SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Performance Improvement of The Domestic Refrigerator Using Phase Change Materials

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ARTICLE INFO

Article history:
Received 27 January 2022
Received in revised form 12 April 2022
Accepted 16 April 2022
Available online 20 May 2022

Keywords:
Domestic refrigerator; phase change material; experiment; computational fluid dynamics; power consumption; coefficient of performance

ABSTRACT

A growing environmental Impact of global warming and rapidly increasing cost of the electrical energy cause researchers in the field of refrigeration and air conditioning to develop the sustainable cooling technologies. This study investigated the influence of latent heat storage materials on the power consumption and the temperature distribution of a commercial domestic refrigerator. The 2 kg PCMs (Phase change materials) slab of thickness 5 mm, which consisted of a 2:1 by weight mixture of refined paraffin wax and kerosene oil, were located on the back side of the roll-bond evaporator and the copper coated steel tubing coils of the hot-wall condenser, in order to improve the higher performance of refrigerator and to decrease the operating cycle time of the compressor. The experimental and CFD (Computation fluid dynamics) simulation results indicated that the refrigerator equipped with the PCMs storage unit showed a significant enhancement of the system performance and a reduction of the temperature fluctuations in the refrigerator compartment compared to a conventional system. In this investigation, the electric power consumption and the compressor on-time ratio were reduced by 15.69% and 12.13%, respectively. Moreover, the COP (Coefficient of performance) of the refrigeration system was increased by 9.53%.

1. Introduction

Global electricity consumption is the steady increase over the period from 2000 to 2020, because of population and economic growth. Furthermore, higher combustion of fossil fuels for electricity production leads to the increase of greenhouse gas emissions, particularly CO_2 (Carbon dioxide), which contributes to global warming. EPPO (Energy Policy and Planning Office), Ministry of Energy, Royal Thai Government reported that the electricity consumption and greenhouse gas emissions were 190 TWh and 88.3 million tonnes of CO_2 equivalents in 2021, respectively. Both the refrigerator and the air conditioner were widely used household appliances, which consumed approximately 30-40% of the residential electricity demand. The refrigerators are one of the hardest working appliances which operate continuously throughout the year. Therefore, refrigerators still have a large potential

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https://doi.org/10.37934/arfmts.95.2.2028

for energy saving. There are many according technical developments for performance improvement of the domestic refrigerators, such as developing the efficiency of the compressor [1], improving the thermal insulation of the cabinet and door [2-5], and enhancing the heat transfer of the condenser and evaporator [6-9]. Another approach to develop the system performance and to reduce the temperature fluctuations in the refrigerator compartment is the integration of PCMs in refrigerator compartments [10-19].

The PCMs (Phase Change Materials) are latent heat storage materials that freeze and melt at a nearly constant temperature. Moreover, large amounts of energy are accumulated or released during the process. The thermal storage materials are generally classified into three types such as organic, inorganic and eutectics, which can be identified as PCMs from the melting temperature and latent heat of fusion [20-23]. The information and application of the PCMs were introduced by Sharma *et al.,* [24]. The normal paraffins, also called alkanes, are saturated compounds that have the general formula C_nH_{2n+2}. In addition, paraffins containing between 5 to 15 carbon atoms per molecule are usually liquids at room temperature, and the straight chain hydrocarbons having more than 15 carbon atoms per molecule are waxy solids. In general, paraffin wax, a combination of different hydrocarbons, is the most popular commercial organic heat storage PCMs which is obtained from petroleum distillation. The application of PCMs can be found in solar energy storage systems, waste heat recovery systems, and space heating and cooling. The most common PCMs for space cooling are water, ice, eutectic salts, and paraffin wax.

The purpose of this study was to investigate the influence of the integration of PCMs slab (which located on the back side of the roll-bond evaporator and the copper coated steel tubing coils of the hot-wall condenser) on the power consumption and the temperature distribution of a commercial domestic refrigerator.

2. Methodology

2.1 Experimental Study

2.1.1 The PCMs heat storage

The paraffin wax - kerosene oil composite of 2 kg and a 2:1 by weight mixture, the commercial organic latent heat storage materials, were used for thermal storage in the modified PCMs refrigerators. The back side of the roll-bond evaporator and the copper coated steel tubing coils of the hot-wall condenser were equipped with aluminum foil PCMs sheet and aluminum foil tape. Moreover, the characteristics of the PCMs material were as follows: the melting point temperature is 32°C, the latent heat of fusion is 251 $kJkg^{-1}$, the thermal conductivity is 0.514 (solid phase) and 0.224 (liquid phase) $Wm^{-1}K^{-1}$, the specific heat is about 2.1 $kJkg^{-1}K^{-1}$, the density is 785 (solid phase) and 749 (liquid phase) kgm^{-3} and the volumetric expansion is 4.8% when melted.

2.1.2 The modified PCMs refrigerators

The Label No.5 direct-cool single-door household refrigerators, Mitsubishi MR-17KA, were used for comparison. In 2011, TISI (Thai Industrial Standard Institute) indicated that the average annual electric power consumption of the Energy Efficiency Label No.5 refrigerators was about 194.18 kWh. The operating temperature range of the freezer over a period was between -9 and -19^{o}C. Moreover, the characteristics of ordinary commercial domestic refrigerators were as follows

i. Cabinet: an internal volume of 170 L (1.16 x 0.56 x 0.60 m) contained 142 L of fresh food storage compartment and 28 L of frozen food storage compartment;
ii. Evaporator: free convection, aluminium roll-bond evaporator;
iii. Condenser: free convection, hot-wall condensers (copper coated steel tubing coil);
iv. Compressor: Hermetic reciprocating compressor (AZ A1327YK-R);
v. Capillary tube: inner diameter of 0.4 mm and external diameter of 1.8 mm;
vi. Refrigerant: 90 g of Tetrafluoroethane (HFC-134a);
vii. On-off control and automatic defrost.

In the present study of the modified PCMs refrigerators, the effect of the PCMs heat storage was identified to evaluate the change of the system performance. The integration of the PCMs slab of thickness 5 mm on the back side of the roll-bond evaporator coils and the copper coated steel tubing of the hot-wall condenser coils were investigated, as shown in Figure 1. In both cases, the PCMs of 0.8 and 1.2 kg were integrated into the evaporator and the condenser, respectively.

2.1.3 Measurement of temperature and system performance

The operating condition in a laboratory was maintained at the uniform temperature of 25°C and the relative humidity of 50% by an air conditioner and an air dehumidifier. The primary of collected data after 24 hours of continuous operation included temperature, pressure and power consumption of the refrigerator and were sampled every 60 s. The temperatures of the three points at evaporator coils, three points in the frozen food storage compartment and five points in fresh food storage compartment were measured with T-type (copper–constantan) thermocouples of 0.5 mm diameter. The inlet and outlet pressure of the compressor were measured with pressure transducers. Moreover, the power consumption of refrigerators was collected by the power meter. All calibrated instruments (by a manufacturing company) were equipped with a data logger system linked to a personal computer. The measured parameters and the associated uncertainties for this experiment were summarized in Table 1. The COP (Coefficient of performance) of the refrigeration system was defined by the ratio of cooling effect and compressor work.

Table 1
Estimated uncertainties of measurement

Measured parameter	Measuring device	Uncertainty
Temperature	Thermocouples	±0.5°C
Pressure	Pressure transducers	±0.01 bar
Humidity	Humidity transducers	±1% RH
Power	Power meter	±0.5 W

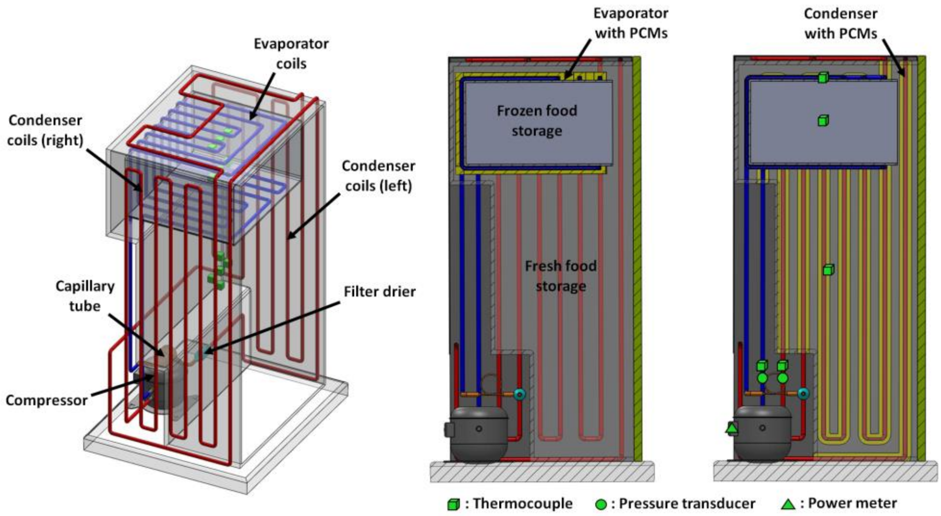


Fig. 1. Experimental setup: refrigerator components and instrumentation

2.2 Numerical study

The ANSYS software, a CFD (Computation fluid dynamics) program which is often used to solve the governing equation of the fluid dynamic and heat transfer problems such as the Navier–Stokes or energy equations by numerical method, was used to explain the phenomena of the temperature distribution in the refrigerator compartment. The effect of the PCMs heat storage was investigated by arranging elements on the back side of the roll-bond evaporator. To simplify the numerical study, only half the cross-section of the domain geometry was simulated assuming symmetry. The grid size of mesh independency and time step used for this simulation were 0.015 m and 1 s, respectively. The physical properties of the air, aluminum, polyurethane foam insulation and PCMs were assumed to be constant and the melting/freezing process for the PCMs was not included. The governing equations for this fluid flows problem were three-dimensional, viscous-laminar, incompressible and transient heat transfer. Both the radiation and the natural convection heat transfer were investigated. A simple algorithm gives a method of calculating pressure and velocities. Under the finite volume method, although the first-order upwind scheme discretization can yield better convergence, it generally will lead to less accurate results with only first-order accuracy. Therefore, the QUICK (quadratic upwind differencing) scheme discretization with third-order accuracy was used in calculating momentum and energy equations.

3. Results and Discussion

3.1 The Effect of PCMs on Temperature Fluctuations in The Refrigerator Compartment

In experimental results of the steady state condition (about 75 min), Figure 2 indicated, for the ordinary commercial domestic refrigerators, the evaporator temperature varied from -19.8 to -8.5^{o}C, the frozen food temperature varied from -6.3 to 4.3^{o}C, and the fresh food temperature varied from 7.6 to 14.2^{o}C. In the case of modified PCMs refrigerators as condenser with PCMs, Figure 3(a) illustrated the evaporator temperature varied from -20.2 to -8.4^{o}C, the frozen food temperature varied from -6.5 to 4.3^{o}C, and the fresh food temperature varied from 7.7 to 14.3^{o}C. Further, the modified PCMs refrigerators as evaporator with PCMs, Figure 3(b) shown that the evaporator temperature varied from -17.5 to -9.1^{o}C, the frozen food temperature varied from -4 to 3.8^{o}C, and the fresh food temperature varied from 9.8 to 14.1^{o}C. Moreover, the temperature distributions in the refrigerator compartment for CFD numerical results were illustrated in Figure 4 and Figure 5 for the ordinary refrigerators and the modified PCMs refrigerators as evaporator with PCMs, respectively.

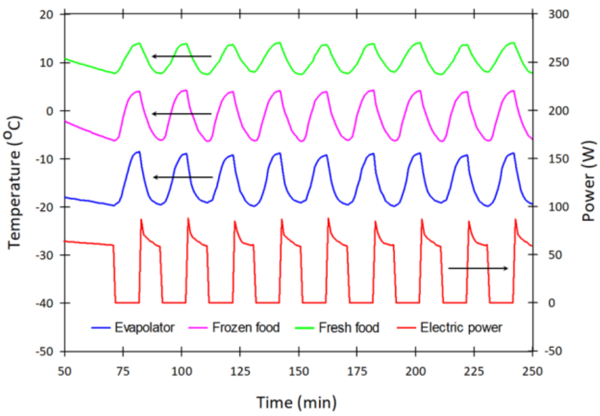
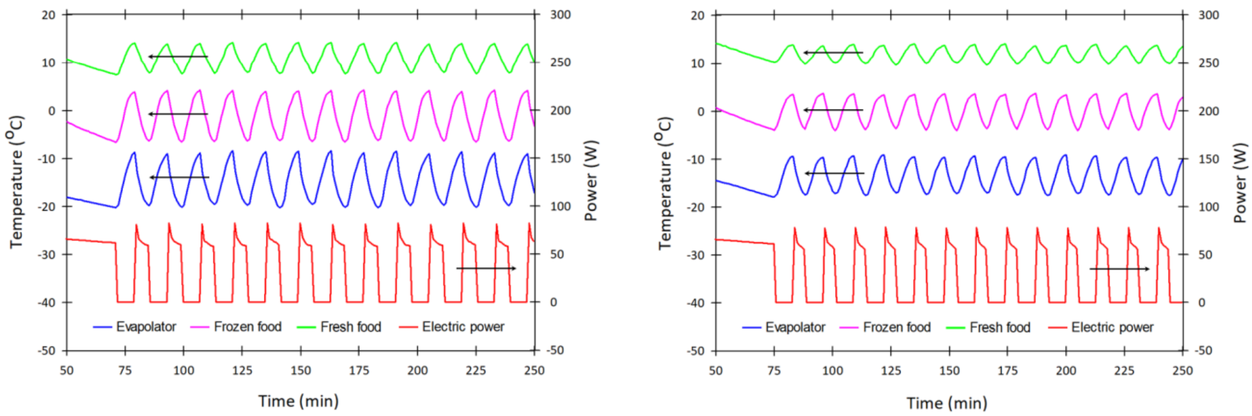


Fig. 2. Experimental results: ordinary commercial domestic refrigerators



(a) Condenser with PCMs

(b) Evaporator with PCMs

Fig. 3. Experimental results: modified PCMs refrigerators

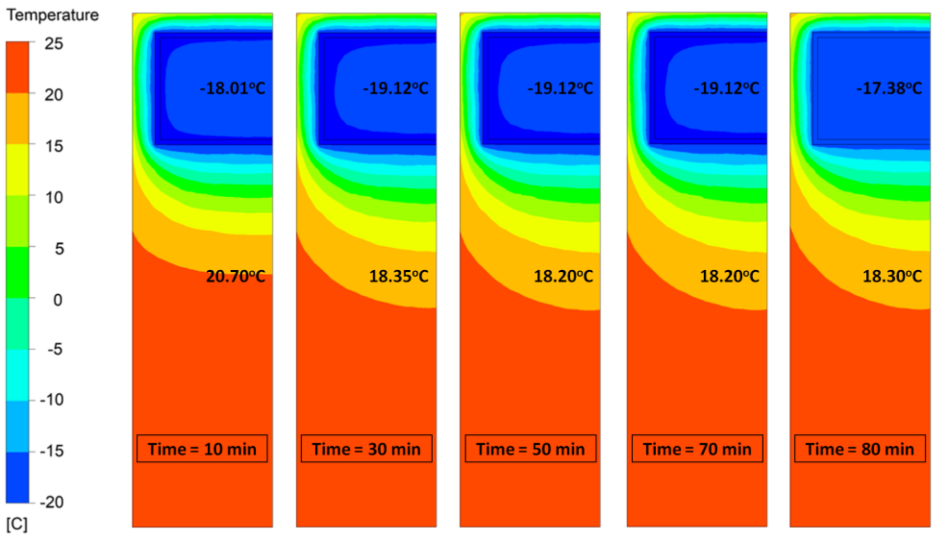


Fig. 4. Numerical results: ordinary commercial domestic refrigerators

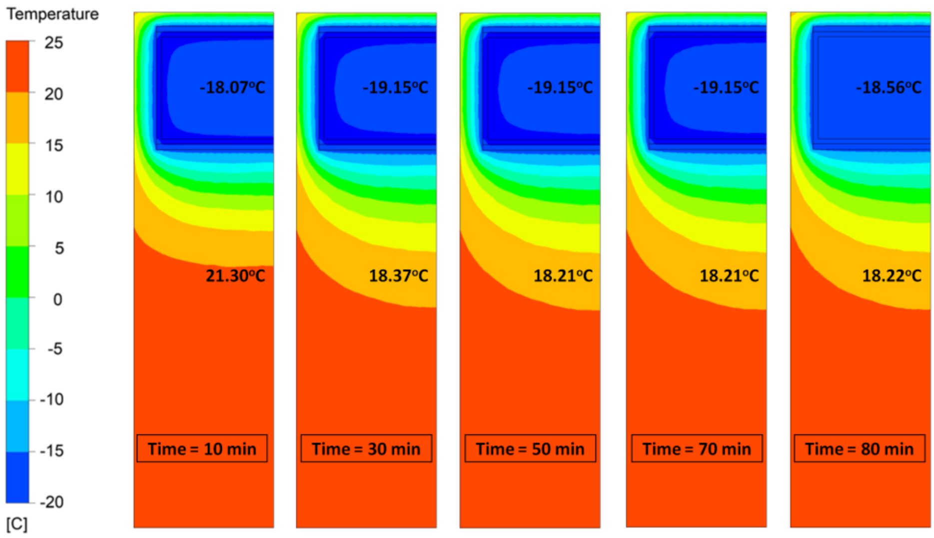


Fig. 5. Numerical results: evaporator with PCMs

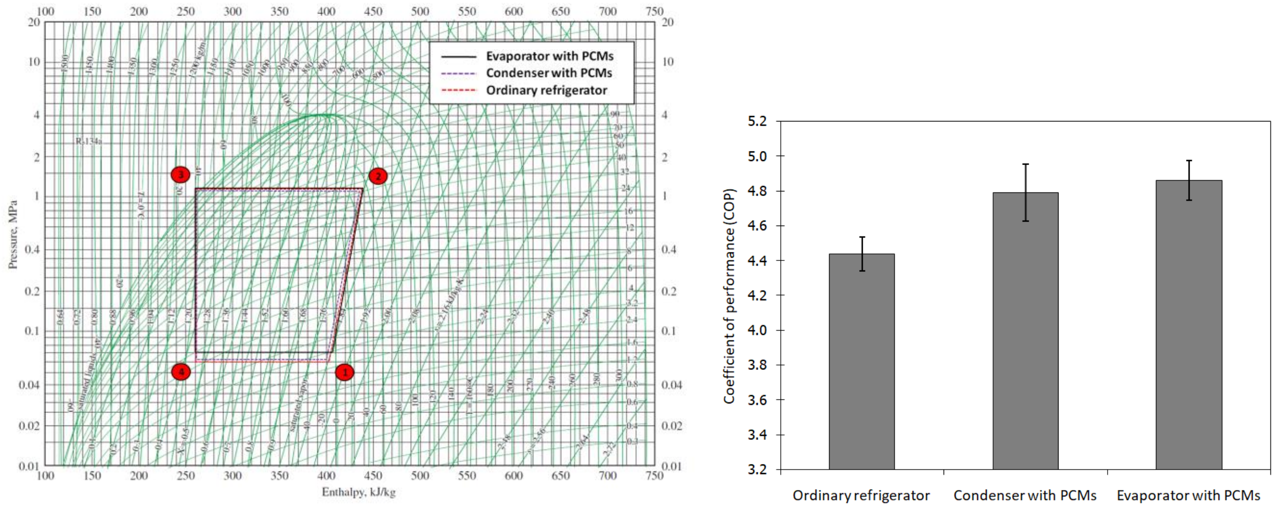
In short, the temperature profile of the refrigerator with PCMs heat storage on the back side of the roll-bond evaporator varied in a short range. The results indicated that the lowest and the average evaporator temperature of the modified PCMs refrigerators were higher than the ordinary refrigerators about 2°C and 1.5°C, respectively.

3.2 The Effect of PCMs on System Performance

The results of energy consumption measurements for the ordinary commercial domestic and modified PCMs refrigerators were summarized in Table 2. The electric power consumption of the modified PCMs refrigerators was lower than the ordinary refrigerators about 5.27% and 15.69% for the condenser with PCMs and the evaporator with PCMs, respectively. The PCMs heat storage absorbed the heat of the compartment and after that the heat was transferred to the evaporator. Therefore, the cooling load of the evaporator during the on-time was greatly reduced and the running time of the compressor was decreased from 47.47% to 45.59% (condenser with PCMs) and 41.71% (evaporator with PCMs). Moreover, the modified PCMs refrigerators as evaporator with PCMs worked under the higher temperature and pressure of evaporator operation compared to the ordinary refrigerators, as shown in Figure 6(a). The COP (Coefficient of performance) of the refrigeration system was increased by 9.53%, as Figure 6(b).

Table 2
Result of energy consumption measurements for the ordinary commercial domestic and modified PCMs refrigerators

	Ordinary refrigerator	Condenser with PCMs	Evaporator with PCMs
Evaporator temperature (°C)	-19.8 to -8.5	-20.2 to -8.4	-17.5 to -9.1
Frozen food temperature (°C)	-6.3 to 4.3	-6.5 to 4.3	-4 to 3.8
Fresh food temperature (°C)	7.6 to 14.2	7.7 to 14.3	9.8 to 14.1
COP (Coefficient of performance)	4.44	4.79	4.86
Compressor on time (min)	684	657	601
Compressor off time (min)	757	784	840
Running time (%)	47.47	45.59	41.71
Daily energy consumption (kWh/24 h)	0.76	0.72	0.64
Annual energy consumption (kWh/year)	190.64	180.60	160.73
Energy savings (%)	-	5.27	15.69



(a) Pressure-enthalpy (P-h) (b) Average coefficient of performance

Fig. 6. The refrigeration cycles for 1,1,1,2-Tetafluoroethane (HFC-134a) refrigerant (Reference state; h=200 kJ/kg; s=1.0 kJ/kg^{-1}K^{-1} for saturated liquid at 0°C)

4. Conclusions

The performance and the temperature distribution of a commercial domestic refrigerator using the latent heat storage materials were investigated. The results indicated that the evaporator with PCMs storage unit showed a significant enhancement of the system performance and a reduction of the temperature fluctuations in the refrigerator compartment compared to an ordinary system. In this study, the electric power consumption was reduced by 15.69% and the COP (Coefficient of performance) of the refrigeration system was increased by 9.53%. For further improvement of energy efficiency, the amount and the location of different PCMs on the domestic refrigerator compartment must be optimized in accordance with the heat gain of refrigerator at standard operating temperature.

Acknowledgement
This research was funded by a grant from King Mongkut's Institute of Technology Ladkrabang.

References

[1] Knabben, Fernando T., Adriano F. Ronzoni, and Christian JL Hermes. "Effect of the refrigerant charge, expansion restriction, and compressor speed interactions on the energy performance of household refrigerators." *International Journal of Refrigeration* 130 (2021): 347-355. https://doi.org/10.1016/j.ijrefrig.2021.06.006

[2] Susan Thiessen, Fernando T. Knabben, Cláudio Melo and Joaquim M. Gonçalves. "A study on the effectiveness of applying vacuum insulation panels in domestic refrigerators." *International Journal of Refrigeration* 96 (2018): 10-16. https://doi.org/10.1016/j.ijrefrig.2018.09.006

[3] Sankarshan Verma and Harjit Singh. "Vacuum insulation in cold chain equipment: A review." *Energy Procedia* 161 (2019): 232-241. https://doi.org/10.1016/j.egypro.2019.02.086

[4] Piyanut Saengsikhiao, Juntakan Taweekun, Kittinan Maliwan, Somchai Sae-ung, and Thanansak Theppaya. "The green logistics idea using vacuum insulation panels (VIPs) for freezer logistics box in normal truck." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 21, no. 1 (2020): 15-21. https://doi.org/10.37934/araset.21.1.1521

[5] Muhieldeen, Mohammed W., Lim Chong Lye, M. S. S. Kassim, Tey Wah Yen, and K. H. Teng. "Effect of Rockwool Insulation on Room Temperature Distribution." *Journal of Advanced Research in Experimental Fluid Mechanics and Heat Transfer* 3, no. 1 (2021): 9-15.

[6] Raveendran, P. Saji, and S. Joseph Sekhar. "Performance studies on a domestic refrigerators retrofitted with building-integrated water-cooled condenser." *Energy and buildings* 134 (2017): 1-10. https://doi.org/10.1016/j.enbuild.2016.11.013

[7] WafirulHadi, Mohamad, Titin Trisnadewi, and Nandy Putra. "Thermal Management System Based on Phase Change Material (PCM) and Heat Pipe in Lithium-ion Electric Vehicle Batteries." *Journal of Advanced Research in Experimental Fluid Mechanics and Heat Transfer* 3, no. 1 (2021): 26-35.

[8] Mustafa Ahmed Abdulhussain. "Investigation of heat transfer enhancement in the refrigerator freezer via utilizing elliptical-shaped scars." *CFD Letters* 12, no. 5 (2021): 60-81. https://doi.org/10.37934/cfdl.12.5.6081

[9] Sami Missaoui, Zied Driss, Romdhane Ben Slama and Bechir Chaouachi. "Experimental and numerical analysis of a helical coil heat exchanger for domestic refrigerator and water heating." *International Journal of Refrigeration* 133 (2022): 276-288. https://doi.org/10.1016/j.ijrefrig.2021.10.015

[10] Azzouz, K., Denis Leducq, and D. Gobin. "Enhancing the performance of household refrigerators with latent heat storage: an experimental investigation." *International journal of refrigeration* 32, no. 7 (2009): 1634-1644. https://doi.org/10.1016/j.ijrefrig.2009.03.012

[11] Wen-Long Cheng, Bao-Jun Mei, Yi-Ning Liu, Yong-Hua Huang and Xu-Dong Yuan. "A novel household refrigerator with shape-stabilized PCM (Phase Change Material) heat storage condensers: An experimental investigation." *Energy* 36, no. 10 (2011): 5797-5804. https://doi.org/10.1016/j.energy.2011.08.050

[12] Khan, MD Imran Hossen, and Hasan MM Afroz. "Experimental investigation of performance improvement of household refrigerator using phase change material." *International Journal of Air-Conditioning and Refrigeration* 21, no. 04 (2013): 1350029.https://doi.org/10.1142/S2010132513500296

[13] Dongliang Zhao and Gang Tan. "Experimental evaluation of a prototype thermoelectric system integrated with PCM (phase change material) for space cooling." *Energy* 68 (2014): 658-666. https://doi.org/10.1016/j.energy.2014.01.090

[14] Marques, A. C., G. F. Davies, G. G. Maidment, J. A. Evans, and I. D. Wood. "Novel design and performance enhancement of domestic refrigerators with thermal storage." *Applied Thermal Engineering* 63, no. 2 (2014): 511-519. https://doi.org/10.1016/j.applthermaleng.2013.11.043

[15] Sonnenrein, G., A. Elsner, E. Baumhögger, A. Morbach, K. Fieback, and J. Vrabec. "Reducing the power consumption of household refrigerators through the integration of latent heat storage elements in wire-and-tube condensers." *International journal of refrigeration* 51 (2015): 154-160. https://doi.org/10.1016/j.ijrefrig.2014.12.011

[16] Yusufoglu, Y., T. Apaydin, S. Yilmaz, and H. O. Paksoy. "Improving performance of household refrigerators by incorporating phase change materials." *International Journal of Refrigeration* 57 (2015): 173-185. https://doi.org/10.1016/j.ijrefrig.2015.04.020

[17] Elarem, R., S. Mellouli, E. Abhilash, and A. Jemni. "Performance analysis of a household refrigerator integrating a PCM heat exchanger." *Applied Thermal Engineering* 125 (2017): 1320-1333. https://doi.org/10.1016/j.applthermaleng.2017.07.113

[18] Zhongbao Liu, Danfeng Zhao, Qinghua Wang, Yuanying Chi and Lingfei Zhang. "Performance study on air-cooled household refrigerator with cold storage phase change materials." *International Journal of Refrigeration* 79 (2017): 130-142. https://doi.org/10.1016/j.ijrefrig.2017.04.009

[19] Bakhshipour, S., M. S. Valipour, and Y. Pahamli. "Parametric analysis of domestic refrigerators using PCM heat exchanger." *International journal of refrigeration* 83 (2017): 1-13. https://doi.org/10.1016/j.ijrefrig.2017.07.014
[20] Ahmad Tajuddin Mohamad, Nor Azwadi Che Sidik and M'hamed Beriache. "Thermo physical enhancement of advanced nano-composite phase change material." *Journal of Advanced Research in Applied Mechanics* 54, no. 1 (2019): 1-8.
[21] Chow Hoong Kee, Nor Azwadi Che Sidik, Siti Nurul Akmal Yusof, M'hamed Beriache, and Ahmad Tajuddin Mohamad. "Performance Enhancement of Cold Thermal Energy Storage System Using Nanofluid Phase Change Materials." *Journal of Advanced Research in Applied Mechanics* 62, no. 1 (2019): 16-32.
[22] Tung Hao Kean and Nor Azwadi Che Sidik. "Thermal Performance Analysis of Nanoparticles Enhanced Phase Change Material (NEPCM) in Cold Thermal Energy Storage (CTES)." *CFD Letters* 11, no. 4 (2019): 79-91.
[23] Azmi, Mohd Irwan Mohd, Nor Azwadi Che Sidik, Yutaka Asako, Wan Mohd Arif Aziz Japar, Nura Muaz Muhammad, and Nadlene Razali. "Numerical Studies on PCM Phase Change Performance in Bricks for Energy-Efficient Building Application–A Review." *Journal of Advanced Research in Numerical Heat Transfer* 1, no. 1 (2020): 13-21.
[24] Sharma, S. Dutt, and Kazunobu Sagara. "Latent heat storage materials and systems: a review." *International journal of green energy* 2, no. 1 (2005): 1-56. https://doi.org/10.1081/GE-200051299