كلية الهندسة بشبرا
FACULTY OF ENGINEERING AT SHOUBRA
ERJ
ISSN:1687-1340

ENGINEERING RESEARCH JOURNAL (ERJ)
Volume (52) , Issue (3)
July 2023, pp:40-46
https://erjsh.journals.ekb.eg

An Experimental Study on Solidification and Melting Processes of Ice-On-Bare U-Tube Copper Coil

M. S. Zeid*[a], A. A. Abdel-Aziz [a], H. E. Abdelrahman [a], H. A. Refaey [a]

[a]Department of Mechanical Engineering, Faculty of Engineering at Shoubra, Benha University, Cairo, Egypt.
* Corresponding Author
E-mail:mohamedsalahzeid@gmail.com,ali.ali@feng.bu.edu.eg,hany-elsawy@feng.bu.edu.eg,
hassanein-refaey@feng.bu.edu.eg.

Abstract: Thermal energy storage (TES) offers a significant benefit not only in shifting the superior electric power utilized by air conditioning systems from (on-peak) times to (off-peak) times but also reducing the air condition equipment size, improving operation of HVAC equipment subsequently reducing operation cost and save energy. An experimental study of storing ice systems involved in a bare U-tube coil submerged in distilled water as a phase change material is conducted in the present study. During the charging (solidification) and discharging (melting) operations, the effects of modifying the ethylene glycol solution, Heat Transfer Fluid (HTF), temperature and flow rate on the charging/discharging time and the average charging/discharging rate are explored. The outcomes revealed that, time required for complete charging (solidification) decreased by decreasing HTF temperature and increasing HTF volume flow rate. Also, time required for complete discharging (melting) decreased by increasing HTF temperature and increasing HTF volume flow rate.

Keywords: **:** Thermal energy storage; operation parameters; bare u-tube copper coil; Ice-on-coil internal melt.

1. INTRODUCTION

Nowadays in modern buildings, including homes, offices, and factories, air conditioning systems are used, particularly in regions with protracted, hot summers. Hence, the electrical power consumption is increased with the increased cooling demand. Consequently, to lower the electrical demand during the off-peak period, cooling energy is kept in thermal energy storage tanks. At night (off-peak times) chillers are utilized for the charging process to sore cooling energy. Then, during the day (during peak periods), cold stored energy is released to meet the building's cooling demands. Sait [1] experimentally investigated the solidification of water ice-on-coil thermal energy storage on 5 parallel tubes coil subjected to several falling film types. The results disclosed that about 1.73 $g/m^2.s$ of ice was formed on the tube at falling film jet mode. Xie and Yuan [2] utilized the Taguchi method to investigate numerically the thin layer ring effect on ice growth in a rectangular space. The outcomes disclosed that, the period needed for the ice formation could be reduced by raising the thin layer ring area. Jannesari and Abdollahi [3] presented experimental and numerical studies on ice accumulation in thermal energy storage systems. The result revealed that utilizing thin rings and annular fins around coils showed 21% and 34 % enhancement in ice formation respectively, compared to bare tubes. ElGhnam et al. [4] experimentally studied heat transfer inside spherical capsules on the solidification and melting of water. The results revealed that using a small size metallic capsule, lowering heat transfer fluid (HTF) temperatures, and increased heat transfer fluid volume flow rate.

Gasia et al. [5] carried out an experiment on the storage period and its effect on solidification and melting in a TES system employing partial load functioning conditions. The results indicated that the first charging period (first 30 min) had a slight effect on the profiles of temperatures and heat transfer. Bai et al. [6] ran a research experiment to determine the impact of open-cell metallic foam with inserted copper fins. The results exposed that the solidification rate of water had been improved by fixing copper fins on metal foam. Li et al. [7] presented a theoretical and experimental study thermal energy storage system in a heat exchanger coil. The outcomes revealed that the temperature of evaporating tube increased according to the agitator height increased. Mahdi et al. [8] performed an experimental study on paraffin wax melting rate while using a conical and normal coil. The results showed that using a conical coil with HTF inlet temperatures of 70 °C the paraffin wax melting rate was enhanced by 20.97 % compared with the normal coil.

Mahdi et al. [9] numerically studied latent heat thermal energy storage systems (LHTES) utilizing double pipe helical coil tubes which was the best compared to straight double pipe, both vertically and horizontally. Fanga et al. [10] experimental research on the (LHTES) capacity in shell and tube utilizing different Phase change materials under circumstances of both laminar and turbulent flow (Re: 500–14,500). The findings showed that the TES capacity using pentadecane-EG composite with keff = 8.6 W/(m·K) was twice that of an ideal stratified-water-storage tank running at Re = 4300. Hamzeh and Miansari [11] performed numerical analyses of the thermal energy performance of an ice-on-coil thermal storage tank by utilizing fins around tubes with different design conditions and arrangements. In a cavity with a refrigerant carrier, the ice formation was carried out. The results indicated that the freezing rate with notably increased as fin height increased. Abdelrahman et al. [12] carried out an experimental study using a twin concentric helical coil to enhance the thermal energy efficiency of an ice storage system (TCHC), with different operating conditions. The outcomes disclosed that approximately 90% of the thermal energy reserved was obtained at 59% to 74% of the full Charge duration related to the parameters that were tested. Ismail and Lino [13] experimentally studied how turbulence intensifiers and the diameter of radial fins could improve the rate of heat transfer around a horizontal tube submerged in PCMs. The results revealed that the solidification process around a radially finned tube was strongly influenced by the temperature of the working fluid. While the impact of various mass flow rates was relatively smaller than working fluid temperatures. Moreover, the utilities of turbulence promoter led to short solidification time, thus effects are not as strong as those brought on by radial fins. Cláudia et al. [14] studied the utilization of axially finned tubes submerged in PCM in cooling applications. The outcomes disclosed that increasing fins number and its width improved the interface location while reduced the complete solidification time. Ismail et al. [15] the impact of cooling fluid temperature and flow rate on interface velocity, an experimental and numerical analysis of PCM solidification around a curved cold tube to determine the time for full solidification and the solidified mass. The results revealed that less than 8% of the solidified mass and less than 4% of time required for full solidification and interface velocity were agreed upon in comparative studies of the impacts of the working heat transfer fluid flow rate. The study also showed that the time for complete solidification and the interface velocity was found to be less than 8% predictable when the working heat transfer fluid temperature was considered.

Xie and Yuan [16] investigated numerically ice formation from thin ring structures in the case of a thermal storage system. The findings revealed that the ring thickness affected the pace of ice formation. Furthermore, the rings staggered structure introduced the greatest ice formation. Ezan and Erek [17] performed an experimental study on TES with various ice-on-coil conditions. The outcomes showed that the external melting phase supplied low outlet temperatures with a longer time compared to internal melting. López-Navarro et al. [18] performed an experimental investigation on the thermal behavior of TES ice-on-coil during the melting phase for various operational conditions.

Sait and Selim [19] performed an experimental study on ice creation around cold vertical banks of horizontal tubes that were subjected to falling film-jet mode at specific operational conditions. The outcomes showed that the gained ice and melting time were somewhat influenced by the inlet heat transfer fluid. Sharma et al. [20] performed a parametric numerical study of ice formation for a tube-in-tank storage system with water as PCM. The findings revealed that there was an optimal number of fins that increased the solidification rate.. Rahimi et al. [21] made an experimental investigation on the heat transfer during charging/discharging of the PCMs (RT35) in a heat exchanger with fins and tubes. The findings revealed that melting time decreases dramatically for simple heat exchangers with turbulent water side while utilizing fins has a greater impact on the charging/discharging processes. Lohrasbi, et al. [22] executed a numerical analysis of the melting process of LHTESS by a new fin array configuration. The results exposed that immersing a fin in LHTESS considerably improved the solidification rate. Hossein and Mehdii [23] numerically simulated the ice formation in a cavity in an ice-on-coil tank. Furthermore, the influence of fins with several dimensions and tube shapes was performed. The outcomes disclosed that the height of the fin affected the freezing rate. Huang et al. [24] numerically investigated the impact of utilizing novel hierarchical fins on enhancing the thermal performance of horizontal LHT. The findings showed that the used fins enhanced the solidification rate. Recently, Refaey et al. [25] presented an experimental investigation on the geometrical effects of twin concentering helical coil on solidification/melting processes. The outcomes revealed that the discharge time improved by 79% for total energy achieved when coil pitch grows from 30 to 50 mm for tube diameter 9.52 mm. While the discharge time was expanded at tube diameter 15.88 mm.

From the previous review, it could be summarized that most of the studies were carried out for straight tubes, falling film on rings. Most of the results were numerical for fins with different shapes around a tube. Some of them were experimental studies but with a helical coil. While the reduction ln the heat transfer coefficient when additional ice accumulated on the coil/tube in line with the resistance of the ice layer. Consequently, the present work focuses on analyzing the effectiveness of ice storage systems, by using an ice-on-copper bare U-tube. Furthermore, the impact of operational parameters (including the ethylene glycol (HTF) volume flow rate and intake temperature) on the thermal behavior of bare U-tube inside the storage tank are studied.

2. EXPERIMENTAL SETUP

An experimental testing apparatus is assembled to investigate the solidification and melting processes of an ice-on-coil using bare copper tube. Fig. 1 shows a real photo of the test rig. In addition, Fig. 2 illustrates a schematic design and the details of the test rig in the current work. It comprises two cycles (vapor compression cycle and ice storage cycle) which were presented in detail by Abdelrahman et al. [12].

Fig. 1: Real photo of the experimental setup.

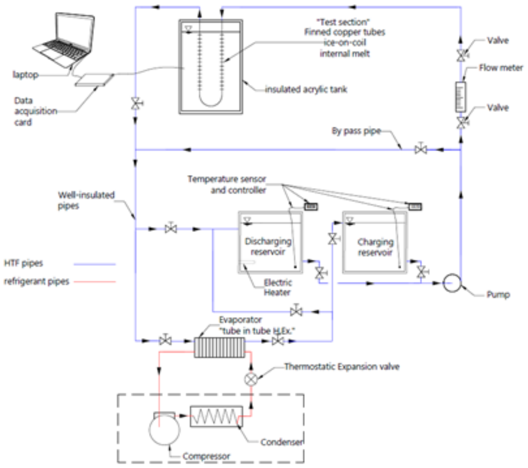

Fig. 2: Schematic illustration of the experimental setup

A well-insulated acrylic storage tank (6mm thickness, 280 mm length, 63 mm depth, and 32 mm width) containing bare copper U-tube that is submerged in distilled water as a (PCM). Two individual and identically charging and discharging basins (613 x 296 x 422 mm) with isolated top cover. They are containing ethylene glycol solution is employed as the heat transfer fluid (HTF) with 35 % concentration by weight with -19℃ freezing temperature. The acrylic tank is occupied with the PCM. From Fig. 2, the charging and discharging experiments are controlled by many isolation valves and fittings as assembled in the schematic illustration of the test rig.

The PCM temperatures are measured using six calibrated copper-constantan (T-type) thermocouples during solidification and melting experiments around the bare copper U-tube coil. Those thermocouples are attached to data acquisition to record the temperatures continuously. The utilized bare copper U-tube coil is illustrated in Fig. 3. A calibrated digital temperature sensor ranging from -50℃ to +70℃ (embedded TPM-30) with a resolution of 0.1℃ is employed in the measurement of temperature. A calibrated rotameter is used to monitor the HTF volume flow rate. with an adjusting valve. Besides, a digital temperature controller to adjust the HTF temperatures during the solidification and melting operations, inside the charging and discharging tanks, correspondingly, with a fixed-point differential of ± 1℃.

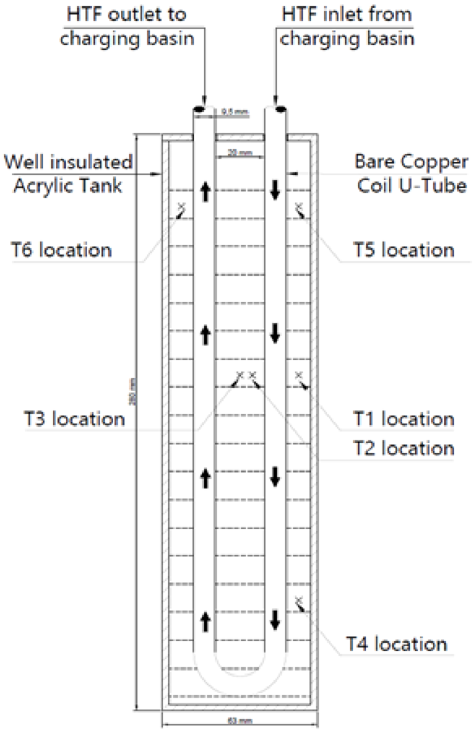

Fig. 3: Schematic representation of the utilized bare copper U-tube coil showing the thermocouples locations.

3. EXPERIMENTAL PROCEDURES

The experiments are conducted in a controlled-climate laboratory with a continuous indoor environment of 22 ±1 °C for the dry bulb temperature and 50±5% for relative humidity. The charging and discharging processes are carried out under different experimental operation parameters as listed in Table 1. The refrigeration system works to chill the HTF that is being circulated between the evaporator and the charging reservoir. When the HTF temperature set point is achieved, The HTF volume flow rate is set to the test flow rates, and the HTF is permitted to pass through one of the test sections. The data acquisition system monitors and records PCM temperature values once every 30 s. When the temperature of the ice or water inside the storage tank approaches the temperature of the HTF, the charging or discharging tests have been paused. During the discharging operation, the DTC sensor adjusts the HTF temperature via the electric heater inside the discharging reservoir.

Table 1: operation parameters of the bare copper U-tube coil during charging and discharging processes.

Process Description	Charging process	Discharging process
HTF inlet temperature, °C	-8, -10 and -12	10, 12 and 14
HTF volume flow rate, LPM	10, 15 and 20	

4.DATA REDUCTION

The average charging/discharging rates with time is calculated as a bulk energy stored/regained by monitoring the thermocouples temperature readings at several points during the entire charging and discharging cycles as demonstrated in Fig.3.

The average thermal energy stored and regained is computed as follows.

$$\mathrm{Q_{st}} = \mathrm{m_o}\{\mathrm{c_w}(\mathrm{T_o}-\mathrm{T_l}) + \vartriangle H_{fus} + \mathrm{c_i}(\mathrm{T_{pc}}-\mathrm{T_s})\}$$

$$\mathrm{Q_{reg}} = \mathrm{m_o}\{\mathrm{c_i}(\mathrm{T_s}-\mathrm{T_o}) + \vartriangle H_{fus} + \mathrm{c_w}(\mathrm{T_l}-\mathrm{T_{pc}})\}$$

The specifications of PCM (distilled water), that is used in the present work in both phases liquid and solid are shown in Table 3.

Table 2: Attributes of PCM (distilled water).

Property	Water at 0°C	Ice at 0°C
Density, kg/m^3	ρ_w =1000	ρ_i = 920
Specific heat, J/kg°C	c_w =4230	c_i =2040
Latent heat of fusion, J/kg	$\vartriangle H_{fus}$ =333.7×10^3	

The uncertainties in the main parameters are stated in Table 3 for all experimental runs. It was determined according to Kline and McClintock [26].

Table 3: Average uncertainties in the parameters.

Parameter	Uncertainty (ω)
T, (°C)	$\pm$0.28
t, (s)	$\pm$1
V, (cm^3)	± 0.5
Flow rate, (l/min)	± 0.5
$\dot{\mathrm{Q}}_{\mathrm{ch}}$ or $\dot{\mathrm{Q}}_{\mathrm{dis}}$, (W)	$\pm$8.6%

5. RESULTS and DISCUSSION

Investigating the effects of the operation parameters (HTF inlet temperatures and volume flow rates) on the thermal storage of CTES system including the average charging and discharging rate during water solidification and ice melting processes, is the primary goal of the current experimental study.

5.1 Test Rig Validation and Temperature Gradient of PCM Inside Acrylic Tank

Firstly, the present measurement data is validated with the available literature by comparing with Abdelrahman et al. [12]. The experiments of Abdelrahman et al. [12] were conducted on twin concentric helical coil “TCHC” immersed in a storage tank having 9.6 liters of distilled water “PCM”. The experiments parameters were HTF volume flow rate of 10 l/min, an initial PCM temperature of 20°C for distilled water and -12°C for ice, inlet HTF temperatures of -12°C and 12°C during charging and discharging modes, respectively as shown in Fig. 4. The present measurement is carried out on u shape bare tube immersed in a storage tank having 0.6 liter of distilled water with an initial PCM temperature of 20°C for distilled water and -12°C for ice, HTF volume flow rate of 20 l/min, inlet HTF temperatures of -12°C and 10°C during charging and discharging modes, respectively as shown in Fig. 4. The observed difference can be returned to the difference in coil geometry, PCM volumetric capacity, HTF volume flow rate and the thermocouple location relative to coil surface. From Fig. 4, it can be seen that the present experimental measurements are in good agreement, regarding trend behaviour, with the previous studies which reveals the accuracy of experimental setup and measuring techniques.

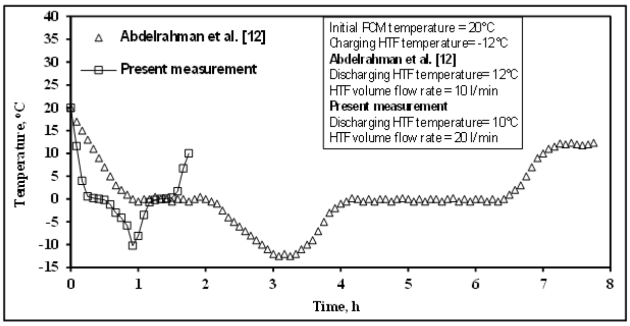

Fig. 4: Comparison between present measurements and Abdelrahman et al. [12].

5.2Effect of HTF Inlet Temperature and Volume Flow Rate throughout the Charging Process

The impact of HTF flow rates on the charging time against HTF temperatures is shown in Fig. 5. It can be seen that the charging time decrease by increasing HTF flow rates and decreasing HTF inlet temperatures. Moreover, the impact of HTF flow rates on the average charging rate against HTF temperatures is shown in Fig. 6. It can be seen that the average charging rates increase by increasing HTF flow rates and decreasing HTF inlet temperatures.

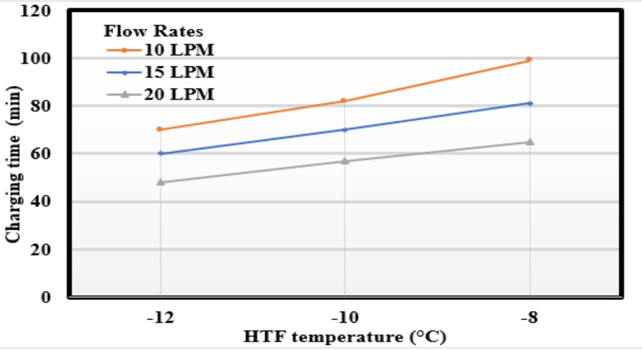

Fig. 5: Variation of the charging time using different operation parameters.

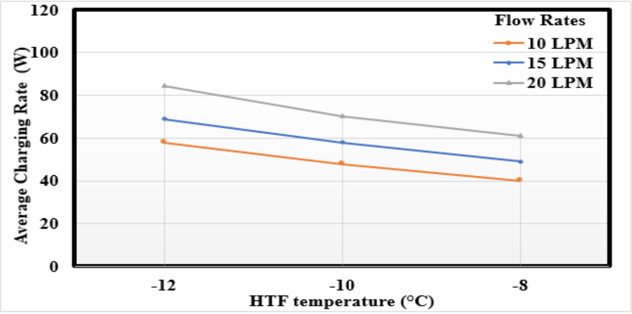

Fig. 6: Variation of the average charging rates using different operation parameters.

5.3Effect of HTF Inlet Temperature and Volume Flow Rate throughout Discharging Process

The impact of HTF flow rates on the discharging time against HTF temperatures is shown in Fig. 7. It can be seen that the discharging time decrease by increasing HTF flow rates and increasing HTF inlet temperatures. Moreover, the effect of HTF flow rates on the average discharging rate against HTF temperatures is shown in Fig. 8. It can be seen that the average discharging rates increase by increasing HTF flow rates and increasing HTF inlet temperatures.

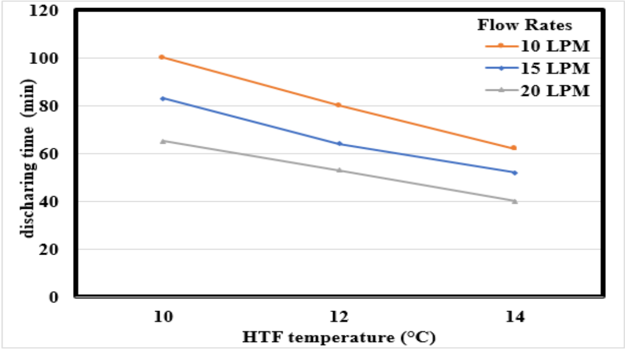

Fig. 7: Variation of the discharging time using different operation parameters.

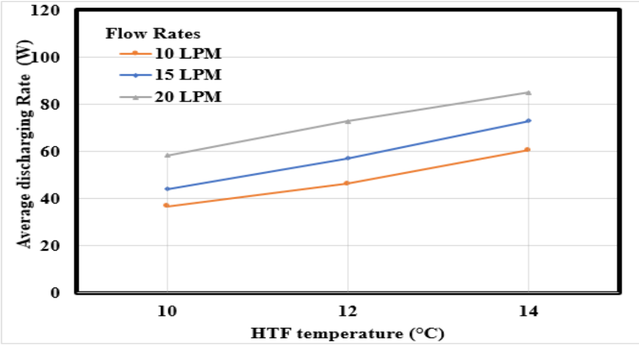

Fig. 8: Variation of the average discharging rates using different operation parameters.

6 .CONCLUSIONS

Regarding to the present study's results, the following significant features can be drawn:

1. The time for complete charging is decreased by using HTF with lower temperatures and higher volume flow rates.
2. The average charging rate is increased by using HTF with lower temperatures and higher volume flow rates.
3. The time for complete discharge is increased by using HTF with lower temperatures and volume flow rates.
4. The average discharging rate is increased by using HTF with higher temperature and flow rate.

Nomenclature

c_i	Specific heat of ice	J/kg.°C	T_l	Liquid phase temperature	°C
c_w	Specific heat of water	J/kg.°C	T_o	Initial temperature	°C
			T_{pc}	Phase change temperature	°C
ΔH_{fus}	Latent heat of fusion of water	J/kg	T_s	Solid phase temperature	°C
m_o	Total mass of the PCM stored in the tank	kg	***Greek symbols***		
			ρ_i	Ice density	
$\dot{Q}_{ch}$	Average charging rate	kg	ρ_w	Water density	kg/m^3
$\dot{Q}_{dis}$	Average discharging rate	W	τ	Time	s
Abbreviations			HTF	Heat transfer fluid	
CTES	Cool thermal energy storage		l/min	Liter per min	
DTC	Digital temperature controller		PCM	Phase change material	

References

[1] H. H. Sait, Experimental study of water solidification phenomenon for ice-on-coil thermal energy storage application utilizing falling film, Applied Thermal Engineering, Volume 146, 2019, Pages 135-145.

[2] J. Xie, C. Yuan, Parametric study of ice thermal storage system with thin layer ring by Taguchi method, Applied Thermal Engineering, Volume 98, 2016, Pages 246-255 J.

[3] H. Jannesari, N. Abdollahi, Experimental and numerical study of thin ring and annular fin effects on improving the ice formation in ice-on-coil thermal storage systems, Applied Energy, Volume 189, 2017, Pages 369-384.

[4] R. I. Elghnam, R. A. Abdelaziz, M. H. Sakr, and H. E. Abdelrhman, An experimental study of freezing and melting of water inside spherical capsules used in thermal energy storage systems, Ain Shams Eng. J., vol. 3, no. 1, pp. 33–48, 2012.

[5] J. Gasia, A. de Gracia, G. Zsembinszki, L. F. Cabeza, Influence of the storage period between charge and discharge in a latent heat thermal energy storage system working under partial load operating conditions, Applied Energy, Volume 235, 2019, Pages 1389-1399.

[6] Q. Bai, Z. Guo, X. Cui, X. Yang, L. Yanhua, L. Jin, Y. Sun, Experimental investigation on the solidification rate of water in open-cell metal foam with copper fins, Energy Procedia, Volume 152, 2018, Pages 210-214

[7] Y Li, Z. Yan, C. Yang, B. Guo, H. Yuan, J. Zhao, N. Mei, Study of a Coil Heat Exchanger with an Ice Storage System. Energies 2017, 10, 1982.

[8] M. S. Mahdi, H. B. Mahood, A. N. Campbell, A. A. Khadom, Experimental study on the melting behavior of a phase change material in a conical coil latent heat thermal energy storage unit, Applied Thermal Engineering, Volume 175, 2020.

[9] M.S. Mahdi, H.B. Mahood, J.M. Mahdi, A.A. Khadom, A.N. Campbell, Improved PCM melting in a thermal energy storage system of double-pipe helical-coil tube, Energy Conversion and Management, 203 (2020) 112238.

[10] Y. Fanga, H. Xub, Y. Miaob, Z. Baib, J. Niua, S. Deng, Experimental study of storage capacity and discharging rate of latent heat thermal energy storage units, Applied Energy 275 (2020) 115325.

[11] H.A. Hamzeh, M. Miansari, Numerical study of tube arrangement and fin effects on improving the ice formation in ice-on-coil thermal storage. International Communications in Heat and Mass Transfer 113 (2020) 104520.

[12] H. E. Abdelrahman, H. A. Refaey, A. Alotaibi, Ali A. Abdel-Aziz, M.F. Abd Rabbo, Experimental investigations on the thermal performance of an ice storage system using twin concentric helical coil, Applied Thermal Engineering, Volume 179, 2020.

[13] K.A.R. Ismail, F.A.M. Lino, Fins and turbulence promoters for heat transfer enhancement in latent heat storage systems, Experimental Thermal and Fluid Science, Volume 35, Issue 6, 2011, Pages 1010-1018.

[14] Cláudia R.E.S. Nóbrega, Kamal A.R. Ismail, Fátima A.M. Lino, Solidification around axial finned tube submersed in PCM: Modeling and experiments, Journal of Energy Storage, Volume 29, 2020.

[15] Kamal Abdel Radi Ismail, Lourival Matos de Sousa Filho, Fátima Aparecida Morais Lino, Solidification of PCM around a curved tube, International Journal of Heat and Mass Transfer, Volume 55, Issues 7–8, 2012, Pages 1823-1835.

[16] J. Xie, C. Yuan, Numerical study of thin layer ring on improving the ice formation of building thermal storage system, Applied Thermal Engineering, Volume 69, Issues 1–2, 2014, 46–54.

[17] A. Ezan, M., and A. Erek, "Solidification and Melting Periods of an Ice-On-Coil Latent Heat Thermal Energy Storage System." ASME. J. Heat Transfer. June 2012; 134(6).

[18] A. López-Navarro, J. Biosca-Taronger, B. Torregrosa-Jaime, J.M. Corberán, J.L. Bote-García, J. Payá, "Experimental investigations on the influence of ice floating in an internal melt ice-on-coil tank, " Energy and Buildings, Volume 57, 2013, Pages 20-25.

[19] H.H. Sait, A.M. Selim, Charging and discharging characteristics of cool thermal energy storage system with horizontal pipes using water as phase change material, Energy Conversion and Management, Volume 77, 2014, Pages 755-762.

[20] Amrita Sharma, P. Parth, S. Shobhana, M. Bobin, B.K. Hardik, Numerical study of ice freezing process on fin aided thermal energy storage system, International Communications in Heat and Mass Transfer 130 (2022) 105792.

[21] M. Rahimi, A.A. Ranjbar, D.D. Ganji, K. Sedighi, M.J. Hosseini, R. Bahrampoury, Analysis of geometrical and operational parameters of PCM in a fin and tube heat exchanger, International Communications in Heat and Mass Transfer, Volume 53, 2014, Pages 109-115.

[22] S. Lohrasbi, M. Sheikholeslami, D. Ganji, Multi-objective RSM optimization of fin assisted latent heat thermal energy storage system based on solidification process of phase change Material in presence of copper nanoparticles, Applied Thermal Engineering, Volume 118, 2017, Pages 430-447.

[23] Hossein Akhavan Hamzeh, Mehdi Miansari, Numerical study of tube arrangement and fin effects on improving the ice formation in ice-on-coil thermal storage systems, International Communications in Heat and Mass Transfer, Volume 113, 2020.

[24] Y. Huang, F. Yao, X. Liu, Numerical study on the thermal enhancement of horizontal latent heat storage units with hierarchical fins, Renewable Energy, Volume 180, 2021.

[25] Refaey, H.A.; Alotaibi, A.S.A.; Abdel-Aziz, A.A.; Abd Rabbo, M.F.; Abdelrahman, H.E. Geometrical Parameter Effects on Solidification/Melting Processes Using Twin Concentric Helical Coil: Experimental Investigations. *Appl. Sci.* 2022, *12*, 11047.

[26] S. J. Kline, F. A. McClintock, Describing Uncertainties in Single-Sample Experiments, Journal of Mechanical Engineering, Volume 75, No. 1, 1953, Pages 3-8.