13.

[5] Cheng, W. L., Mei, B. J., Liu, Y. N., Huang, Y. H., Yuan, X. D., (2011), A novel household refrigerator with shape-stabilized PCM (Phase Change Material) heat storage condensers: An experimental investigation, *Energy*, vol. 36, no. 10, pp. 5797–5804.

[6] Cheng, W. long, Ding, M., Yuan, X. Dong, Han, B. C., (2017), Analysis of energy saving performance for household refrigerator with thermal storage of condenser and evaporator, *Energy Convers. Manag.*, vol. 132, pp. 180–188.

[7] Dandotiya, D., Banker, N. D., (2017), Performance Enhancement of a Refrigerator Using Phase Change Material-Based Condenser: An Experimental Investigation, *Int. J. Air-Conditioning Refrig.*, vol. 25, no. 4, pp. 1–9.

[8] Elarem, R., Mellouli, S., Abhilash, E., Jemni, A., (2017), Performance analysis of a household refrigerator integrating a PCM heat exchanger, *Appl. Therm. Eng.*, vol. 125, pp. 1320–1333.

[9] Gin, B., Farid, M. M., Bansal, P., (2011), Modeling of phase change material implemented into cold storage application, *HVAC R Res.*, vol. 17, no. 3, pp. 257–267.

[10] Horbaniuc, B., (2006), *Refrigeration and air conditioning systems for the food industry, Cermi Publishing House (Instalații frigorifice și de climatizare pentru industria alimentară)*, Editura Cermi, Iași, Bucuresti.

[11] Kraemer R., Plouff A., Venn J., (2013), *Design of a small-scale Low-Cost Cold Storage System BE*. 487: Biosystems Design Project.

[12] Kumar, P., Elakkiyadasan, R., Sathishkumar, N., Prabhu, G., Balasubramanian, T., (2020), Performance enhancement of a domestic refrigerator with Nanoparticle Enhanced PCM over the condenser side, *FME Trans.*, vol. 48, no. 3, pp. 620–627.

[13] Khan, M., Afroz, H. M. M.,(2015), Effect of phase change material on compressor on-off cycling of a household refrigerator," *Sci. Technol. Built Environ.*, vol. 21, no. 4, pp. 462–468.

[14] Liu, Z., Zhao, D., Wang, Q., Chi, Y. , Zhang, L., (2017), Performance study on air-cooled household refrigerator with cold storage phase change materials, *Int. J. Refrig.*, vol. 79, pp. 130–142.

[15] Qu, M., Xia, L., Deng, S., Jiang, Y., (2012), *Appl. Energy,* 91, pp.122–129.

[16] Regin, A.F., Solanki, S.C., Saini, J.S., (2008), *Renew. Sustain. Energy Rev*. 12, 24382458.

[17] Rahman, R.,(2013), Performance Improvement of a Domestic Refrigerator Using Phase Change Material (PCM), *IOSR J. Mech. Civ. Eng.*, vol. 10, no. 4, pp. 08–16.

[18] Wang, F., Maidment, G., Missenden, J., Tozer, R. (2007), The novel use of phase change materials in refrigeration plant. Part 1: Experimental investigation, *Appl. Therm. Eng.*, vol. 27, no. 17–18, pp. 2893–2901.

[19] Yusufoglu, Y., Apaydin, T., Yilmaz, S., Paksoy, H.O. (2015), Improving performance of household refrigerators by incorporating phase change materials, *Int. J. Refrig.*, vol. 57, pp. 173–185.

[20] Zarajabad Ghahramani O., Ahmadi R., (2018), Employment of finned PCM container in a household refrigerator as a cold thermal energy storage system, *Therm. Sci. Eng. Prog.*, vol. 7, no. June, pp.115–124.

[21] *** *Engineering Equation Solver Academic Professional*, V.10.664-3D #4487, Faculty of Mechanical Engineering, University Politehnica of Bucharest, 2019.

[22] https://www.rubitherm.eu/en/productcategory/anorganische-pcm-sp

[23] https://www.rubitherm.eu/en/productcategory/organische-pcm-rt