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# An experimental investigation of the charging process of thermal energy storage system filled with PCM and metal wire mesh



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#### HIGHLIGHTS

- Melting of composite PCM (PCM with metal wire mesh) is investigated experimentally.
- Composite PCM ( $\epsilon$  = 75%) results in maximum 24% improvement in charging time.
- Time required to achieve thermal equilibrium is reduced by up to one-third.
- A correlation is developed for Nusselt number as a function of dimensionless time.

#### ARTICLE INFO

Keywords: Thermal energy storage system Phase change material Latent heat Thermal conductivity enhancement Porous medium Metal wire mesh

#### ABSTRACT

The low thermal conductivity of the phase change materials limits the performance of latent heat thermal energy storage systems. The thermal conductivity of the phase change materials can be enhanced by incorporating a highly conductive porous medium. The studies available in the literature are limited to the application of metal foams in different geometries of latent heat thermal energy storage systems. In the present study, experimental investigations have been carried out to study the effect of adding copper wire mesh having two different porosities (i.e., 75% and 87%) and pore density of 16 pores per inch inside a cylindrical latent heat thermal energy storage system subjected to three different isothermal surface temperatures. The effect of adding metal wire mesh and isothermal surface temperatures on the heat flux, Nusselt number, and energy stored during the melting process are analysed. The results indicate that embedding copper wire mesh into the phase change materials leads to a uniform temperature distribution inside the latent heat thermal energy storage system, which is more pronounced at lower porosity. The maximum improvement in the charging times by using copper wire mesh with porosities of 87% and 75% are to be 17% and 24%, respectively. Moreover, it is observed that by using composite phase change materials (i.e., a combination of phase change material and metal wire mesh) the rate of heat transfer and energy stored is increased due to higher effective thermal conductivity of composite phase change materials. A correlation is proposed to predict the Nusselt number for different cases of the experiment. It is anticipated that these prospective results will be valuable for optimizing the energy transport in practical thermal energy storage applications.

#### 1. Introduction

Thermal energy storage (TES) systems have been developed with the aim of storing/releasing thermal energy in an efficient way. TES system can be a proper solution to the concerns of climate change since by storing thermal energy in an efficient way from the renewable and clean energy sources, less amount of fossil fuel will be consumed, which, in the long run, decreases the amount of greenhouse gas emissions. Latent Heat Thermal Energy Storage (LHTES) system, Sensible Heat Thermal Energy Storage (SHTES) system, and Thermo-Chemical Energy Storage (TCES) systems are the major categories of TES systems. However, LHTES systems have invoked more interest than SHTES and TCES systems due to the larger storage capacity and smoother operating temperature fluctuations [1]. Existing literature suggests that considerable research works has been performed where phase change material (PCM), TES, and LHTES are applied to different categories of thermal systems. For example, the review article by Soares et al. [2] summarizes the applications of LHTES systems for the thermal management and energy efficiency improvement of building, while, Kumar and Shukla [3] reviewed the works on the application of TES on solar

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Nomen	clature	ε	porosity
0	accuracy of the device #i	0	dimensionless time ( <i>Sterro</i> )
$u_i$	accuracy of the device #1	Subcerint	·
$c_p$	specific field at constant pressure [kJ/kg·K]	Subscript	5
E	energy Stored [J]		convolution based value
FO	Fourier Number	0	correlation based value
H 1	neight of the filled PCM [m]	exp	divid (i.e. maltan PCM)
h <sub>fg</sub>	latent heat of fusion [kJ/kg]	f	fluid (i.e. molten PCM)
k	thermal conductivity [W/m·K]	h	hot
Nu	Nusselt Number	in	internal
n	number of data points	l	liquid
Q	heat transfer rate [W]	т	melt
ġ	heat flux [W/m <sup>2</sup> ]	0	external
Ra	Rayleigh Number	\$	solid
r	radius of the cylindrical enclosure [m]	р	U-PVC pipe
Ste	Stefan Number	у	local (with respect to H)
t	time [second/minute]	0	initial
Т	temperature [°C]		
T <sub>ci</sub>	temperature measurement by thermocouple #i [°C]	Abbreviat	ion CSP concentrated solar power
U	uncertainty		
$x_i$	measured value by device #i	TES	thermal energy storage
	-	SHTES	sensible heat thermal energy storage
Greek sy	mbols	TCES	thermo-chemical energy storage
-		LHTES	latent heat thermal energy storage
α	thermal diffusivity	C-LHTES	cylindrical latent heat thermal energy storage
в	coefficient of thermal expansion [1/K]	PCM	phase change material
r D	dynamic viscosity $[m^2/s]$		F
0	density $\left[ kg/m^3 \right]$		
٢			

thermal power plants. Liang et al. [4] reviewed the application of PCM on thermal management of electronics, batteries, and photovoltaic cells. PCMs are used as a medium to store and release thermal energy in LHTES systems. Different PCMs with a wide range of phase change temperatures (T<sub>m</sub>) including paraffin waxes, hydrated salts, and organic compounds have been used as storage media in LHTES systems for cooling/heating purposes. Despite the desirable features of PCMs, they suffer from low thermal conductivity, which degrades the performance of LHTES systems by increasing the required time for charging and discharging processes [1]. The charging and discharging times can be reduced either by enhancing the effective thermal conductivity of PCM or by employing different configurations of LHTES system to enhance the heat transfer. However, the enhancement achieved is limited for efficient usage of PCM for large scale applications such as industrial waste heat recovery and energy storage for Concentrated Solar Power (CSP) plants. Thus, it is evident that, besides developing thermal conductivity enhancement techniques and analyzing different LHTES configurations, there is a need for exploring other avenues to enhance the performance of the LHTES system. The decrease in the mean distance of PCM from the heat transfer surface significantly enhances the heat transfer through the PCM. This could be achieved by encapsulating PCM in multiple smaller storage units, rather than a single large storage

unit. Fig. 1 shows an approach of using multiple cylindrical LHTES (C-LHTES) units placed in a bath filled with Heat Transfer Fluid (HTF). The HTF flows into the bath from one end, exchanges thermal energy with the PCM inside C-LHTES units, and leaves the bath through the opposite end. This approach increases the thermal interaction time of the HTF, besides, it increases the ratio of heat transfer surface area to the volume of PCM. Different configurations of PCM holding containers, such as spherical, rectangular, and cylindrical shapes have been used as LHTES systems. Cylindrical LHTES systems offer the advantages of ease of manufacturing and can be installed both vertically and horizontally. Comprehensive reviews of different configurations of LHTES systems are available in [5,6]. Several methods, such as, inserting highly conductive porous materials, dispersing metal nanoparticles into PCM, and inserting metal fins have been proposed by researchers to enhance the effective thermal conductivity of the PCMs [7,8]. However, there are some disadvantages for each of the above methods. For instance, sedimentation of nanoparticles due to the use of high weight/volume fractions of the nanoparticles into PCM limits the significant enhancement in thermal conductivity of PCM [8]. Moreover, metal fins and porous materials such as metal foams and metal wire meshes occupy a considerable portion of the volume of LHTES systems that results in a lower amount of filled PCM, which degrades the amount of stored



Fig. 1. Schematics of bath containing multiple C-LHTES with inlet and outlet for HTF.

energy in LHTES systems [9,10]. Several investigations are available in the literature regarding the use of porous materials (e.g. metallic foams) to enhance the thermal performance of LHTES systems with different configurations filled with PCM [11-15]. Some recent literatures examine the hybrid heat transfer enhancement for LHTES using two or more heat transfer enhancement techniques. Mahdi et al. [16] conducted a literature review on the hybrid heat transfer enhancement techniques for LHTES. The study [16] uncovered that heat pipe with fins or metal foam shows the best thermal performance. Nanoparticles with fins or metal foams is more efficient than the use of nanoparticles alone within the same containment volume. A computational fluid dynamics study conducted by Mahdi et al. [17] on a novel pin fin configuration in the triplex tube heat exchanger suggested better solidification performance of PCM than incorporating aluminum oxide nanoparticles for the identical system's volume usage. Mahdi et al. [18] conducted a numerical study of the solidification enhancement of PCM using multiple PCMs cascaded metal foam and nanoparticles in the shell-and-tube LHTES. The study [18] revealed that multiple PCMs with cascaded foam showed better solidification enhancement potential than multiple PCMs with nanoparticles. However, considering the main aim of this investigation, only research works using metallic wire mesh have been thoroughly reviewed in the present study.

# 1.1. Metallic wire mesh

Highly conductive metal wire meshes have been used in the heat exchangers to increase the thermal performance of such systems by increasing the heat transfer surface area. Metal wire meshes can be built in different configurations (i.e. different wire diameters and porosities) with the advantages of ease of manufacturing and low cost [19]. Interestingly, it was found to be more efficient than using porous metal foams due to efficiently transferring the conducted heat to the lateral walls while restraining the axial conduction due to minimal contact between each mesh [20]. In addition, Yilbas et al. [21] numerically compared the heat transfer improvement during melting of PCM by using metallic mesh and metal foam. Same porosity of metal mesh showed faster melting of PCM compared to the case which metal foam was used. Xu et al. [22] numerically and experimentally studied the heat transfer behavior of a wire-screen mesh heat exchanger. It was reported that the heat transfer is dominated by the porosity and density of the surface area of the wire mesh. In addition, conduction heat transfer was decreased by increasing the porosity of the mesh while the convection regime was enlarged. Furthermore, it was reported that the material properties of the metallic wire such as thermal conductivity and heat capacity are other important parameters affecting the performance of the wire mesh heat exchangers. Dyga and Placzek [23] experimentally investigated the heat transfer and pressure drop of air and water passing through a channel where wire mesh was embedded. It was reported that the use of wire mesh inside the channel increased the heat transfer rate and reduced the temperature gradient between the hot surface and fluid. However, it was concluded that from the energy point of view, this method was not reasonable for heating the liquid, as the increase in the heat transfer could not compensate the pressure drop caused by wire meshes. Kurian et al. [24] experimentally compared the thermal performance of three heat exchangers, which were plain copper tubes, copper tubes embedded in aluminum porous foam, and copper tubes embedded in a stainless-steel wire mesh. The outlet temperature of fluid and pressure drop was measured by passing air and water at different flow rates. Generally speaking, the porosity of the commercially available metal foams (e.g., Duocel® from ERG Material and Aerospace Corporation) are high, ranges from 88% to 96%. For the metallic wire mesh, the range of porosity can be much larger than the metal foam. It is concluded from the experimental measurement by Kurian et al. [24] that wire mesh heat exchanger has performed better than the metal foam heat exchanger under identical conditions. Wire mesh porous medium are much simpler in construction and cheaper than the metal foam porous medium. An experimental study on the effect of adding aluminum wire meshes to a plain tube heat exchanger was performed by Fu et al. [25]. Three different porosities and wire diameters of aluminum mesh were examined. The authors found that the thermal performance of the heat exchanger was improved due to the presence of wire meshes.

# 1.2. Metallic wire mesh integrated with PCM

A very limited number of researchers have studied the melting process of PCMs integrated with metal wire mesh. Mustaffar et al. [26] experimentally investigated the melting process of salt hydrate as the PCM, which filled the void spaces of an aluminum mesh embedded in a rectangular enclosure. The melting time was reduced by 14% due to the presence of the aluminum mesh. Shuja et al. [27] numerically studied the effect of using different geometries of metal mesh during the melting process of n-octadecane. Three different mesh geometries including triangular, rectangular, and hexagonal were examined. The results showed that triangular mesh geometry had the best heat transfer enhancement during the melting process compared to the rectangular and hexagonal geometries. Regarding the thermal management of batteries, Wu et al. [28] conducted an experimental study on the thermal management of batteries by the integration of copper mesh and paraffin wax as the composite PCM. It was found that using the composite PCM resulted in better heat dissipation and uniform temperature distribution. An experimental and numerical study on the thermal management of lithium-ion batteries was performed by Azizi and Sadrameli [29]. In their work, Poly Ethylene Glycol 1000 (PEG100) and aluminum wire mesh were used as the composite PCM. The batteries were placed in a rectangular enclosure filled with composite PCM. The results indicated that by using composite PCM for heat absorbance from the batteries, the surface temperature of the batteries can be significantly reduced which improves the performance and the operation lifetime of the batteries. Wei and Malen [30] investigated the impact of using spatially-enhanced metal mesh on the thermal performance of an LHTES system during melting and solidification processes. They concluded that although embedding uniformly structured metal meshes improved the heat transfer rate, the spatially-enhanced design of metal mesh exhibited better performance. In this regard, comparing the performance of uniformly- and spatially-enhanced design showed that the melting rate was 140% improved by the suggested spatially-enhanced design.

According to the literature reviewed, no published work is identified regarding the use of metal wire mesh as the porous medium embedded inside a vertical cylindrical LHTES (C-LHTES) system which is the main motivation of performing the present investigation. Comparing to metal foams, use of highly conductive metal wire meshes offer the advantages of a better heat transfer enhancement during charging process of PCM, ease of manufacturing, and being more affordable [19-21]. For a given maximum linear dimension (i.e., diameter, diagonal distance), cylindrical geometry offers a higher surface area than rectangular geometry of equal height. The heat transfer rate is directly proportional to the surface area. Thus, cylindrical geometries can be a better choice for applications perspective. As a result, authors believe that the findings of this manuscript can have a significant contribution to the efforts of developing affordable and efficient LHTES system. Several experimental investigations on the detailed charging process of n-octadecane with the melting temperature  $(T_m)$  of 28 °C, filled vertical C-LHTES systems in the presence of copper wire mesh as the thermal enhancer are performed. The C-LHTES system is thermally insulated from the bottom and isothermally heated from its lateral walls. Effects of displacing two different porosities ( $\varepsilon$ ) of metal wire mesh (i.e.  $\varepsilon = 75\%$  and 87%) inside the C-LHTES system on the temperature distributions, averaged Nusselt number, local and total heat transferred rate, and rate of energy stored at three different isothermal conditions including  $T_h$  = 38 °C,  $T_h$  = 48 °C, and  $T_h$  = 58 °C are

#### examined.

# 2. Experimental approach

To perform the experimental work a C-LHTES system was designed and built. Next, the composite PCM (i.e. the combination of n-octadecane and copper mesh) was prepared and filled the C-LHTES enclosure. The experimental setup utilized T-type thermocouples, a 16 channel DAQ system to monitor the temperature distribution inside the C-LHTES system, and a temperature regulator to achieve uniform isothermal conditions during the experiments. The detailed information regarding the experimental approach is discussed in Sections 2.1–2.4.

#### 2.1. C-LHTES system

A transparent unthreaded PVC (or UPVC) pipe with the total length of 30 cm, thickness of 6 mm, and an inner diameter of 4.8 cm was used as the cylindrical enclosure. The reason for using unthreaded PVC pipe is to prevent having fractures due to the thermal stresses. Moreover, it was found to be more machinable than regular acrylic pipes. Initially, an acrylic pipe was used as the cylindrical enclosure, however, during the experiments, the C-LHTES system failed since several fractures appeared due to applying different temperatures to the wall of the enclosure. The cylindrical UPVC pipe was vertically attached to a 3-cm thick plastic plate (i.e., the base plate) by using a bonding cement (manufacturer: Oatey, model: 30834). The plastic plate acted as a thermal insulator at the bottom of the cylindrical enclosure as well as the cap to seal one side of the UPVC pipe. As a result, one side of the UPVC pipe was closed while the other side was kept open to avoid any pressure on the top of the PCM during the melting process. To monitor the temperature distribution at the inner wall of the UPVC pipe, eight Ttype thermocouples (manufacturer: Omega, model: 5TC-TT-T-30-36) were attached to the inner wall of the UPVC pipe at eight different heights with an interval of 1 cm, starting from 1 cm from the bottom of C-LHTES system. To attach the thermocouples, eight holes with the same diameter of the thickness of thermocouple wires (i.e. 0.65 mm) were made at the wall of the C-LHTES system. Then, the thermocouples

were placed inside the wall of C-LHTES system in a way that the head of the thermocouples was attached to the inner wall of C-LHTES system. To keep the thermocouples at their positions and for sealing purposes, an instant glue was used. It should be noted that to avoid the effect of additional thermal resistance caused by using the glue, only a small amount of glue was used inside the holes. In addition, to monitor the temperature profile at the center of the C-LHTES system, a thin acrylic rod with the diameter of 3.23 mm, was installed at the center of the enclosure where four T-type thermocouples at different heights (i.e. 2 cm, 4 cm, 6 cm, and 8 cm from the bottom) were attached to it. All thermocouples were initially calibrated by placing them inside an Omega Temperature Regulator. The accuracy of the Omega Regulator is 0.01 °C. Thermocouple calibration was performed for a range of temperatures, including the temperature range used in the current work. From the calibrated group, required numbers of thermocouples were finally selected for the experiment based on two factors: similar trend in the calibration profile and close values of Root Mean Square (RMS) errors. A schematic of the C-LHTES system is shown in Fig. 2(a) and (b).

# 2.2. Preparation of composite PCM

In the present work, the composite PCM refers to the combination of PCM and metal wire mesh. To prepare the composite PCM, 150 ml of noctadecane (CH<sub>3</sub> (CH<sub>2</sub>)<sub>16</sub> CH3) with the purity of 99% (supplier: Alfa Aesar) and the melting temperature (T<sub>m</sub>) of 28 °C was used as the base PCM. Highly conductive metal wire mesh (i.e., copper wire mesh) was used as the porous medium.

Thermophysical properties were measured at the facilities located in the "Advanced Energy Conversion and Control (AECC) Lab" and "Bio-Research Innovation Lab (BRIL)", University of Guelph, Ontario, Canada. Solid PCM properties are measured at  $T_{\rm m}$  – 10 °C, while the liquid properties are at  $T_{\rm m}$  + 10 °C. Thermal conductivities are measured using KD2-Pro (Decagon Devices, Inc.) and THW-L2 Transient Hot Wire Thermal Conductivity Meter (Thermtest Inc.) with a measurement accuracy of ± 5%. Viscosity of the liquid PCM is measured using a Vibration Viscometer (Cole-Parmer Canada) with a measurement accuracy of ± 2.5%. A DMA 35 Density meter (Anton Paar Inc.)



Fig. 2. A schematic of the C-LHTES system: (a) 3-D design, (b) location of the thermocouples.

and a Solid Density Meter (Mettler Toledo) are used to measure densities of solid and liquid PCM with a measurement accuracy of  $\pm$  1.0%. Specific heats, melting temperature, and heat of fusion of the PCM are measured using a Differential Scanning Calorimeter (DSC) with a measurement accuracy of  $\pm$  1.0%. Properties are summarized in Table 1.

Moreover, two sheets of copper wire mesh (supplier: Mcmaster-Carr) with different configurations were used as the porous medium. The detailed specifications of the copper wire mesh are presented in Table 2a, while, Table 2b presents the volume and mass ratios of PCM to metal mesh.

A piece of copper mesh with dimensions of 9 cm  $\times$  140 cm was cut out from each model of the mesh. Subsequently, each metal mesh piece was firmly wrapped around an acrylic rod (see Fig. 2(b)) to give the piece a cylindrical shape so that it can be fitted within the inner diameter of C-LHTES system (i.e., 4.8 cm). The wrapping process was performed in a way that a small gap (i.e. less than 5 mm) between the head of thermocouples mounted at the inner wall and the center of C-LHTES system and the copper mesh remained. The reason of having such a gap was to avoid the fluctuations of the temperature reading by thermocouples caused by the direct contact of the head of thermocouples with the metal mesh as it was seen in the primary experimental trials. Once the wrapping is done, precision dial gauge and caliper were used to check the dimensions and profile of the metal mesh cylinder at different locations. The two ends of the acrylic rod were extended beyond the longitudinal length of the wrapped metal mesh. At the bottom part of the wrapped metal mesh the acrylic rod was extended approximately 5 mm, while at the top part it was extended beyond the acrylic cylinder. A hole was pre-drilled at the center of the base plate (attached to the acrylic cylinder) to hold the bottom extension of the acrylic rod firmly. Photographs of copper meshes are presented in Fig. 3.

Subsequently, the C-LHTES system was filled with molten PCM. The rounded copper meshes were placed inside the C-LHTES system separately. An increase in the height of the PCM due to displacing the copper meshes inside the C-LHTES system was recorded. According to Eq. (1), the porosities of copper meshes were calculated as 75% and 87%.

$$\varepsilon = \frac{\text{solid volume of the metal mesh}}{\text{total volume of the metal mesh}} \times 100 \tag{1}$$

#### 2.3. Description of the experimental setup

A transparent acrylic tank was used with the dimensions of 30 cm  $\times$  30 cm  $\times$  30 cm. Because of high the specific heat, water (in the deionized form) was used in the acrylic tank to create an isothermal environment. A thermal regulator (manufacturer: Omega, model: HCTB-3020) was used which was equipped with a circulating pump for providing the isothermal condition during the melting experiments. The accuracy of the Omega thermal regulator is  $\pm$  0.01 °C. The minimum and maximum uncertainties of adjusting the hot wall temperature (i.e.  $T_{h}$ ) during the melting experiments by using the thermal regulator are obtained as  $\pm$  0.01% and  $\pm$  0.02%, respectively. Besides, two T-type thermocouples were used to check the temperatures at two locations inside the acrylic water tank close to the C-LHTES system (i.e.  $T_{\rm C}13$  and  $T_{\rm C}$ 14 as showed in Fig. 4a). A 16 channel DAQ system was used (manufacturer: National instruments, model: NI9213) that was connected to the T-type thermocouples. The thermal regulator was placed at one side of the acrylic water tank while the C-LHTES system was placed at the other side of the water tank during the experiments. To prevent the possible effects of turbulent flow caused by the direct movement of water due to the operation of the circulating pump, an acrylic barrier was placed between the water circulating pump and the C-LHTES system. A 5-cm gap between the bottom of the acrylic water tank and the barrier was maintained to allow the water circulation. The

water inside the acrylic tank was pre-heated by the thermal regulator to achieve the desired hot wall temperature before starting any melting experiments. For three isothermal wall conditions (i.e.,  $T_{\rm h} = 38$  °C, 48 °C, and 58 °C), temperatures at locations Tc13 and Tc14 are presented in Fig. 4b. Transient temperature variations, as observed in Fig. 4b, confirm isothermal conditions for the experiments. To decrease the heat losses between the acrylic water tank and the experimental environment, the lateral walls of acrylic water tank was insulated. In addition, another water tank equipped with a thermal regulator (manufacturer: Cole-Parmer, model: CR250WU) was used for solidification processes and maintaining an identical initial temperature of 25 °C for all cases of the melting experiments. It should be noted that solidification at temperatures close to the melting point of a PCM provides the advantages of less trapped air inside the PCM and avoidance of the sub-cooling effect. A schematic diagram of the experimental setup is shown in Fig. 4a.

# 2.4. Experimental procedure

The experiments were carried out in different steps. The first set of experiments were conducted for the case using pure n-octadecane without embedding copper mesh, at three different isothermal temperatures of  $T_h = 38$  °C, 48 °C, and 58 °C. The temperature of PCM in C-LHTES system was maintained at 25 °C in the water bath (i.e. the one that was used for solidification process) for approximately one day. After ensuring the uniformity of temperature of 25 °C inside the solidified n-octadecane by monitoring the temperatures using the installed T-type thermocouples, the C-LHTES was ready to initiate the melting experiment. At the first set of experiments, the temperature of the acrylic water tank was set to  $T_h = 38$  °C (i.e. 10 °C above the  $T_m$ ). Next, the C-LHTES system, having the initial temperature of 25 °C, was immediately placed inside the acrylic water tank to initiate the melting process. The T-type thermocouples recorded the temperature distributions at the inner wall and at the center of the C-LHTES system every ten seconds until the end of the melting process and reaching to the thermal equilibrium condition. The same experimental steps were carried out for the other sets of experiments with isothermal temperatures of  $T_h$  = 48 °C (20 °C above the melting point) and  $T_h$  = 58 °C (30 °C above the  $T_m$ ) with the same initial temperature of 25 °C. The justification of selecting these temperatures was based on having a proper difference with the melting temperature of the n-octadecane and the limitation in the operating temperature of the cement glue used to attach the UPVC pipe to the plastic plate. The same experimental procedures were performed for the composite PCM with the porosity of 87%. To do so, the same amount of n-octadecane was maintained inside the C-LHTES system and the rounded copper mesh was placed inside the molten n-octadecane. This offers the advantage of a fair comparison of thermal performance of C-LHTES system filled with the pure PCM and the composite PCM since the amount of the filled PCM inside the C-LHTES system remained the same. The C-LHTES system was placed in the water tank having a temperature of 25 °C for the solidification process. Again, the C-LHTES system was kept inside the bath for one day. Then, the melting experiment was performed for  $T_{\rm h} = 38$  °C, 48 °C, and 58 °C, respectively. The last set of experiment was conducted for

# Table 1

Thermophysical property of n-octadecane measured at the AECC and BRIL lab facilities, University of Guelph.

Thermophysical property	Value
k: Thermal conductivity (solid/liquid)	0.334/0.148 (W/m·K)
Cp: Specific heat (solid/liquid)	1823/2252 (J/kg·K)
ρ: Density (solid/liquid)	867/770 (kg/m <sup>3</sup> )
$\mu$ : Dynamic viscosity (liquid)	0.00318 (Pa·s)
$h_{fg}$ : Latent heat of fusion	236.98 (kJ/kg)
$T_m$ : Phase change temperature	28 °C

#### Table 2a

Specifications of the copper wire meshes used in the present work.

	Model I (Code: 9224T54)	Model II (Code: 9224T55)
Mesh Size [31] Opening Size [31] Open Area [31] Wire Diameter [31] Pore Density [31] Thermal Conductivity [32]	16 × 16 0.114 cm (0.045") 50% 0.045 cm (0.018") 16 401 (W/m·K)	16 × 16 0.132 cm (0.052") 67% 0.027 cm (0.011") 16
Density [32] Specific Heat [32]	8960 (kg/m³) 390 (J/kg.K)	

# Table 2b

Volume and mass ratios of PCM to metal mesh.

Parameters	Porosity, $\varepsilon = 75\%$		Porosity, $\varepsilon = 87\%$		
	Liquid PCM	Solid PCM	Liquid PCM	Solid PCM	
Volume ratio $=\frac{\varepsilon}{1-\varepsilon}$	3	3	6.7	6.7	
Mass Ratio = $\frac{\varepsilon \rho PCM}{(1-\varepsilon)\varepsilon \rho_{Metal Mesh}}$	0.26	0.29	0.58	0.65	

the composite PCM having the porosity of 75%. The copper mesh having a porosity of 87% from the previous experiment was taken out and instead, the copper mesh with a porosity of 75% was placed inside the C-LHTES system filled with molten n-octadecane. The same experimental procedure was followed for this case. Each set of experiments was repeated at least twice to ensure the repeatability of the results obtained.

#### 2.5. Uncertainty analysis

The uncertainty of the experimental result is due to the accuracy of the measurement devices including the T-type thermocouples, DAQ system, and the temperature regulators (i.e. for melting and solidification processes) used in the experiment. The accuracy (i.e. provided by manufacturer/supplier) and the relative uncertainty of the measurement devices are shown in Table 3.

The uncertainty (*U*) associated with the temperature measurements during the experiments is associated with the use of T-type thermocouples and the DAQ system, which can be obtained by using the following equation [33]: (2)

$U = \sqrt{\sum_{0}^{i} \left(\frac{a_i}{x_i}\right)^2}$	

Therefore, the minimum and maximum uncertainties of the temperature measurements are  $\pm 1.7\%$  and  $\pm 4\%$ , respectively. Similarly, the minimum and maximum uncertainties of adjusting the hot wall temperature (i.e.  $T_h$ ) during the melting experiments by using the Omega thermal regulator can be obtained as  $\pm 0.01\%$  and  $\pm 0.02\%$ , respectively. Lastly, the uncertainty associated with using the Cole-Parmer thermal regulator for the solidification process and maintaining identical initial temperatures for all cases before initiating the melting experiments is obtained as  $\pm 0.4\%$ .

# 3. Results and discussion

Results obtained are presented as temperature distributions inside the C-LHTES system, local and total heat transfer, the energy stored inside the C-LHTES system during the melting experiment, and the trend of the surface averaged Nusselt number. In addition, a correlation is developed to predict the trend of surface averaged Nusselt number derived by using the experimental data during melting process.

# 3.1. Temperature variations

In this section, the temperature distributions recorded by the twelve thermocouples (i.e. eight thermocouples at the wall and four thermocouples at the center) located at the inner wall and center of the C-LHTES system during the melting process are discussed. For brevity, only the temperature distributions for the set of experiments subjected to  $T_h = 48$  °C are presented since a similar behavior was seen for the experiments subjected to  $T_h = 38$  °C and 58 °C.

# 3.1.1. Effect of metal mesh porosity

Fig. 5 shows the temperature profiles recorded by the eight calibrated T-type thermocouples installed at the inner wall of the C-LHTES system. To have a fair comparison, the initial temperature of the PCM and the isothermal boundary temperature were maintained at 25 °C and 48 °C, respectively. As it can be seen from Fig. 5(a)–(c), at the early stages of the melting process (i.e. up to 10 min), there is a sharp linear increase in the temperature profiles, which is as a result of near wall conduction dominated melting process and heat transfer. From this point onward, natural convection appeared as the buoyancy force overcomes the viscous force in the liquid PCM. Therefore, the heat transfer occurred due to combined contribution from conduction and



Fig. 3. Photographs of the copper wire mesh: (a) flat sheet, (b) rounded copper wire mesh.



Fig. 4a. The schematics of experimental setup.



Fig. 4b. Transient temperature variations at location Tc13 and Tc14.

convection followed by a dominance of convection at later stages of melting. The rate of increase in the temperature profiles degrades due to the decrease in the temperature gradient between the solid PCM and hot isothermal walls of the C-LHTES system. This pattern continues until thermal equilibrium is reached at the end of melting experiment. Comparing the experiment without copper mesh (see Fig. 5(a)) with the experiments with composite PCMs (see Fig. 5(b) and (c)) reveals a uniform temperature distribution along the C-LHTES system that resulted by using copper mesh as the porous medium embedded inside the C-LHTES system. Table 4 compares the temperatures recorded by the thermocouple located at the lowest height of the inner wall (i.e.  $T_{C1}$  and H = 1 cm) and the thermocouple located at the highest height of the inner wall (i.e.  $T_{C8}$  and H = 8 cm) at two selected times of 50 and 100 min.

As it is shown in Table 4, by embedding the copper mesh inside the C-LHTES system, heat is transferred uniformly through the copper mesh along the C-LHTES, which resulted in a uniform temperature distribution in the PCM. This effect is more significant by using a composite PCM having  $\varepsilon = 75\%$ , which is due to a larger effective thermal conductivity than using a composite PCM with  $\varepsilon = 87\%$ . As it can be seen from Fig. 5(a)–(c), comparing the temperatures at the top of the C-LHTES system (i.e.  $T_{C7}$  and  $T_{C8}$ ) at the times before reaching to the thermal equilibrium shows that the onset of natural convection is delayed due to the obstacles in upward current of the molten PCM caused by using the copper mesh. This can be identified by the lower temperatures recorded by  $T_{C7}$  and  $T_{C8}$ . However, and overall, the thermal equilibrium was reached earlier by using a composite PCM because the thermal conductivity of PCM was enhanced. This is quantified in Table 5.

Based on the time required to reach the thermal equilibrium at the center of C-LHTES system, the enhancement of the charging time of C-LHTES system by using composite PCMs having  $\varepsilon = 87\%$  and 75%, can be shown in Table 6.

As it can be seen from Table 6, the maximum improvement in the charging time is related to use of composite PCM with  $\varepsilon = 75\%$  at

#### Table 3

1

accuracy of the measuremen	t and	experimental	devices	used	in	the	present	stud	y
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Equipment	Accuracy (a <sub>i</sub> )	Measured values $(x_i)$	Relative uncertainty $(a_i/x_i)$
T-type thermocouples	Standard LOE*: ± 1.0 [°C] Special LOE*: ± 0.5 [°C]	Min: 25 °C/Max: 58 °C Min: 25 °C/Max: 58 °C	0.04/0.0086 0.02/0.0172
DAQ system	± 0.02 [°C]	Min: 25 °C/Max: 58 °C	0.0008/0.0003
Omega thermal regulator	± 0.01 [°C]	Min: 38 °C/Max: 58 °C	0.0002/0.0001
Cole-Parmer Polystat	± 0.1 [°C]	25 °C	0.004

\* LOE (Limit of Error) (https://www.omega.ca/en/resources/thermocouple-types).



Fig. 5. Temperature variations recorded by the thermocouples attached to the inner wall of C-LHTES system and  $T_h = 48$  °C: (a) pure PCM ( $\varepsilon = 100\%$ ), (b) composite PCM with  $\varepsilon = 87\%$ , and (c) composite PCM with  $\varepsilon = 75\%$ .

**Table 4** Temperature values at two selected times and  $T_h = 48$  °C.

	50 min			100 min		
	$T_{\rm C1}$	$T_{C8}$	$\Delta T$	$T_{\rm C1}$	$T_{C8}$	$\Delta T$
Pure PCM ( $\varepsilon$ = 100%) Composite PCM ( $\varepsilon$ = 87%) Composite PCM ( $\varepsilon$ = 75%)	39.5 °C 40.5 °C 40.5 °C	44.1 °C 42.2 °C 41.7 °C	4.6 °C 1.7 °C 1.2 °C	40 °C 42.7 °C 44.5 °C	47 °C 44.8 °C 45 °C	7 °C 2.1 °C 0.5 °C

 $T_{\rm h} = 58$  °C which is 24%.

Fig. 6 shows the temperatures recorded by the four T-type thermocouples at the center of the C-LHTES system during the melting process. Comparison of Fig. 6(a) with Fig. 6(b) and (c) shows that the discrepancies in temperatures are decreased by using a composite PCM

that is resulted by a uniform temperature distribution along with the C-LHTES system. In addition, as it is shown in Table 5, the time required for reaching the thermal equilibrium at the center of the C-LHTES system was also decreased due to embedding copper mesh inside the C-LHTES systems. By monitoring the temperature distributions reported by the thermocouple located at the lowest height of the rod installed at the center of C-LHTES systems (i.e.,  $T_{C9}$ , H = 2 cm), it can be identified that the melting process at that location, occurred at 100 min for pure PCM and at 90 min after initiating the melting process for the experiments in which composite PCMs were used. From this point onward, there is a sharp increase in the temperature reported at  $T_{C9}$  for composite PCMs, which suggests a faster melting process due to embedding copper mesh inside the C-LHTES system. The ratio of the increase in the temperature profile reported by  $T_{C9}$ , is enlarged when a composite PCM with  $\varepsilon = 75\%$  was used since a higher overall thermal conductivity was achieved.

#### Table 5

Time required to reach the ther	nal equilibrium for p	oure PCM and composite	PCMs having $\varepsilon = 75\%$ and 87%.
---------------------------------	-----------------------	------------------------	---

$T_h$	Pure PCM ( $\varepsilon = 100\%$ )		Composite PCM ( $\varepsilon = 87\%$ )		Composite PCM ( $\varepsilon = 75\%$ )	
	Wall	Center	Wall	Center	Wall	Center
38 °C 48 °C 58 °C	280 min 185 min 160 min	275 min 180 min 145 min	245 min 150 115	250 min 155 120	235 min 135 min 110 min	235 min 140 min 110 min

#### Table 6

The decrease in the charging time of C-LHTES system by using composite PCM.

$T_h$	Pure PCM ( $\varepsilon = 100\%$ )	Composite PCM ( $\varepsilon = 87\%$ )	Composite PCM ( $\varepsilon = 75\%$ )	
38 °C	275 min	250 min (9%)	235 min (15%)	
48 °C	180 min	155 (14%)	140 min (22%)	
58 °C	145 min	120 (17%)	110 min (24%)	

# 3.1.2. Effect of the isothermal boundary temperature

Fig. 7 presents the temperature distributions during the melting process for the composite PCM with  $\varepsilon = 75\%$  at three different operating conditions including  $T_h = 38$  °C, 48 °C, and 58 °C. In this regard, Fig. 7a depicts the temperature profile at the inner wall of C-LHTES system and Fig. 7b shows the temperature distribution at the center of C-LHTES system. As it can be seen from Figs. 7a and b, the temperature of isothermal boundary wall significantly decreased the required time



Fig. 6. Temperature variations recorded by the thermocouples located at the center of C-LHTES system and  $T_h = 48$  °C: (a) pure PCM ( $\varepsilon = 100\%$ ), (b) composite PCM with  $\varepsilon = 87\%$ , and (c) composite PCM with  $\varepsilon = 75\%$ .



Fig. 7a. Temperature variations recorded by the thermocouples located at the inner wall of C-LHTES system for composite PCM with  $\varepsilon$  = 75% at three different isothermal temperatures: (i) T<sub>h</sub> = 38 °C, (ii) T<sub>h</sub> = 48 °C, and (iii) T<sub>h</sub> = 58 °C.

for completion of melting process and reaching the thermal equilibrium condition. For instance, the required time to reach the thermal equilibrium was shortened by 42% by increasing the temperature of the isothermal wall from  $T_h = 38$  °C to  $T_h = 48$  °C, and 53% for the experiment in which  $T_h = 58$  °C. This improvement in the melting process is due to the higher heat transfer rate between the cold PCM and isothermal wall due to the larger temperature gradient. The stable temperature of the PCM is slightly lower than the isothermal wall temperature for  $T_h = 48$  °C and 58 °C due to the increase in the heat losses from the C-LHTES system and the environment. Overall, a similar pattern with a sharper increase in the temperature for  $T_h = 58$  °C can be seen.

#### 3.2. Local and total heat transfer

Figs. 8 and 9 present the local heat transferred from the hot water bath to the inner wall of the C-LHTES system in the form of conduction at eight different locations where thermocouples are installed. The local heat flux ( $\dot{q}$ ), at the internal surface of the C-LHTES system, is calculated by the following equation.

$$\dot{q}_{y} = k_{p} \left(\frac{dT}{dr}\right) = k_{p} \frac{T_{h} - T_{y}}{r_{in} \ln\left(\frac{r_{0}}{r_{in}}\right)}$$
(3)

where  $k_p$ ,  $T_y$ ,  $r_o$ , and  $r_{in}$  represent the thermal conductivity of the U-PVC pipe, the experimentally measured temperature of each probe point (with respect to *y*) recorded by the thermocouples, the outer and inner radius of the U-PVC pipe, respectively. The magnitude of  $k_p$  in Eq. (3) is equal to 0.16 W/m-K.

Fig. 8 presents the effect of embedding copper mesh of different porosities (i.e,  $\varepsilon = 75\%$  and 87%) at  $T_{h} = 58$  °C. At the beginning of the melting process, the magnitude of the heat transfer is high due to the large temperature difference between the hot isothermal wall and the cold PCM. The heat is transferred in the form of conduction at the early



Fig. 7b. Temperature variations recorded by the thermocouples located at the inner wall of C-LHTES system for composite PCM with  $\varepsilon$  = 75% at three different isothermal temperatures: (i) T<sub>h</sub> = 38 °C, (ii) T<sub>h</sub> = 48 °C, and (iii) T<sub>h</sub> = 58 °C.

stages of melting where the local heat transfer profile is asymptotic to the y-axis of the q-t plots. As the melting proceeds, the solid-liquid interface departs from the boundary surface, the viscosity of the PCM decreases as the phase changes, and the temperature of liquid PCM increases. As the buoyant force overcomes the viscous force, the liquid PCM with higher temperature moves upward due to the lower density and leads to onset of natural convection. The higher temperature of the PCM on the top reduces the temperature gradient across the wall and thus the heat flux through the surface decreases with the increase in the height. Besides, the variation in the heat flux with height signifies nonuniform distribution of PCM's temperature along the height resulted from the natural convection. As the melting experiment proceeds toward the end, the heat flux decreases to its minimum value as the temperature gradient between hot lateral wall and PCM degrades significantly. The marginal constant value of heat flux indicates that the thermal equilibrium is achieved.

As it is discussed in Section 3.1.1, using a composite PCM resulted in

a uniform temperature distribution inside the C-LHTES system. Distributing heat uniformly inside the C-LHTES system led to a uniform local heat transfer through the PCM as it is depicted in Fig. 8b and c, which is more significant for the composite PCM with  $\varepsilon = 75\%$ . The presence of the metal mesh not only enhances the thermal conductivity of PCM, but also reduces the permeability. The lower permeability limits buoyancy driven motion, thus reducing the natural convection. The increase in the thermal conductivity enhances conductive heat transfer and thus limiting the dominance of convection further. It can be seen from Fig. 8(b) and (c) that convection is suppressed in lower porosity of metal mesh, as the difference in the local heat flux with height decreases as porosity decreases. The decrease in the porosity reduces the time required to reach thermal equilibrium as it can be observed from Fig. 8(b) and (c), as the heat transfer rate reaches to a minimum constant value earlier when composite PCM is used. In conclusion, heat flux profiles for pure PCM is sparse due to the development and propagation of the non-uniform thermal boundary layer.



Fig. 8. Trend of local heat transferred through the inner wall of C-LHTES system at  $T_h = 58$  °C: (a) Pure PCM ( $\varepsilon = 100\%$ ), (b) composite PCM ( $\varepsilon = 87\%$ ), and (c) composite PCM ( $\varepsilon = 75\%$ ).

However, for the composite PCM (i.e., PCM embedded in metal mesh case), heat flux profiles remain within a narrow band and such pattern is due to the uniformity in the temperature distribution in the presence of the porous medium as can be observed from Fig. 5(b) and (c).

Fig. 9 presents the effect of different isothermal wall temperatures  $(T_h)$  on the trend of local heat transfer. The magnitude of the local heat transfer increases as  $T_h$  increases from 38 °C to 58 °C. For instance, the magnitude of the local heat transfer was increased by approximately 74% and 187% by increasing  $T_h = 38$  °C to 48 °C and  $T_h = 38$  °C to 58 °C, respectively. The higher isothermal surface temperature increases the heat transfer rate since the temperature gradient across the boundary increases. Besides, the buoyancy-driven motion improves with the increase in the boundary temperature. The higher isothermal boundary temperature leads to higher Rayleigh number, thus, dominance of convective heat transfer increases. The total heat transfer can be obtained by integrating the heat flux through the C-LHTES system at each probe multiplied by the heat transfer surface area. This can be calculated by using the following equation.

$$\dot{Q} = 2\pi r_{in} \int_{0}^{H} \dot{q}_{y} dy$$
(4)

Fig. 10 presents a comparison of total heat transfer between pure PCM and composite PCMs at  $T_h = 48$  °C. Initially, as it can be confirmed by the temperature variations discussed in Section 3.1, there is an insignificant effect by using the composite PCM on the total heat transfer. However, at the later stages, the heat is transferred uniformly through the PCM due to a higher effective thermal conductivity by using composite PCMs. Because of a uniform temperature distribution inside the C-LHTES system, the temperature gradient between hot lateral walls of C-LHTES system and the PCM reaches to its minimum value in a shorter time due to the use of composite PCMs. This leads to a higher rate of heat transfer for composite PCMs compared to the pure PCM.

The melting process of PCM inside a rectangular enclosure, heated from one vertical side and insulated remaining walls, are well described problems in the literature [38]. In general, four distinct melting regimes (i.e., conduction, transition, convection, and shrinking solid regimes)



Fig. 9. Trend of local heat transferred through the inner wall of C-LHTES system for composite PCM having  $\varepsilon = 75\%$  at three different isothermal temperatures: (a)  $T_h = 38$  °C, (b)  $T_h = 48$  °C, and (c) 58 °C.

are proposed and it is concluded that the general trend of the variation in heat transfer with time depends on melting regimes [38]. However, for a PCM filled cylindrical geometry, heated from its peripheral area, the transition between one melting regime to the next is not as distinct as the case with the rectangular geometry [34]. For example, both transition and shrinking solid regimes may exist together for a considerable amount of melting time, which impacts the profile shape of the variation in heat transfer with time and observed in Fig. 10 as well. For approximately first 10 min, the trend of the curve (i.e., rapid drop of heat transfer as time advances) in Fig. 10 conforms to a typical conduction regime heat transfer profile. Approximately from 10 to 25 min, an influence from the initial shrinking solid on the transition regime of melting slows down the drop in heat transfer rate. The concave cup shaped pattern in  $\dot{Q}$ -t profile, as reported in [38], is not visible here. Subsequently, the strong convection dominated regime (25-75 min) has the influence of the shrinking solid and, therefore, variation in  $\dot{Q}$  is no longer independent of *t*, as reported in [38]. Approximately from 75 min to 135 min, Q-t profile is dominated by

shrinking solid regime as a significant portion of the PCM is melted already and reached close to the wall temperature. The remaining solid PCM melts slowly until the completion of melting process. Beyond 135 min, the enclosure is filled with liquid PCM only (i.e., single phase) and heat transfer rate drops and approaches to zero once the liquid PCM reaches to thermal equilibrium with the wall.

# 3.3. Energy stored

As the primary goal of designing an industrial TES system is the potential of storing thermal energy in an efficient way, it is critical to study the trend of stored energy during the charging (melting) process. The amount of stored energy during the melting process can be approximated by the integration of instantaneous heat transfer from the isothermal hot water bath to the C-LHTES system during the melting process. Therefore, the following equation is used to calculate the energy stored during the melting process [34,35].



**Fig. 10.** A comparison of the total heat transferred for three different values of  $\varepsilon$ , at  $T_h = 48$  °C.

$$E = \int_{0}^{t} \dot{Q}(t) dt$$
(5)

Fig. 11 presents the transient trend of energy stored during the melting process at three different values of isothermal boundary temperatures. For brevity, the selected result for composite PCM having  $\varepsilon = 75\%$  is presented. At the beginning of the melting process, a large temperature gradient between the hot lateral walls of the C-LHTES system and the cold PCM exists that leads to a sharp increase in the amount of stored energy. This trend continues almost linearly with a lower slope as the rate of heat transfer is degraded. Towards the final stages of the melting process, the value of stored energy reaches its maximum value where the thermal equilibrium condition is achieved. The thermal energy is stored as sensible heat at early stages of melting process since the cold PCM adjacent to the hot lateral walls of the C-LHTES system is in the solid state (i.e., below the melting temperature of the PCM). As the melting process progresses, the temperature of the PCM close to the hot lateral walls of the enclosure rises from  $T_0$  to  $T_m$ , and a thin layer of molten PCM appears. At the transient stage (i.e. solid state to liquid state), the energy is stored as latent heat during the melting process. As the melting process completes, where all PCM is fully melted, again the energy will be stored as sensible heat. In addition, energy will be stored in the copper mesh as sensible heat since there is no change in the phase of the copper mesh. As it can be observed from Fig. 11, as the temperature of isothermal bath increases from  $T_h = 38$  °C to  $T_h = 58$  °C, the amount of energy stored increases which can be verified by the higher rate of heat transfer. The increase in the isothermal bath temperature enhances the heat transfer rate and energy storage capacity of the C-LHTES system. The higher isothermal bath temperature leads to a larger temperature gradient across the wall of C-LHTES system and it improves the convection current. Thus, enhancing the heat transfer rate leads to a higher rate of energy stored with time. Table 7 quantifies the increase in the amount of stored energy by increasing  $T_h$ .

Fig. 12 compares the trend of energy stored inside the C-LHTES system for pure PCM, composite PCM with porosity of 87%, and composite PCM with porosity of 75% at  $T_h = 38$  °C. Using the copper mesh as the porous medium leads to a higher effective thermal conductivity in the composite PCMs. As a result, thermal energy will be added to the

C-LHTES system relatively faster than for the pure PCM case. The increase in the rate of the stored energy is more significant when a lower porosity of copper mesh (i.e. e = 75%) embedded into the PCM (i.e., more conductive material) is used. However, towards the final stages of the melting process, the energy profiles of the three cases are close to each other since the PCM has reached to its maximum energy absorbing point, and the thermal equilibrium is the same for all cases of porosities. At the end of the melting process, the amount of stored energy for the pure PCM case is higher than that for the composite cases. By implementing the copper mesh, part of the supplied energy is absorbed by the copper mesh. As a result, the amount of the stored energy in the pure PCM case is approximately 2% higher than that for the composite PCM. A similar trend was seen when  $T_h = 48$  °C and 58 °C.

#### 3.4. Nusselt number

As mentioned earlier, temperatures, as well as temperature gradients were measured at eight pre-selected locations inside the inner surface of the C-LHTES system. Based on the measured temperature gradient at each location, the local Nusselt number  $(Nu_y)$  was calculated using the Eq. (6).

$$Nu_{y} = \frac{H}{k_{f}} \left( \frac{\dot{q}_{y}}{T_{h} - T_{m}} \right)$$
(6)

where *H* is the height of the PCM,  $k_f$  is the thermal conductivity of the fluid (i.e. molten PCM), and  $\dot{q}_y$  is calculated by using Eq. (3). Subsequently, the average Nusselt number (*Nu*) is calculated by integrating  $Nu_y$ . Fig. 13 presents the trend in the surface-averaged Nusselt number at three different porosities of copper mesh subjected to the different values of  $T_h$ . Note that *Nu* profiles in Fig. 13(a)–(c) are presented as a function of the product of Stefan and Fourier numbers (i.e., *Ste Fo*), which can be calculated by using Eq. (7) [36,37].

Ste Fo = 
$$\left[\frac{c_{ps}(T_m - T_o) + c_{pl}(T_h - T_m)}{h_{sf}}\right] \times \left(\frac{\alpha t}{H^2}\right)$$
(7)

where  $c_{ps}$  and  $c_{pl}$  are the specific heat of n-octadecane at the solid and liquid states, respectively, is the thermal diffusivity, and *t* represents the time. The thermal diffusivity ( $\alpha$ ) is calculated using  $k/(\rho c_p)$ . Solid PCM properties are considered in case of  $T < T_m$ , while liquid PCM properties are considered in case of  $T > T_m$ . At the initial stages of melting



Fig. 11. Transient trend of energy stored in composite PCM with  $\varepsilon$  = 75%.

#### Table 7

Energy stored (kJ) and its increment by increasing  $T_h = 38$  °C to 58 °C, pure PCM.

Time (min.)	$T_h = 38$ °C	$T_h = 48 \ ^\circ \mathrm{C}$	$T_h = 58 \ ^\circ \mathrm{C}$
20	2.80	4.83 (+72.5%)	8.05 (+188%)
50	5.75	10.36 (+80%)	15.98 (+178%)
120	11.44	19.25 (+68%)	23.66 (+107%)



Fig. 12. A comparison of energy stored for three different porosities ( $\epsilon$ ), at  $T_h = 38$  °C.

process, where conduction is the dominant form of heat transfer, the rate of heat transfer through the lateral walls of the C-LHTES system is high due to a large temperature gradient between cold PCM and isothermal water bath. Therefore, as it can be depicted from Fig. 13(a) to (c), the magnitude of *Nu* number is higher than other stages of melting process at the begging of experiment. An exponential decrease in the Nusselt number characterizes the conduction regime. As the melting process proceeds, the PCM in the vicinity of the wall melts and its temperature rises. As a result, the viscosity of the PCM decreases which lead to the dominancy of buoyant force. At this point, there is a change in the slope of Nu-SteFo graph which is due to the onset of natural convection. The onset of the natural convection delays with the decrease in the porosity, due to the lower permeability and higher effective thermal conductivity. The increase in the isothermal bath temperature leads to faster melting and rise in the temperature of the PCM near the wall, due to the larger temperature gradient. Hence, the onset of natural convection takes place earlier. Besides, the higher isothermal bath temperature increases the dominance of convection as Rayleigh increases. As the melting proceeds, the heat transfer rate is primarily through convection, especially in higher porosity and higher isothermal bath temperature. As the melting front reaches to the center of the cylinder, the height of the solid PCM starts to decrease, and this is known as variable height regime, and identified by a decrease in the Nusselt to a minimum constant value.

#### 3.5. The proposed correlation

An attempt was made to develop a correlation between the experimentally derived Nusselt number vs. dimensionless time parameter (i.e.,  $\Theta = SteFo$ ) during different stages of the charging process

(melting), using curve fitting technique. Fig. 14 presents a comparison of the proposed correlation of *Nu-SteFo* vs. the experimentally derived *Nu-SteFo* for two selected cases (i.e.,  $T_h = 38$  °C: (a) composite PCM ( $\varepsilon = 75\%$ ) and (b) pure PCM ( $\varepsilon = 100\%$ )). The correlation obtained between experimentally calculated *Nu* and  $\Theta$  during conduction dominant region as in Eq. (8), closely follows the correlation by Jany and Bejan [38] using scale analysis. The additional coefficient *a* presents a finite value of measured *Nu* at  $\Theta = 0$ , in contrary to the notion of *Nu* approaching to infinity as  $\Theta$  approaches to zero. The coefficients of the correlation for melting of PCM during conduction dominant region, in different porosities of copper mesh (i.e., 100%, 87%, and 75%) at different isothermal temperatures (i.e., 38 °C, 48 °C, and 58 °C) are given in Tables 8–10.

$$Nu = \frac{1}{a + b \Theta^c}; \quad (0 < \Theta < 0.005)$$
(8)

As the melting front progresses, the viscous force degrades that leads to the onset of natural convection. The Nu plotted against  $\Theta$  can be observed to form a convex, as a result of two terms arising from conduction and convection, in the mixed region. By using scale analysis Janv and Bejan [38] showed that in the conduction region Nu number decreases exponentially by increasing  $\Theta$ , while, in the convection region, it increases exponentially, and the dominance of the two terms governs the profile of Nu vs.  $\Theta$  in the mixed region. The height at which the deviation in the solid-liquid interface occurs, reduces, and eventually touches the bottom, this marks the transition to convection dominant heat transfer. The Nu can be observed to be independent of  $\Theta$ in this region. The melting rate is higher on the top due to convection. Thus, the solid-liquid interface approaches center first on the top and the height of the solid region starts to decrease. This is known as variable height region. The height of the solid region reduces and eventually completed melting takes place, and the heat transfer through the isothermal surface raises the temperature of the PCM until the thermal equilibrium is achieved. The variation in Nu vs.  $\Theta$  in the mixed, convection, and variable height regions are correlated by a fifth order polynomial as given by Eq. (9).

$$Nu = a + b\Theta + c\Theta^{2} + d\Theta^{3} + e\Theta^{4} + f\Theta^{5}; \quad 0.0005 < \Theta < 0.04$$
(9)

The coefficients of the correlation for melting of PCM at different porosities of copper mesh (i.e., 100%, 87%, and 75%) and at different isothermal boundary temperatures (i.e., 38 °C, 48 °C, and 58 °C) are given in Tables 11–13.

The standard deviation of the proposed correlation is calculated by using Eq. (10) and, quantified in Table 14. In Eq. (10), U is the standard deviation, n is the total number of data points,  $Nu_{exp}$  is the experimentally derived Nusselt number, and  $Nu_{co}$  is the Nusselt number obtained by using the proposed correlation.

$$U = \sqrt{\frac{\sum_{i=1}^{n} (Nu_{\exp} - Nu_{co})^2}{n}}$$
(10)

It was intended to identify a single correlation that would establish relationship between *Nu* and *SteFo* for all regimes of the melting, as oppose to different correlations for different regimes. A wide range of possible correlations were examined and the proposed fifth order polynomial can provide best possible relationship between Nu and SteFo when there is no porous mesh inside the PCM. Therefore, the same polynomial is applied for the cases with porous mesh. As observed from Fig. 14(a) that there is a discrepancy between the experimental data and the data obtained from the correlation in the transition regime, which may be the major source triggering the difference in the standard deviation in Table 14. Therefore, further analysis regarding a rigorous correlation is left for a future work.



Fig. 13. Trend of surface averaged Nusselt number: (a) Pure PCM ( $\varepsilon = 100\%$ ), (b) composite PCM with  $\varepsilon = 87\%$ , and (c) composite PCM with  $\varepsilon = 75\%$ .

# 4. Conclusions

In the present investigation, the effect of embedding copper wire mesh as a porous medium inside a C-LHTES system filled with n-octadecane as the PCM is experimentally studied. A comparison of temperature distributions, local and total heat transfer, Nusselt number, and rate of stored energy between pure PCM and composite PCMs subjected to three different values of isothermal temperature including  $T_{h} = 38$  °C, 48 °C, and 58 °C is performed. A correlation is proposed to predict the Nusselt number for different cases of the experiment. The following conclusions can be drawn from the present experimental work:

- The uniformity of thermal energy distributions inside the C-LHTES system increases upon embedding the copper wire mesh, the effect is more significant at lower porosity of copper wire mesh (i.e., ε = 75%) due to the enhanced effective thermal conductivity by using composite PCM.
- The addition of copper wire mesh reduces the time required to achieve thermal equilibrium.

- The onset of natural convection is delayed due to lower permeability and higher effective thermal conductivity when the composite PCM filled the C-LHTES system. This delay is found to be more significant at lower porosity ( $\varepsilon = 75\%$ ) of composite PCM.
- A maximum of 24% improvement in the charging time is achieved by using composite PCM with porosity of  $\varepsilon = 75\%$ .
- A good agreement is achieved when comparing the correlated *Nu* number with the experimentally derived *Nu* number.

# **Declaration of Competing Interest**

On behalf of all authors of this paper, I hereby confirm that there is no conflict of interest with any educational and financial organizations regarding the content of this paper.

#### Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.applthermaleng.2020.115266.



Fig. 14. Proposed Nu-SteFo correlation Vs. experimentally derived Nu-SteFo at isothermal temperature of  $T_h = 38$  °C: (a) composite PCM ( $\varepsilon = 75\%$ ) and (b) pure PCM ( $\varepsilon = 100\%$ ).

# Table 8

Coefficients for correlation in the conduction region for melting of pure PCM at three different isothermal boundary conditions.

Coefficients	38 °C	48 °C	58 °C
a b c	$\begin{array}{l} 4.1763 \\ 4.0643 \\ 5.7211  \times  10^{-1} \end{array}$	$\begin{array}{l} 4.9322\times10^{-2}\\ 1.0325\times10^{1}\\ 7.0867\times10^{-1} \end{array}$	$\begin{array}{l} 5.2344  \times  10^{-2} \\ 2.9413  \times  10^{1} \\ 8.8353  \times  10^{-1} \end{array}$

# Table 9

Coefficients for correlation in the conduction region for melting of PCM having 87% porosity of copper mesh for three different isothermal boundary conditions.

Coefficients	38 °C	48 °C	58 °C
a b c	$\begin{array}{l} 4.2991  \times  10^{-2} \\ 4.0777 \\ 5.8177  \times  10^{-1} \end{array}$	$\begin{array}{l} 4.9705  \times  10^{-2} \\ 2.1804  \times  10^{1} \\ 8.1151  \times  10^{-1} \end{array}$	$\begin{array}{l} 5.1851 \times 10^{-2} \\ 3.1945 \times 10^{1} \\ 8.9028 \times 10^{-1} \end{array}$

# Table 10

Coefficients for correlation in the conduction region for melting of PCM having 75% porosity of copper mesh at three different isothermal boundary conditions.

Coefficients	38 °C	48 °C	58 °C
a b c	$\begin{array}{l} 4.3493 \times 10^{-2} \\ 6.1399 \\ 6.137 \times 10^{-1} \end{array}$	$\begin{array}{l} 5.0076 \times 10^{-2} \\ 9.0017 \\ 6.8126 \times 10^{-1} \end{array}$	$\begin{array}{l} 5.1309 \times 10^{-2} \\ 1.9312 \times 10^{1} \\ 8.4884 \times 10^{-1} \end{array}$

# Table 11

Coefficients for correlation in Eq. (9) for melting of pure PCM at three different isothermal boundary conditions.

Coefficients	38 °C	48 °C	58 °C
a b c d e f	$\begin{array}{c} 1.0764 \times 10^1 \\ -1.2526 \times 10^3 \\ 1.2448 \times 10^5 \\ -5.9493 \times 10^6 \\ 1.2536 \times 10^8 \\ -9.7093 \times 10^8 \end{array}$	$\begin{array}{c} 1.0148 \times 10^{1} \\ -9.2902 \times 10^{2} \\ 9.5424 \times 10^{4} \\ -4.8376 \times 10^{6} \\ 1.0437 \times 10^{8} \\ -8.0479 \times 10^{8} \end{array}$	$\begin{array}{c} 1.1111 \times 10^{1} \\ -1.1188 \times 10^{3} \\ 1.1479 \times 10^{5} \\ -5.8242 \times 10^{5} \\ 1.2834 \times 10^{8} \\ -1.0255 \times 10^{9} \end{array}$

# Table 12

Coefficients for correlation in Eq. (9) for melting of PCM having 87% porosity of copper mesh at three different isothermal boundary conditions.

Coefficients	38 °C	48 °C	58 °C
a b c d e f	$\begin{array}{c} 1.02 \times 10^{1} \\ -7.7 \times 10^{2} \\ 3.08 \times 10^{4} \\ 6.28 \times 10^{5} \\ -6.60 \times 10^{7} \\ 9.89 \times 10^{8} \end{array}$	$\begin{array}{c} 1.0766 \times 10^1 \\ -1.2075 \times 10^3 \\ 1.1346 \times 10^5 \\ -4.6802 \times 10^6 \\ 7.1858 \times 10^7 \\ -2.661 \times 10^8 \end{array}$	$\begin{array}{c} 1.142 \times 10^{1} \\ -1.3716 \times 10^{3} \\ 1.3968 \times 10^{5} \\ -6.3095 \times 10^{6} \\ 1.1471 \times 10^{8} \\ -6.7174 \times 10^{8} \end{array}$

#### Table 13

Coefficients for correlation in Eq. (9) for melting of PCM having 75% porosity of copper mesh at three different isothermal boundary conditions.

Coefficients	38 °C	48 °C	58 °C
a b c d e f	$\begin{array}{c} 9.1243 \\ -\ 6.3245 \times 10^2 \\ 6.1915 \times 10^4 \\ -\ 3.0419 \times 10^6 \\ 5.6152 \times 10^7 \\ -\ 2.9998 \times 10^8 \end{array}$	$\begin{array}{c} 9.7608 \\ - \ 9.1848 \times 10^2 \\ 1.0948 \times 10^5 \\ - \ 6.2084 \times 10^6 \\ 1.4379 \times 10^8 \\ - \ 1.1528 \times 10^9 \end{array}$	$\begin{array}{c} 1.2278 \times 10^1 \\ -1.4481 \times 10^3 \\ 1.5339 \times 10^5 \\ -7.7008 \times 10^6 \\ 1.6452 \times 10^8 \\ -1.2415 \times 10^9 \end{array}$

# Table 14

The standard deviation of the proposed Nu-SteFo correlation with the experimentally derived Nu-SteFo.

	38 °C	48 °C	58 °C
Pure PCM ( $\varepsilon = 100$ ) Composite PCM ( $\varepsilon = 87\%$ ) Composite PCM ( $\varepsilon = 75\%$ )	0.085 0.13	0.065 0.19 0.16	0.077 0.195

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