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CFD Simulation on an Improvised Ice Cream Container

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ABSTRACT

A temperature-sensitive product such as ice-cream may cause the industry to face several challenges throughout the production, storage, packaging, and distribution processes. With the purpose to improve the performance of an ice cream container that acts as cold storage during the delivery process, the integration of a tube-type phase change material (PCM) thermal storage system was studied. In this work, a Computational Fluid Dynamic (CFD) method was used to model and analysed eight designs of phase change thermal storage systems incorporated within the ice-cream container. The tube type PCM was modeled, with and without the conducting pins, aiming to maximise the heat exchange within the system. To obtain a proper design, parametric studies on the number of pins and its diameter were further analysed. For all simulations, the initial time for freezing simulation was set to 2℃, assuming the PCM was fully in a liquid state with the ice mass fraction was set to 0. With that, the PCM average temperature and the total mass fraction was observed and analysed. From the results, the ice mass fraction percentage of the systems was observed to increase with the increasing number of pins. Model with (the maximum) 40 pins has improved ice mass fraction for at least 67.58% when compared to the configuration without pin. Also, the average temperature of PCM for model with maximum pins, was observed to be 37.14% lower when compared to the configuration without pins and less pin numbers. Nevertheless, although the presence of pins has proven to enhance the heat exchange within the system, the percentage of ice formation was considered to be low and the average temperature was still as high as 0.66℃ after 12 hrs of freezing process. This indicating that a proper design of TES is inevitably needed, in order to maximise both heat exchanges and PCM storage ability within the system.

1. Introduction

The global ice cream market size was valued at USD 79.0 billion as in 2021 [1]. The ice cream industry is expected to experience a continuous uptick in sales due to the increasing in demands for innovative flavors, types and impulse ice creams. Nevertheless, as a temperature-sensitive product, the key player in the industries may face several challenges along the supply chain that involves the

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production, storage, packaging, and distribution processes. Kozłowicz *et al.,* [2] has listed few undesirable changes that may occur during the storage, include the loss of product durability, decline in aeration, crystallisation of lactose, and reduction of probiotic bacteria. Besides, a process named recrystallisation was highlighted as one of the major problems for ice cream manufacturers [3]. It was influenced by an abusive-storage conditions, where the recrystallisation rate increased with the storage temperature and fluctuating temperatures [4]. For instance, refreezing the melted ice cream was found to affect the quality or texture due to the recrystallization of large chunks of liquid cream [5]. Besides, Donhowe and Hartel [4] reported that ice cream temperature was found to rise as high as 6°C due to the on/off regulation of refrigeration systems itself. Subjected to the temperature changes during storage of 2℃ or 3℃ and during traveling, the ice cream's temperature could rise to 3℃ to 8℃ based on the form of delivery. In order to cope with these demands and challenges, numerous studies on that subject matter have been conducted, involving the raw materials and technology improvement along the supply chain. The use of stabiliser with aim to slow down the recrystallisation was a popular method that being implemented by the industry. Nonetheless, the stabilizer employment may depend on type of ice cream, storage temperature, ice phase volume and concentration of stabilizer [6].

On the other hand, the improvement of technologies used along the supply chain of cold storage have been numerously studied [7-10]. An efficient cold storage is a key factor in frozen food industries that mostly involves ice cream, dairies, seafood, and ready-to-eat meal. Thermal Energy Storage (TES) based Phase Change Material (PCM) has been discussed a viable cold storage technology with the advantages of providing a nearly isothermal storage process and high energy storage density [11]. The effectiveness of PCM thermal storage systems is highly depending on the system configurations and the PCM used as the storage material [12]. PCM was categorised into several materials such as organic materials: paraffin and non-paraffins, Inorganic materials: Salt hydrates and metallics, and eutectics: a mixture of organics and/or inorganics [13]. The mechanism of PCM is to store latent heat by absorbing and releasing thermal energy which means charging and discharging process of liquid-to-solid or solid-to-liquid state [14].

The PCM can be encapsulated inside a cylindrical tube and rectangular wall. In addition, the wall of encapsulation may attach pins or fins purposely to increase heat transfer rate and efficiency along the exposed surface area towards surrounding or ambience temperature, in this context, Heat Transfer Fluid (HTF) [5,15,16].

The thermal energy released into HTF that flows around encapsulated wall known as convection heat transfer. In cold storage, PCM might help to keep the working temperature without a proper refrigeration system by using only circulated HTF such as air to provide sufficient working temperature of the storage during delivery [3]. A common method or packaging to deliver ice cream mostly utilizes dry ice, regular ice, and large mechanical working component such as a refrigeration system. In such method, it might require a large compartment to ratio the volume fraction between products and cooling components. This will lead to incapability such as lesser product quantity can be stored. The integration of PCM thermal energy storage was seen as a viable alternative that could enhance the performance of cold storage.

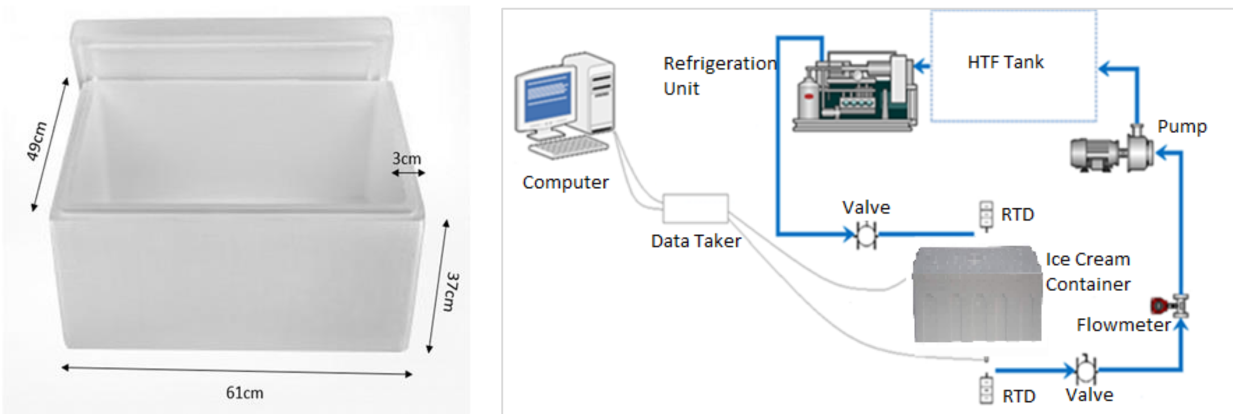
The general purpose of this work was to study the effect of tube-type PCM thermal storage being incorporated within the ice cream container wall, and furthermore, observe the influence of different PCM thermal storage configurations on the performance. The change in a configuration changes the amount of heat transfer area system that may yield a better performance heat exchange. In this paper, 8 system configurations with varied numbers of pins and their dimension were modeled. Accordingly, the Computational Fluid Dynamic (CFD) simulation method was employed to simulate and analysed the models under the same condition. The simulation involves freezing simulation, with the initial ice mass fraction and temperature was set to 0°C and 2°C, respectively. The outcome of this work is expected to provide a solution to an optimum design of PCM with pins by using available products in the market. The long-term aim is for the performance of the ice cream container used in the supply chain can be improved. Besides, a novel simulation studies of the conducting pins employment within a thin wall for heat transfer enhancement could be a great initiation and further be applied to other thermal storage system.

2. Methodology

This section discusses the approach and the procedures used to accomplish the research aims. For that purpose, a conceptual design for the system was developed by benchmarking the actual ice cream container from a local ice cream company in Malaysia with the dimensions of 61 × 34 × 49cm and 3cm thickness (Figure 1(a)). The ice cream container was used to keep the ice cream during the delivery process.

This ice cream container was then modeled to be integrated with a thermal energy storage system studied by Amin *et al.,* [17] and Aziz *et al.,* [18]. In this work, the thermal energy storage tank filled with encapsulated PCM spheres studied by Amin *et al.,* [19] was replaced by an ice cream container as illustrated in Figure 1(b). The experimental test rig was designed to be similar, including the type of PCM and HTF and its mass flow rate. For the PCM thermal storage system integrated with the container to be effectively working, the system will undergo charging and discharging process, purposely to freeze and melt the PCM within the container wall.

In this work, the ice cream container was assumed to be used for 12 hrs delivery process. During the delivery process, the ice cream container was assumed to be fully charged, in solid state (ice), therefore the ice will undergo the natural melting process. On the other hand, after 12 hrs in operation, the ice was assumed to be fully melted. At this state, the PCM in the ice cream container wall was assumed to be fully in liquid state thus the charging process would take part. Considering this scenario, this paper therefore analysed the impact of the conductors to the freezing simulation of the system.



(a) (b)

Fig. 1. (a) Cold storage/Ice cream container sample (b) Ice cream container integrated with PCM thermal storage system

2.1 Geometry Modeling and Meshing

In order to mimic the system illustrated in Figure 1(b), the CAD model for each part was designed and simulated using the commercial CAD and CFD software. By using CATIA, three main parts were created, which are (1) an ice cream container wall that was assumed to be a well-insulated box filled with PCM, (2) a straight hollow tube that allows the HTF to flow through in the middle of the ice cream container wall, and (3) the pin that was pierced outside the straight tube. Overall, eight CFD models were developed, in which the same 3D model of ice cream container wall was designed with eight different tube configurations. These include two simulation models for copper tube available in the market, with the diameter for Tubes 1 and 2 were 6.53mm and 9.525mm, respectively. Both Tubes 1 and 2 were modeled without any heat conductors. The best tube model was then selected for the integration with conducting pins.

For the models with conducting pins, the number of pins was varied to two, four (Figure 2), six and eight pins. As illustrated in Figure 2(c), five sets of pins at a similar distance to each other were designed along the tube. The details of the model dimension are tabulated in Table 1. The copper pins used in this study was a simplified model of a flat-round cap and rectangular cross-section leading to a sharp edge (Figure 3(a)), benchmarked from Aziz *et al.,* [18]. For the simulation, the nail was simplified and assumed to be a cylinder-shaped pin with the same contact area and length of 25mm as shown in Figure 3(b). Nevertheless, due to the narrow thickness of the container wall, the 25mm in length pins could not be fitted well if the pins numbers are to be increased. Therefore, by employing the similar simplified method, the simulation was run with a shorter pin design, benchmarked from 8mm copper nails available in the market.

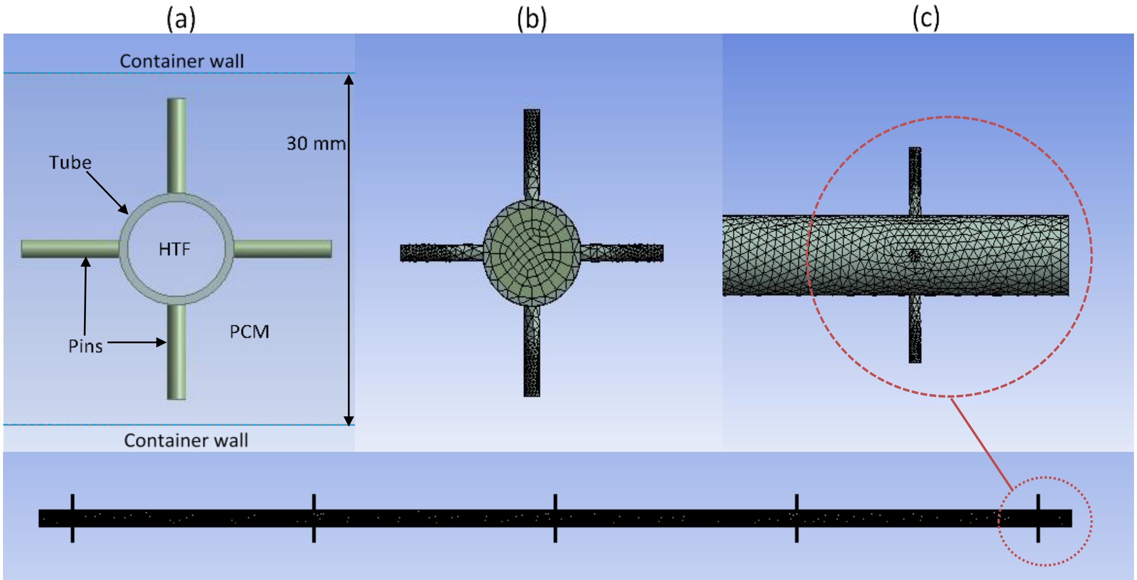
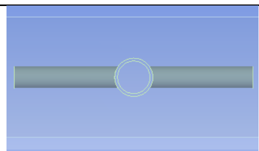
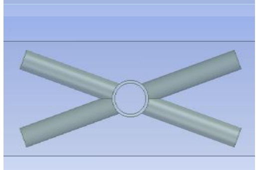
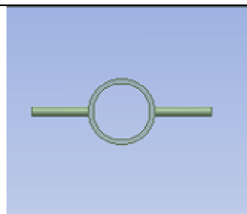
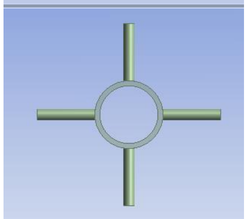
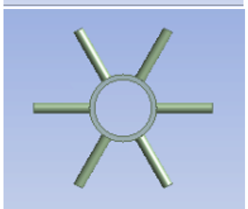
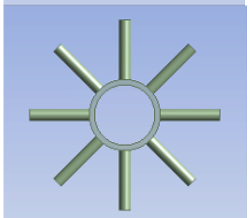


Fig. 2. (a) 3D model and meshing model (b) front view (c) side view of a tube with 5 set of 4 pins incorporated within the ice cream container wall

Table 1
Model specification

Model	Tube Model	Pins design (for 1 set)	Total numbers of pins in the system	Pins 3D model (front view)
1	Tube 1 (d=6.350mm)	-	-	
2	Tube 2 (d=9.525mm)	-	-	
Pins A (d_{pinA}=5.4mm, l_{pinA} =25.0mm)				
3	Tube B (d=9.525mm)	2	10	
4	Tube B (d=9.525mm)	4	20	
Pins B (d_{pinB}=3.0mm, l_{pinB} =8.0mm)				
5	Tube B (d=9.525mm)	2	10	
6	Tube B (d=9.525mm)	4	20	
7	Tube B (d=9.525mm)	6	30	
8	Tube B (d=9.525mm)	8	40	

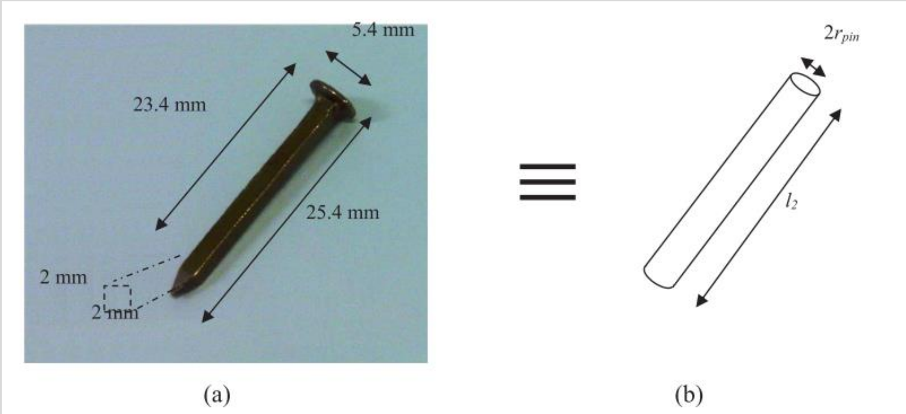


Fig. 3. (a) Benchmarked copper pin, and (b) simplified pin used in the simulation [18]

These PCM models were then simulated using a commercial computational fluid dynamic software to determine the best model that could improve the heat transfer within the system. A good mesh quality is essential for performing a good CFD analysis. Therefore, assessment of the mesh quality prior to performing large and complex CFD analysis has been done properly. For this modeling work, the physic and solver preferences are automatically set to CFD and CFX by default, including the use of default mesh setting combination of tetrahedrons and hex dominant. Nevertheless, due to the complicated geometry, the edge sizing method was employed to ensure the mesh quality satisfies the requirement of 0.85 maximum 'skewness' and achieve a low 'aspect ratio'. To observe the best meshing result, all three-relevance center sizing (fine, medium and coarse) were tested and the best meshing model was selected for the simulation.

2.2 Simulation Setup

For all simulations, three domains were created, namely the PCM, HTF and Pins. The material for PCM was set to PCM0 (water/ice), while the HTF and Pins were set to Dynalene HC40 and copper, respectively. Dynalene HC40 was chosen as HTF because it is non-toxic for food and beverages application, cost-effective, very suitable for low temperature, and more stable in fully liquid form compared to other low temperature refrigerants such as R134a, R12 and R22 [20]. The PCM and HTF domains were set as fluid domains, with continuous fluid morphology, non-buoyant buoyancy model, and stationary domain motion, while tube was set as a solid domain. All simulation setups including the governing equations were applied exactly as discussed by Aziz *et al.,* [18]. The thermal energy option was turned on to allow the heat transfer to occur within the CFD simulation model shown in Figure 4.

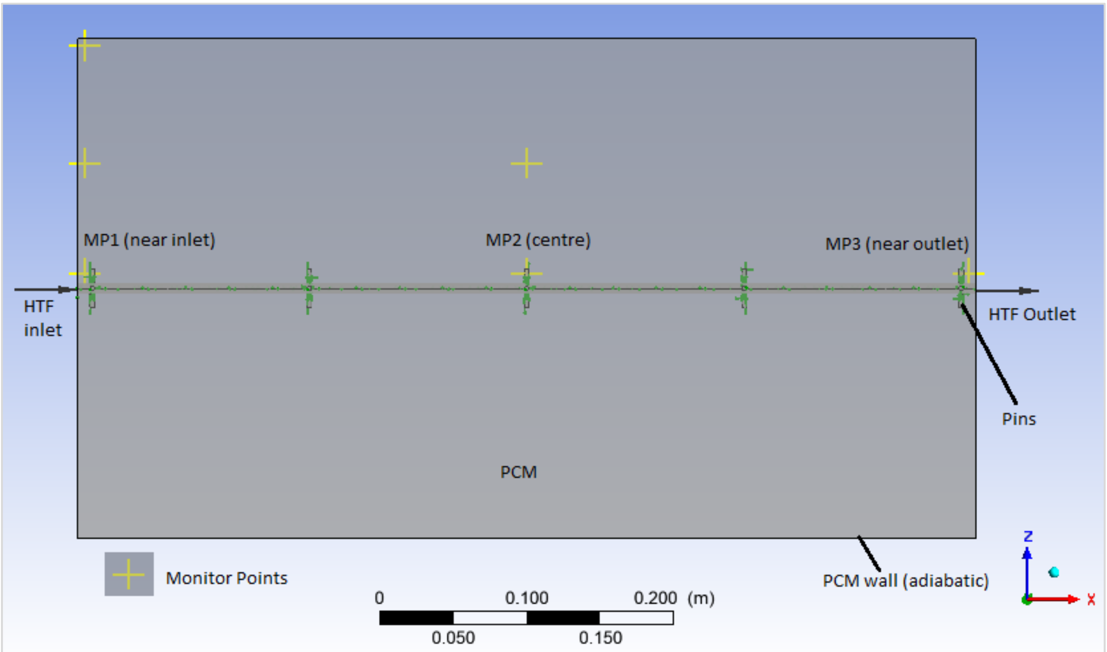


Fig. 4. CFD model of ice cream container wall integrated with tube-type PCM thermal storage system

As shown in Figure 4., the Inlet and Outlet boundary condition were defined at the location where the HTF enters and leaves the system, respectively. The initial temperature for HTF set as –11.0793 for freezing simulations with the turbulence model was set to k-epsilon with scalable wall function. The mass flow rate was set to 0.05635kg/s. Tube act as a thermal conductor implemented copper metal as medium of heat transfer between HTF and PCM. Thus, to set domain, solid domain was chosen instead of fluid type domain. The material for tube body was a default copper material with its domain motion set to stationary and continuous solid.

Meanwhile, for PCM domain, the component for Ice and Water was set to equilibrium fraction and equilibrium constraint respectively. The initial ice volume fraction was set to 0 with the initial temperature of the PCM was 2°C. The values of ice volume faction of 1 and 0 for melting and freezing simulation is indicating that the PCM is in ice (solid) and water (liquid) form, respectively. In order to focus on the heat conductors influence, PCM Outer Wall was set as adiabatic to prevent from any thermal energy in and/or out from the PCM. The interface models were then defined in between the domains that allowing the heat transfer to occur. In order to observe the temperature within the system, a few monitor points were set, including Monitor Points 1 and 3 (MP1 & MP3) that were set near the inlet and outlet of the system (Figure 4).

3. Results and Discussion

3.1 Effect of Pins to the Ice Mass Fraction

From the simulation, the ice mass fraction was recorded for 12 hrs as shown in Figure 5.

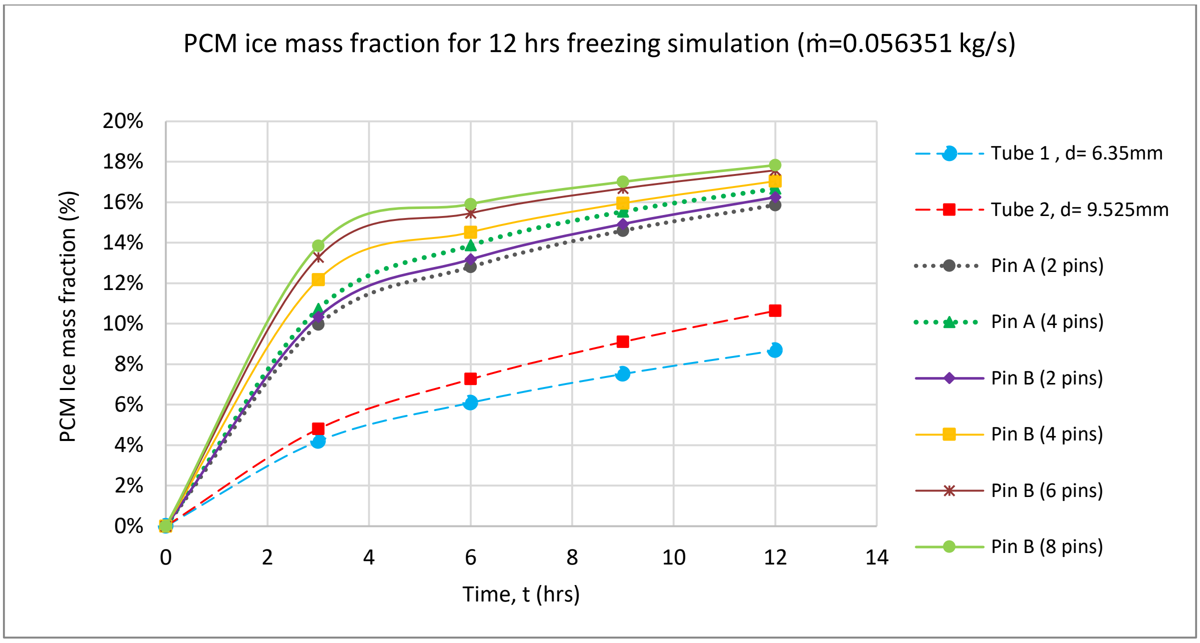


Fig. 5. Graph of PCM ice mass fraction (%) for 12 hrs freezing simulation (ṁ=0.056351 kg/s)

From the graph, it can be observed that the amount of liquid PCM that turns into ice was in the increasing trend over the time. As shown, the ice mass fraction was increased from 0% at 0hrs to 8.98% and 10.64% at 12 hrs. for the configurations without conducting pins. Meanwhile, for the model configurations of 3 to 8, the ice was seen to freeze faster, and the total ice mass fraction was 17.83%, with 67.58% increment when compared to Model 2. These data indicating that the presence of pins was undoubtedly a viable technique to speed up the freezing rate. The ice mass fraction contour was shown in Figure 6. As previously stated, the initial ice mass fraction was set to 0, and it was seen to gradually formed into ice relative to the simulation time. From Figure 6, the ice formation was seen to form following the pin design than the ice formation to the tube without pin.

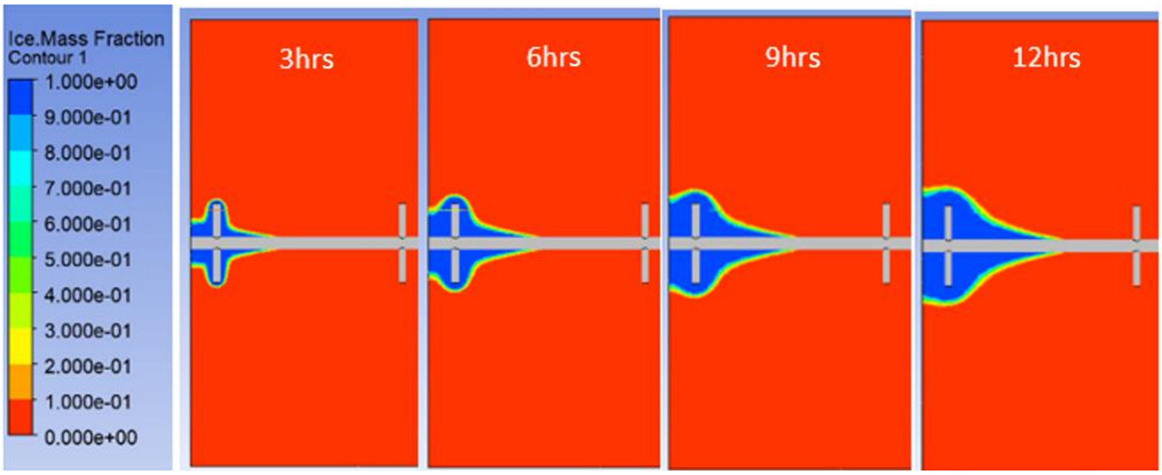


Fig. 6. PCM ice mass fraction (%) contour at 3, 6, 9 and 12 hrs freezing simulation for Model 3

3.2 Effect of Pins to the PCM Temperature Distribution

From the same simulation, the maximum, minimum and average temperature of the PCM was observed and presented in Table 2 and Figure 7.

Table 2
PCM minimum and maximum temperature after 12 hrs freezing simulation

Model	Total pins number	Min Temperature after 12hrs, T (°C)	Max Temperature after 12hrs, T(°C)
Pins A (d_{pinA}=5.4mm, l_{pinA} =25.0mm)			
3	10	-3.99	1.99
4	20	-3.53	1.99
Pins B (d_{pinB}=3.0mm, l_{pinB} =8.0m)			
5	10	-3.99	1.98
6	20	-3.96	1.98
7	30	-3.94	1.98
8	40	-3.92	1.98

In Table 2, for all cases, the maximum temperature was seen has dropped from 2℃ for at least 0.01℃ temperature difference. Meanwhile, the minimum temperature of PCM was observed within the range of -3.9 to 4.0°C. These maximum and minimum temperature in directly indicating the state of PCM, in which the positive value indicating that there was still a liquid state in the PCM, matched the ice mass fraction % showed in Figure 5. On the other hand, the negative temperature value is indicating that PCM0 has turned to the ice form with regards to its phase change temperature at 0°C. Meanwhile, the average temperature of PCM can be depicted from Figure 7.

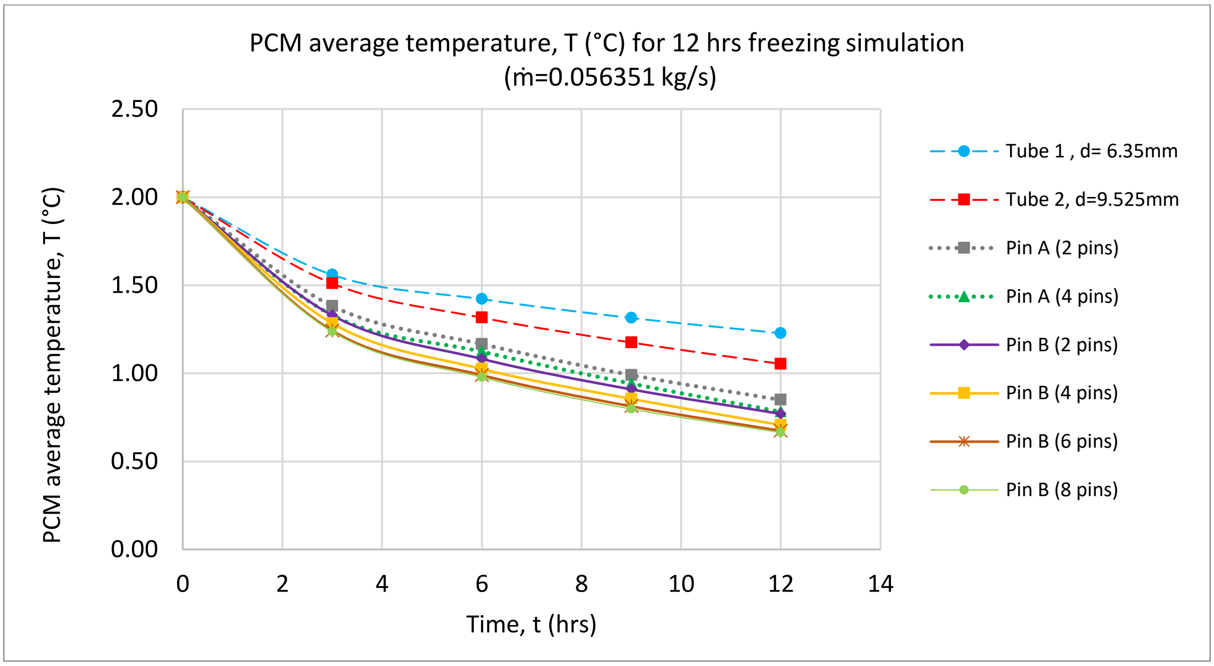


Fig. 7. Graph of PCM average temperature, T (℃) for 12 hrs freezing simulation (ṁ=0.056351 kg/s)

From the graph, it can be observed that the average temperature for PCM in Model 1 and 2 (after 12 hrs simulation time) are 1.23°C and 1.05°C, respectively. On the other hand, the average temperature for Model 3 – 8 are 0.85°C, 0.78°C, 0.77°C, 0.71°C, 0.67°C and 0.66°C, respectively. From these data, it showed that the average temperature of PCM for the TES configurations with conducting pins is lower when compared to the configurations without pins, indicating that the freezing rate has increased with the presence of conducting pins.

3.3 Effect of Pins Number

From Figure 7, it can be observed that the graph trend is in the decreasing trend, in which the PCM average temperature is decreasing with the increasing of pins number. Hence, to highlight the effect of conducting pins number to its performance, the average temperature for Model 3 – 8 was compared to Model 2 (tabulated in Table 3).

Table 3
PCM Temperature difference compared to Model 2 (no pin)

Model	Total pins number	PCM Average Temperature, *T* (°C)	Temperature difference, *T* (°C)	Temperature difference (%)
Pins A (d_{pinA}=5.4mm, l_{pinA} =25.0mm)				
3	10	0.85	0.20	-19.05%
4	20	0.78	0.27	-25.71%
Pins B (d_{pinB}=3.0mm, l_{pinB} =8.0m)				
5	10	0.77	0.28	-26.67%
6	20	0.71	0.34	-33.33%
7	30	0.67	0.38	-36.19%
8	40	0.66	0.39	-37.14%

In Table 3, it can be seen that the presence of pins has increased the heat transfer rate within the systems and has aided the temperature to drop faster when compared to the model with no pin. From the results, the average temperature for Model 4 is observed to be lower than Model 3, shows that there is an effect of the difference in numbers on pins. This is further proven by perceiving the data for Model 5 to 8, in which the PCM average temperature was seen to decrease with the increasing numbers of pins. The PCM average temperature for Model 8 is recorded to be lowered by as high as 37.14% when compared to Model 2.

Other than that, it can be highlighted that the number of pins has shown to be a bigger influence than the pins dimension to the heat exchanges within the system. Nonetheless, though the heat exchanges were improved, the value of ice formed after 12 hrs was considered too low, thus calls for further improvement. Besides, the presence of the pins has also reduced the PCM volume. It is crucial for a thermal storage system to be optimised so that the maximum amount of storage medium can be stored whilst having the heat transfer to be enhanced. The potential comparison of phase change effectiveness on tube with pins discussed in this work can be compared with that reported by Tay *et al.,* [21] when E-NTU correlation is used.

4. Conclusions

In this work, the freezing simulation for a thin wall, with and without heat conductors were conducted via CFD analysis. From the presented results, the best model was Model 8, with the present of 5 sets of 8 pins (total pins = 40) has increased the ice mass fraction for at least 67.58% when compared to the configuration without pin. Besides, the average temperature of PCM for Model 8 was observed to be the highest of 0.66°C, from its initial temperature of 2°C. The presence of 40 pins has lowered the average temperature of PCM for 37.14% when compared to the TES model without pins. Hence, it is inevitable to say including high conductivity material into the thermal storage systems, helps in heat transfer and has yield a better freezing performance. In the future work, the heat loss to surrounding for inner side of the container walls must be considered, thus the natural melting of PCM could further be analysed. Besides, the effectiveness of storage material can further be analysed for any thermal conductivity enhancement via conducting material. This is due to the volumetric spaces needed for the conducting material may replace the amount of PCM thus decreasing the phase change storage ability. Therefore, the insertion of conducting material to the thin wall, specifically for ice cream container needs to be optimised. As for this case, the length of tube, number of pins, type of PCM, and conductor configurations can be further optimised.

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References
[1] Grand View Research. "Ice Cream Market Size, Share & Trends Analysis Report By Product (Bars & Pops, Cups & Tub), By Type (Dairy & Water-based, Vegan), By Flavor (Chocolate, Vanilla, Fruit), By Region, And Segment Forecasts, 2022 - 2030." *Grand View Research Inc*. Accessed September 12, 2022. https://www.grandviewresearch.com/industry-analysis/ice-cream-market#.
[2] Kozłowicz, Katarzyna, Małgorzata Góral, Dariusz Góral, Urszula Pankiewicz, and Urszula Bronowicka-Mielniczuk. "Effect of ice cream storage on the physicochemical properties and survival of probiotic bacteria supplemented with zinc ions." *LWT* 116 (2019): 108562. https://doi.org/10.1016/j.lwt.2019.108562
[3] Hartel, Richard W. "Mechanisms and kinetics of recrystallization in ice cream." *The Properties of Water in Foods ISOPOW* 6 (1998): 287-319. https://doi.org/10.1007/978-1-4613-0311-4_14
[4] Donhowe, Daniel P., and Richard W. Hartel. "Recrystallization of ice during bulk storage of ice cream." *International Dairy Journal* 6, no. 11-12 (1996): 1209-1221. https://doi.org/10.1016/S0958-6946(96)00030-1
[5] Leducq, Denis, F. T. Ndoye, and G. Alvarez. "Phase change material for the thermal protection of ice cream during storage and transportation." *International Journal of Refrigeration* 52 (2015): 133-139. https://doi.org/10.1016/j.ijrefrig.2014.08.012
[6] Patmore, J. V., H. D. Goff, and S. Fernandes. "Cryo-gelation of galactomannans in ice cream model systems." *Food Hydrocolloids* 17, no. 2 (2003): 161-169. https://doi.org/10.1016/S0268-005X(02)00048-6
[7] Sun, Xiaoqin, Quan Zhang, Mario A. Medina, and Shuguang Liao. "Performance of a free-air cooling system for telecommunications base stations using phase change materials (PCMs): in-situ tests." *Applied Energy* 147 (2015): 325-334. https://doi.org/10.1016/j.apenergy.2015.01.046
[8] Selvnes, Håkon, Yosr Allouche, Raluca Iolanda Manescu, and Armin Hafner. "Review on cold thermal energy storage applied to refrigeration systems using phase change materials." *Thermal Science and Engineering Progress* 22 (2021): 100807. https://doi.org/10.1016/j.tsep.2020.100807
[9] Liu, Zhongbao, Fengfei Lou, Xin Qi, Jiawen Yan, Banghua Zhao, and Yiyao Shen. "Performance evaluation of a new ice preservation system for supermarkets." *International Journal of Energy Research* 43, no. 14 (2019): 8802-8810. https://doi.org/10.1002/er.4805
[10] Mahajan, Kanika, Sunil Kumar, Zuhaib F. Bhat, Maninder Singh, Hina F. Bhat, Muhammad A. Bhatti, and Alaa El-Din A. Bekhit. "Aloe vera and carrageenan based edible film improves storage stability of ice-cream." *Applied Food Research* 2, no. 1 (2022): 100128. https://doi.org/10.1016/j.afres.2022.100128
[11] Vadhera, Jatin, Amandeep Sura, Gopal Nandan, and Gaurav Dwivedi. "Study of phase change materials and its domestic application." *Materials Today: Proceedings* 5, no. 2 (2018): 3411-3417. https://doi.org/10.1016/j.matpr.2017.11.586
[12] Aziz, N. A., N. A. M. Amin, M. S. A. Majid, F. Bruno, and M. Belusko. "Optimising a packed bed phase change material of spheres using effectiveness-number of transfer unit method." *Journal of Energy Storage* 49 (2022): 104019. https://doi.org/10.1016/j.est.2022.104019
[13] Mehling, Harald, and Luisa F. Cabeza. "Heat and cold storage with PCM." *Heat and Mass Transfer* (2008): 11-55. https://doi.org/10.1007/978-3-540-68557-9
[14] Nie, Binjian, Anabel Palacios, Boyang Zou, Jiaxu Liu, Tongtong Zhang, and Yunren Li. "Review on phase change materials for cold thermal energy storage applications." *Renewable and Sustainable Energy Reviews* 134 (2020): 110340. https://doi.org/10.1016/j.rser.2020.110340
[15] Aziz, S., N. A. M. Amin, MS Abdul Majid, F. Bruno, and M. Belusko. "Effectiveness-NTU correlation for a TES tank comprising a PCM encapsulated in a sphere with heat transfer enhancement." *Applied Thermal Engineering* 143 (2018): 1003-1010. https://doi.org/10.1016/j.applthermaleng.2018.08.017

[16] Tay, N. H. S., F. Bruno, and M. Belusko. "Comparison of pinned and finned tubes in a phase change thermal energy storage system using CFD." *Applied Energy* 104 (2013): 79-86. https://doi.org/10.1016/j.apenergy.2012.10.040

[17] Amin, N. A. M., Frank Bruno, and Martin Belusko. "Effective thermal conductivity for melting in PCM encapsulated in a sphere." *Applied Energy* 122 (2014): 280-287. https://doi.org/10.1016/j.apenergy.2014.01.073

[18] Aziz, S., N. A. M. Amin, MS Abdul Majid, M. Belusko, and F. Bruno. "CFD simulation of a TES tank comprising a PCM encapsulated in sphere with heat transfer enhancement." *Applied Thermal Engineering* 143 (2018): 1085-1092. https://doi.org/10.1016/j.applthermaleng.2018.08.013

[19] Amin, Nasrul Amri Mohd, M. Belusko, and F. Bruno. "An effectiveness-NTU model of a packed bed PCM thermal storage system." *Applied Energy* 134 (2014): 356-362. https://doi.org/10.1016/j.apenergy.2014.08.020

[20] Dynalene. "Potassium Formate Heat Transfer Fluid (-58°F to 425°F)." *Dynalene Inc*. Accessed May 28, 2023. https://www.dynalene.com/product-category/heat-transfer-fluids/dynalene-hc/.

[21] Tay, N. H. S., M. Belusko, and F. Bruno. "An effectiveness-NTU technique for characterising tube-in-tank phase change thermal energy storage systems." *Applied Energy* 91, no. 1 (2012): 309-319. https://doi.org/10.1016/j.apenergy.2011.09.039