An experimental investigation of discharge/solidification cycle of paraffin in novel shell and tube with longitudinal fins based latent heat storage system

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Abstract

In this article, the discharging cycles of paraffin in novel latent heat storage (LHS) unit are experimentally investigated. The novel LHS unit includes shell and tube with longitudinal fins based heat exchanger and paraffin as thermal energy storage material. The experimental investigations are focused on identifying the transient temperature performance, effective mode of heat transfer, accumulative thermal energy discharge and mean discharge power of paraffin in LHS unit. Moreover, the influences of operating conditions such as inlet temperature and volume flow rate of heat transfer fluid (HTF) on thermal behaviour of LHS unit are experimentally studied. The transient temperature profiles and photographic characterisation of liquid-solid transition of paraffin in LHS unit provide a good understanding of temperature distribution and dominant mode of heat transfer. It is noticed that during discharging cycles, natural convection has an insignificant impact on thermal performance of LHS unit. However, due to inclusion of extended longitudinal fins, conduction is the dominant mode of heat transfer. It is noticed that due to development of solidified paraffin around tubes and longitudinal fins, the overall thermal resistance is increased and thus, discharging rate is affected. However, by regulating inlet temperature or volume flow rate of HTF, the influence of overall thermal resistance is minimised. Mean discharge power is enhanced by 36.05% as the inlet temperature is reduced from 15 ^{o}C to 5 ^{o}C. Likewise, the mean discharge power is improved by 49.75% as the volume flow rate is increased from 1.5 l/min to 3 l/min. Similarly, with an increase in volume flow rate, the discharge time of equal amount of thermal energy 12.09 MJ is reduced by 24%. It is established that by adjusting operating conditions, the required demand of output temperature and mean discharge power can be attained. Furthermore, this novel LHS unit can meet large scale thermal energy demands by connecting several units in parallel and thus, it has potential to be employed in wide-ranging domestic and commercial applications.

Keywords

Thermal energy storage, Latent heat storage, Discharge cycle, Phase change materials, Heat transfer, Shell and tube heat exchanger

1. Introduction

Due to an increase in global economic growth, the urge for consistent supply of energy has increased in both industrial and domestic applications. Fossil fuels have been serving the purpose of generating desired energy for many decades. However, the harmful emissions from fossil fuels have caused climate change and global warming [1-3]. Therefore, the need for efficient and responsive technologies for renewable energy and heat recovery sources are imperative to abridge gap between energy supply and demand. Thermal energy storage (TES) is an environmental friendly technique to capture thermal energy at solar peak hours or from heat recovery sources and releases it to balance out energy demand. Latent heat storage (LHS) is considered as more attractive technique of TES due to its high thermal storage density, almost isothermal energy storage and retrieval, low vapour pressure, chemical stability and small variation in volume during phase transition [4-6].

LHS systems utilises phase change materials (PCM) to capture and release thermal energy during phase transition. LHS systems have been employed in number of practical applications ranging from solar thermal systems, waste heat recovery systems, energy balancing, management and peak shaving, agricultural drying and building air-conditioning systems [7-12]. However, the large scale practical utilisations of LHS systems are hindered by low thermal conductivity of phase change materials (≈ 0.2 W/m.K) [13, 14]. Due to low thermal conductivity, the rapid charging and discharging of LHS system is highly affected. Thus, a responsive heat transfer mechanism is essential to counter low thermal conductivity. Several methods have been proposed to improve heat transfer mechanism and consequently overall thermal performance of LHS system such as: container geometrical orientation, inclusion of extended surfaces, dispersion of high conductive additives and encapsulation [15-22]. The geometrical configuration of heat exchanger in LHS system plays a crucial role. Various types of heat exchangers for LHS systems are examined, however shell and tube configuration is intensely researched due to its easy installation into majority of industrial applications and design simplicity with minimal heat loss benefits [23].

Seddegh et al. [24] performed experimental investigations of paraffin (RT60) in vertical shell and tube configuration with varying tube radius. Four tube radiuses were tested with shell-tube radius ratio of: 8.1, 5.4, 4 and 2.7. It was noticed that by decreasing radius ratio from 8.1 to 2.7, the solidification time was reduced by 44%. Yazici et al. [25] performed an experimental examination of paraffin in horizontal shell and tube configuration of LHS system. The effect of eccentricity of heat transfer fluid (HTF) tube on discharging rate was investigated. Six locations were probed with eccentricity values of: -10, -20, -30, 0, 10 and 20. It was noticed that either upward or downward increase in eccentricity showed a reduction in discharging rate, whereas the concentric orientation had presented a relatively higher discharging rate. Similarly, Seddegh et al. [26] numerically examined the thermal behaviour of paraffin (RT50) in vertical and horizontal orientation of shell and tube based LHS system. It was noticed that geometrical orientation of shell and tube had minimal effect on solidification rate, due to conduction dominated heat transfer. Likewise, Longeon et al. [27] experimentally tested paraffin (RT35) in a vertical shell and tube configuration. It was noticed that conduction was the dominant mode of heat transfer during discharging cycle. Hosseini et al. [28] conducted discharging cycles on paraffin (RT50) in horizontal shell and tube based LHS system. It was observed that the initial temperature of liquid paraffin had a negligible impact on overall thermal efficiency. Avci and Yazici [29] conducted experimental investigations on discharging cycles of paraffin in a horizontal shell and tube orientation. It was deduced that conduction was the dominated mode of heat transfer. Moreover, it was observed that discharging rate can be enhanced by decreasing inlet temperature of HTF. Wang et al. [30] numerically examined the influence of inlet temperature and flow rate of HTF on solidification time of n-octadecane in horizontal shell and tube based LHS system. It was noticed that temperature gradient between HTF and PCM was increased by reducing inlet temperature of HTF and thus, the solidification time was significantly reduced. Similarly, it was deduced that flow rate of HTF had an insignificant impact on overall thermal energy capacity of LHS system. Agarwal and Sarviya [31] performed an experimental study on paraffin wax in horizontal shell and tube based LHS system. It was noticed that solidification time was reduced by 19.09% as the mass flow rate was increased from 0.0015 to 0.003 kg/sec. Likewise, the cumulative thermal energy gain by HTF was increased by 8.7% with an increase in flow rate from 0.0022 to 0.003 kg/sec. Meng and Zhang [32] conducted numerical and experimental study to identify thermal behaviour of paraffin-copper foam composite in rectangular shaped shell and tube configuration of LHS system. It was observed that by increasing temperature gradient between PCM and HTF, the solidification time can be reduced by 34.76%. Likewise, by increasing inlet velocity of HTF from 0.1 m/sec to 0.2 m/sec, a moderate enhancement of 8.4% was observed in discharging rate. Wang et al. [33] performed experimental examination of erythritol as PCM in vertical shell and tube orientation of LHS system. It was noticed that inlet temperature and flow rate of HTF had a significant impact on discharging rate. However, an increase in pressure of HTF demonstrated a trivial impression on discharging rate.

It is evident from previous literature that temperature gradient and flow rate of HTF can influence the discharging rate. However, due to low thermal conductivity of PCM, the optimum benefits could not be achieved. Therefore, the most convenient and cost effective technique is to incorporate extended surfaces [34]. Rabienataj Darzi et al. [35] conducted numerical simulation of n-eicosane in horizontal shell and tube with longitudinal fins. It was noticed that as compared to without fins orientation, the solidification time was increased by 28% to 85% as the number of fins were increased from 4 to 20, respectively. Li and Wu [36] numerically investigated the thermal behaviour of $NaNO_3$ as PCM in horizontal shell and tube configuration with and without longitudinal fins. It was deduced that solidification time is reduced by 14% with inclusion of longitudinal fins. Rathod and Banerjee [37] conducted experimental examination of stearic acid in a vertical shell and tube with three longitudinal fins configuration. It was observed that due to inclusion of three longitudinal fins, the solidification time was reduced by 43.6%. Liu and Groulx [38] experimentally studied the influence of straight and angled longitudinal fins on discharging rate of dodecanoic acid in horizontal shell and tube configuration. Four longitudinal fins were attached to tube. It was noticed that due to conduction dominated heat transfer, both orientations presented almost identical discharging performance. Al-Abidi et al. [39] performed numerical simulation to investigate the solidification process of paraffin (RT82) in a horizontal triplex tube heat exchanger based LHS system. The discharge time was reduced by 35% with longitudinal fins as compared to no fins configuration. Also, the influence of longitudinal fins number, length and thickness were examined. It was reported that number of fins and length had a significant influence on solidification rate. However, the impact of fins thickness was moderate. Likewise, Almsater et al. [40] performed numerical and experimental investigation on solidification process of water as PCM and Dynalene HC-50 as HTF in a vertical triplex tube heat exchanger. It was observed that the solidification time was reduced from 3.67 hr to 3 hr and 2.31 hr by increasing mass flow rate from 0.02 kg/s to 0.044 kg/s and 0.074 kg/s, respectively. Kabbara et al. [41] conducted experimental investigation on solidification process of dodecanoic acid in a vertical shell and tube with rectangular fins configuration. It was noticed that the solidification rate and discharge power was slightly improved by increasing flow rate. However, more experimental tests could have conducted to help in drawing better conclusions. Agyenim et al. [42] experimentally investigated the influence of radial and longitudinal fins on thermal performance of Erythritol as PCM in shell and tube configuration. It was noticed that cumulative thermal energy discharge for no fins, radial fins and longitudinal fins were 4977.8 kJ, 7293.1 kJ and 8813.1 kJ, respectively. Similarly, Lohrasbi et al. [43] performed comparative examinations on thermal performance of PCM in vertical shell and tube configurations with no fins, optimised circular fins and longitudinal fins. It was reported that the phase transition rate for optimised circular fins and longitudinal fins orientations were 3.55 and 4.28 times higher as compared to no fins orientation, respectively. Likewise, Caron-Soupart et al. [44] conducted experimental investigations of paraffin (RT35HC) in shell and tube with three configurations: no fins, radial fins and longitudinal fins. It was reported that longitudinal fins had generated better temperature gradient and thermal power as compared to no fins and radial fins. Therefore, it is concluded from previous literature that longitudinal fins have better thermal performance during solidification process as compared to no fins and radial fins configurations. Moreover, it is observed that shell and tube with single pass orientations are exclusively studied in previous literature, as detailed in **Table 1**. Therefore, the literature lacks experimental investigations of shell and tube with multiple passes and extended surfaces. Also, there is a lack of discussion on thermal energy discharge and mean discharge power of proposed LHS systems. Therefore, there is a need to experimentally investigate shell and tube with multiple passes and longitudinal fins based LHS system which can provide a viable solution for higher thermal storage capacity, discharge rate and discharge power. This article is focused on experimentally investigating a novel geometrical orientation of shell and tube with multiple passes and longitudinal fins which is not reported in previous literature. Furthermore, this article proposes a responsive and compact thermal storage design solution with higher discharge rate, cumulative heat capacity and discharge power.

Table 1
Summary of various studies conducted to examine thermal behaviour of PCM in shell and tube based LHS systems

Ref No.	Study type	Shell and tube		Extended surfaces		PCM
		Tube passes	Orientation	Type	No. of fins	
[24]	Exp.	Single	Vertical	-	-	Paraffin (RT 60)
[25]	Exp.	Single	Horizontal	-	-	Paraffin P56-58
[26]	Num.	Single	Ver. / Hor.	-	-	Paraffin (RT 50)
[27]	Exp./Num.	Single	Vertical	-	-	Paraffin (RT 35)
[28]	Exp./Num.	Single	Horizontal	-	-	Paraffin (RT 50)
[29]	Exp.	Single	Horizontal	-	-	Paraffin P56-58
[30]	Num.	Single	Horizontal	-	-	n-Octadecane
[31]	Exp.	Single	Horizontal	-	-	Paraffin (41-55)
[32]	Exp./Num.	Double	Vertical	-	-	Paraffin (54-64)
[33]	Exp.	Single	Vertical	-	-	Erythritol
[35]	Num.	Single	Horizontal	Longitudinal	4 - 20	n-Eicosane
[36]	Num.	Single	Horizontal	Longitudinal	6	$NaNO_3$
[37]	Exp.	Single	Vertical	Longitudinal	3	Stearic acid
[38]	Exp.	Single	Horizontal	Longitudinal	4	Dodecanoic acid
[39]	Num.	Single	Horizontal	Longitudinal	4 - 8	Paraffin (RT 82)
[40]	Exp./Num.	Single	Vertical	Longitudinal	8	Water
[41]	Exp.	Four	Vertical	Rectangular	58	Dodecanoic acid
[42]	Exp.	Single	Horizontal	Circular Longitudinal	8	Erythritol
Present study	Exp.	21	Vertical	Longitudinal	76	Paraffin (RT44HC)

In this article, the experimental examinations of discharging cycles of paraffin in a novel LHS system are conducted. The novel LHS system consists of shell and tube with longitudinal fins based heat exchanger and paraffin as thermal storage material. The geometrical orientations of novel LHS system is previously designed, simulated and discussed by authors in [45]. Numerical simulations were conducted to examine the influence of parameters such as number of tube passes and their orientations in shell, geometrical configurations of longitudinal fins and construction material; on thermal storage capacity and charging/discharging rate of LHS system. An optimum design of LHS system was developed and constructed to perform experimental investigations. Prior to performing discharging cycles, the paraffin are charged by connecting novel LHS system to flat plate solar collector [46]. In this article, the discharging cycles are performed by directing cold water from building water tank to extract thermal energy from paraffin in LHS system. The experimental investigations of discharging cycles are conducted at various operating conditions of inlet temperature and flow rate of HTF. Moreover, this paper is focused to examine the transient temperature performance, effective mode of heat transfer, total solidification/discharge time, cumulative thermal energy discharge and mean discharge power of paraffin in LHS unit. Furthermore, this article will give comprehensive knowledge of how to adjust operating conditions or connect several LHS units to meet required thermal energy demands.

2. Experimental Setup and Procedure

2.1 Experimental Setup

In this article, the focus is on investigation of thermal performance of LHS unit during discharging process. The schematic representation of experimental setup is demonstrated in **Fig. 1**. The experimental setup consists of flat plate solar collector (FPSC), solar simulator, latent heat storage (LHS) unit, paraffin as thermal storage material, water supply from municipal / building, centrifugal pump, flow meter and data acquisition with computer.

FPSC and solar simulators are utilised to conduct charging cycles at various operating conditions. Solar simulator is operated to deliver steady thermal radiations to FPSC which results in increasing thermal energy of HTF. The high temperature HTF is guided to pass through LHS unit where it loses thermal energy to paraffin. Charging cycle is repeated until the temperature of paraffin inside LHS unit is about 62 ^{o}C, which provides a good baseline for all discharging cycles.

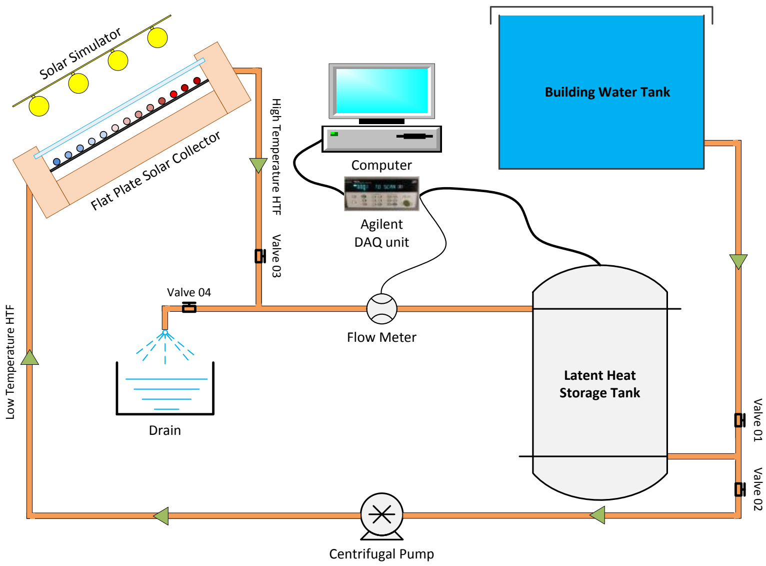

Fig. 1 Experimental setup layout for conducting discharging cycles of LHS unit.

During discharging cycle, the low temperature water is supplied from building water tank to extract thermal energy from paraffin in LHS unit. LHS unit is composed of vertical shell and tubes heat exchanger with longitudinal fins and paraffin as thermal storage material. The physical model of LHS unit is represented in **Fig. 2**. Shell and tubes with longitudinal fins are made up of copper. The outer diameter, length and thickness of shell are 450 mm, 385 mm and 1 mm, respectively. Likewise, the outer diameter and thickness of tubes are 22 mm and 1 mm. Longitudinal fins are connected to tubes having length, width and thickness of 230 mm, 40 mm and 1.5 mm, respectively. Chlorofluorocarbon-free envirofoam insulator of 50 mm thickness is muffled around the outer surface of shell to minimise thermal losses. Further design details on LHS unit can be found in [45]. Moreover, paraffin (RT44HC) is picked as thermal storage material due to its high thermal storage density, long term thermo-physical stability and good compatibility with copper [14, 47]. Thermal and physical characteristics of paraffin (RT44HC) are given in **Table 2**. Likewise, water is employed as heat transfer fluid (HTF).

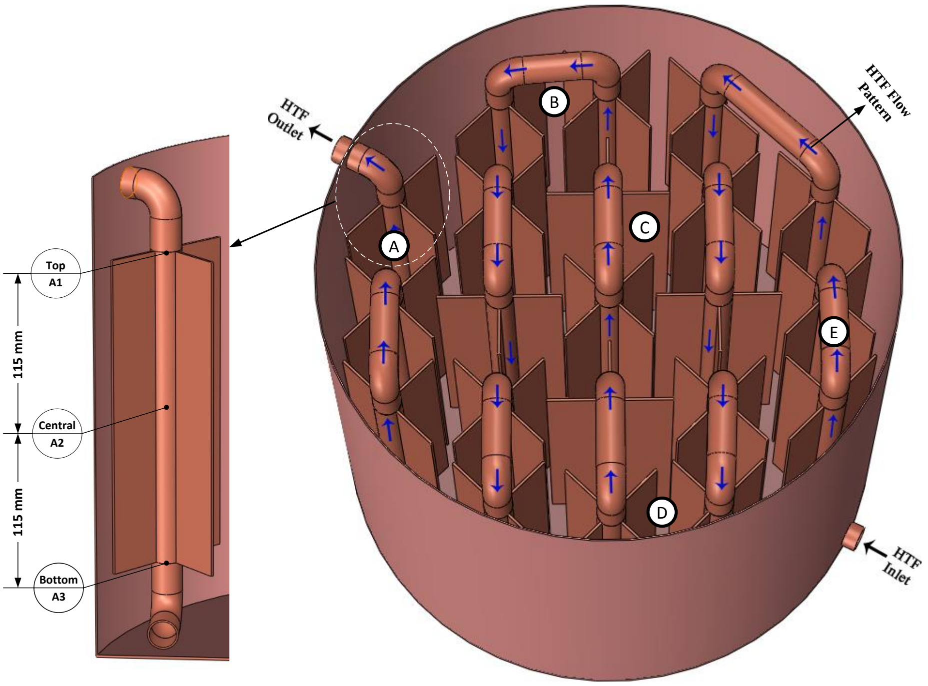

Fig. 2 Physical model representation of LHS unit with longitudinal fins, HTF flow pattern and vertical locations of thermocouples at various zones.

Table 2

Thermal and physical properties of paraffin (RT44HC) [14, 47]

Phase transition temperature	41-44 ^{o}C
Latent heat capacity	255 (kJ/kg)
Specific heat capacity	2.0 (kJ/kg. K)
Thermal conductivity	0.2 (W/m. K) solid, 0.2 (W/m. K) liquid
Density	800 (kg/m^3) solid, 700 (kg/m^3) liquid
Coefficient of thermal expansion	0.00259 (1/K)

Thermal response of paraffin in LHS unit is recorded by installing 15 K-type thermocouples at five zones i.e. A, B, C, D and E; at three vertical positions at each zone, as shown in **Fig. 2**. The vertical positions of thermocouples are categorised as top, central and bottom position. Each thermocouple position is at a vertical distance of 115 mm. Moreover, two thermocouples are installed at inlet and outlet of HTF to LHS unit to register the amount of thermal energy discharge by paraffin to HTF. Likewise, a flow meter (Titan FT2 Hall Effect) is utilised to measure volume flow rate value of HTF. The thermocouples and flow meter have an accuracy of ±0.18% and 1.5%, respectively. In discharging cycle, flow control valve 2 and 3 are turned off to bypass FPSC and centrifugal pump, whereas valve 1 and 4 are operated to conduct discharging cycles at various controlled volume flow rates. The data acquisition (Agilent 34972A) is employed to register temperature and volume flow rate readings from thermocouples and flow meter into computer. Time step of 10 s is used to record data on computer.

2.2 Experimental Procedure

Prior to perform discharging experiments, the paraffin in LHS unit is charged at higher temperature to make sure that entire mass of paraffin is in liquid state. To provide a good baseline, the discharging cycles are started once all thermocouples at top positions at all zones display temperature equal to 62 ^{o}C.

Low temperature water from building water tank is supplied to conduct open loop discharging cycles. To regulate flow rate of water, valve 1 and 4 are adjusted to required value. Discharging cycles are examined at four different volume flow rates of water, such as 1.5, 2.0, 2.5, 3.0 l/min. Low temperature water from building water tank is guided to pass through tube passes in LHS unit. Due to temperature gradient between low temperature water and high temperature paraffin, heat transfer takes place. Paraffin loses thermal energy to water and thus the temperature of water is raised. The high temperature water at outlet of LHS unit can be utilised for desired application. Due to loss of thermal energy to water, paraffin starts solidifying. The discharging cycle is completed once all thermocouples display paraffin temperature less than its phase transition temperature and the temperature difference between inlet and outlet of water is less than 5 ^{o}C. Furthermore, to investigate the thermal response of paraffin at various inlet temperatures of water, three different inlet temperatures are tested which are 5, 10 and 15 ^{o}C.

In order to assess the reliability and repeatability of experimental results, a series of three discharging experiments are conducted at inlet temperature of 10 ^{o}C and flow rate of 1.5 l/min. The experimental results illustrate almost identical transient temperature profiles. The statistical standard deviations for discharging rate at top, central and bottom position at zone C are calculated to be 0.008, 0.029 and 0.033, respectively.

3. Results and Discussion

3.1 Temperature Distribution

To understand the thermal behaviour of paraffin during discharging process, the low temperature HTF at 10 ^{o}C is channelled through tubes in LHS unit. Due to temperature gradient, the low temperature HTF extracts thermal energy from high temperature paraffin. In consequence, the temperature of HTF is increased, whereas paraffin temperature is reduced. In order to understand the transient change in thermal energy of paraffin, the temperature data from all fifteen K-type thermocouples are registered. Transient temperature distribution can help in identifying the dominating mode of heat transfer and phase transition rate at various positions in various zones in LHS unit.

To perform discharging cycle, a first set of experimental test is conducted with an inlet temperature and flow rate of 10 ^{o}C and 1.5 l/min, respectively. The transient temperature profiles acquired from thermocouples at top positions at all five zones are presented in **Fig. 3**. Due to higher temperature gradient between inlet temperature of HTF and paraffin in LHS unit, it is noticed that paraffin at top positions at all five zones rapidly discharges sensible portion of thermal energy to HTF. The sensible portion of thermal energy discharge to HTF is almost linear and as a result, paraffin temperature at top positions is reduced from initial temperature to 44 ^{o}C. Subsequently, latent portion of paraffin thermal energy discharge begins. Due to higher latent heat capacity of paraffin, the temperature of paraffin remains almost constant for a good period of time, as shown in **Fig. 3**. During this stage, the temperature of paraffin is gradually reduced from 44 ^{o}C to 41 ^{o}C. Due to discharge of latent portion of thermal energy, paraffin transforms from liquid phase to mushy phase and subsequently to solid phase. As latent portion of thermal energy is discharged, an instant decline in temperature is observed, which represents the sensible portion of thermal energy discharge.

Moreover, it can be observed that longitudinal fins are close-packed at zone C (centre of LHS unit), as shown in **Fig. 2**. Hence, the solidification/discharging rate of paraffin at top position at zone C is comparatively higher, as shown in **Fig. 3**. In succession, it can be noticed that due to relatively higher temperature gradient between inlet temperature of HTF and paraffin at zone E, the solidification rate is higher than zone A, B and D. The temperature of HTF increases as it extracts thermal energy from paraffin at zone E, D and C. Therefore, the temperature gradient for heat transfer is slightly reduced as HTF reaches zone B and zone A and thus, it affects the solidification rate of paraffin in those zones. Moreover, it can be observed from **Fig. 2** that HTF tube passes are connected at top at zone B, C and E, whereas it is connected at bottom at zone D. Therefore, due to geometrical orientation of connection between HTF tube passes and insignificant influence of natural convection, the discharge rate is comparatively lower at top position at zone D. Furthermore, an average of temperature profiles is obtained from all three thermocouples (top, central and bottom position) installed at each of five zones, as presented in **Fig. 4**. It is evident that due to higher temperature gradient between inlet temperature of HTF and paraffin, the discharging rate of paraffin at zone E is comparatively higher and is followed by zone C, zone B and zone A.

In order to give further insight into thermal performance of paraffin in longitudinal fins based LHS unit, the photographic illustration of discharge cycle is provided in **Fig. 5**. It can be observed that after discharging the system at inlet temperature of 10 ^{o}C and volume flow rate of 3 l/min for 0.25 hr, the paraffin around tubes and longitudinal fins are rapidly discharging latent portion of thermal energy to HTF and therefore the formation of solid layer is noticed. The transparent portion of paraffin represents the liquid phase, whereas the white portion displays the solid phase. It can be verified that the paraffin at inlet (zone E) is rapidly transforming to solid as compared to paraffin at outlet (zone A). This is due to the fact that conduction heat transfer and discharging rate is higher at inlet as compared to outlet. Likewise, after discharging for 0.5 hr, it can be noticed that thickness of solidified paraffin around tubes and longitudinal fins is increasing. The increase in thickness at zone E is more prominent. However, the paraffin in between longitudinal fins is still in liquid phase, which demonstrate the low thermal conductivity of paraffin. Similarly, after discharging for 0.75 hr, it is observed that a mushy phase of paraffin is created at top position, whereas the thickness of solidified paraffin has increased around tubes and longitudinal fins. It shows that natural convection has an insignificant impact on solidification of paraffin, whereas conduction is the dominant mode of heat transfer. Further, after discharging for 1 hr, it can be verified that paraffin at top position at zone C is completely solidified, whereas the top positions of the other zones display mushy phase. Finally, after discharging for 1.25 hr, it can be noticed that paraffin at top position at all zones have entirely discharged latent portion of thermal energy and have phase transformed to solid.

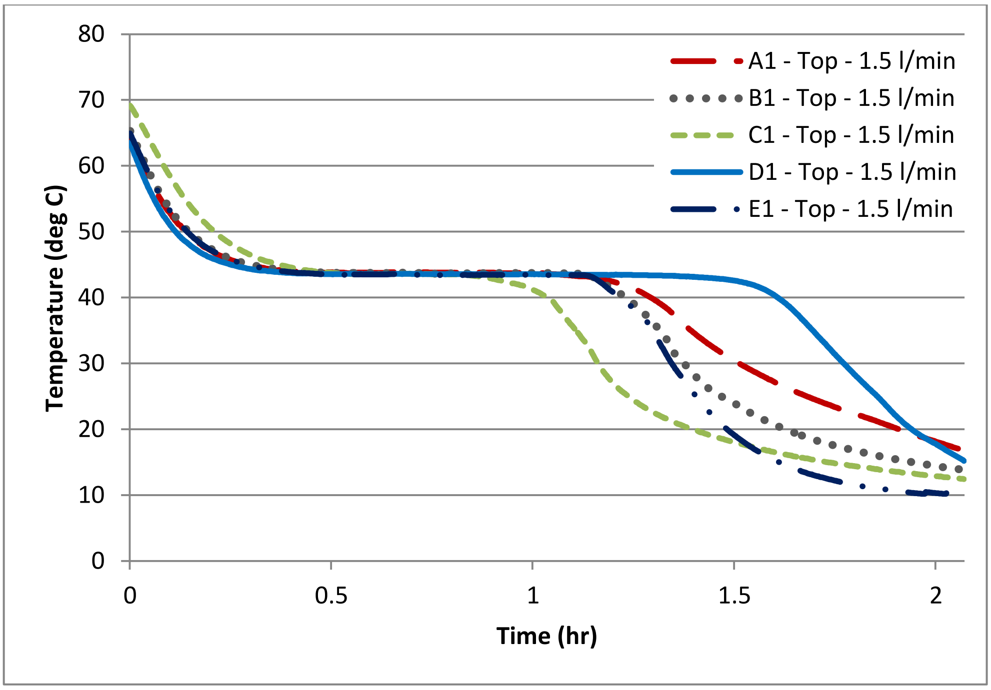

Fig. 3 Illustration of transient temperature profiles recorded at top position at all five zones during discharging process. Inlet temperature and volume flow rate of HTF are set to 10 ^{o}C and 1.5 l/min.

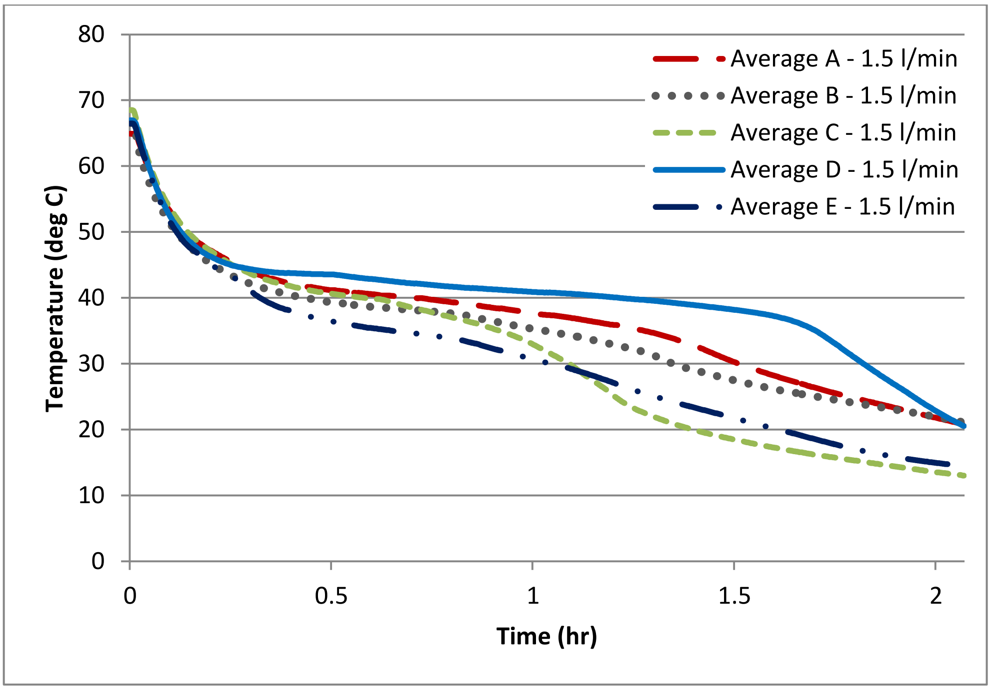

Fig. 4 Time-wise variations in average temperature profiles obtained at all five zones during discharging cycle at inlet temperature and volume flow rate of 10 ^{o}C and 1.5 l/min, respectively.

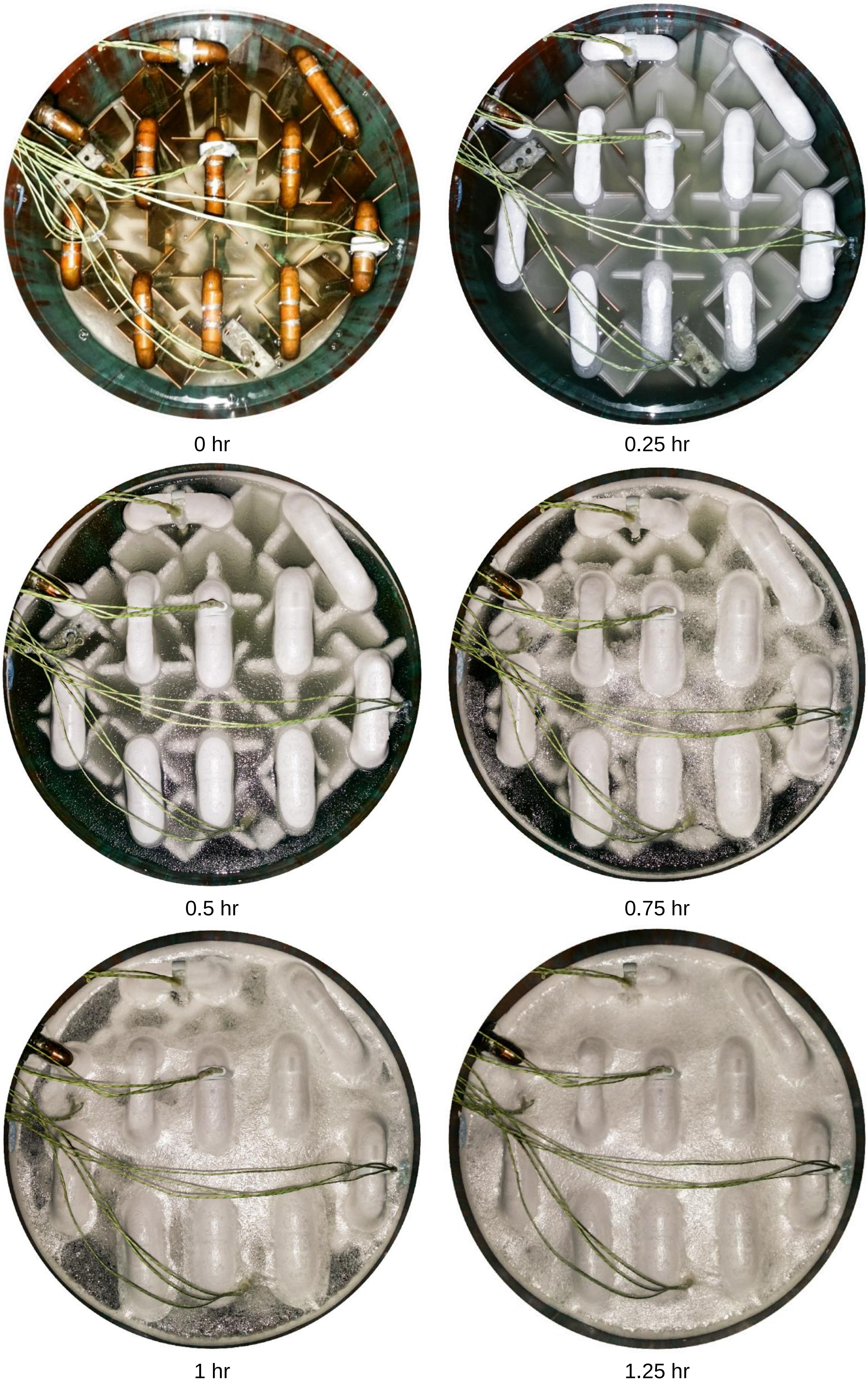

Fig. 5 Photographic illustrations of solidification front of paraffin in LHS unit during discharging cycle at inlet temperature and volume flow rate of 10 ^{o}C and 3 l/min, respectively.

3.2 Influence of Inlet Temperature

In order to investigate the effect of weather fluctuations on thermal behaviour of paraffin in LHS unit, a series of discharging cycle experiments are conducted at varied inlet temperatures of 5 ^{o}C, 10 ^{o}C and 15 ^{o}C. Whereas, the volume flow rate of HTF is set constant to 1.5 l/min. The transient temperature profiles of paraffin acquired from thermocouples installed at top, central and bottom positions within LHS unit are illustrated in **Fig. 6**. Similarly, the time-wise variations in outlet temperatures of HTF are registered, as presented in **Fig. 6**.

It is noticed from experimental investigations that inlet temperature of HTF has a significant impact on discharging rate of paraffin in LHS unit. As shown in **Fig. 6 (A)**, the transient temperature profiles of paraffin at top position at zone A display an identical thermal response to sensible portion of thermal energy discharge at varied inlet temperatures. Therefore, it is noted that inlet temperature of HTF has an insignificant effect on discharging of sensible portion of thermal energy. However, the discharging rate is noticeably influenced during latent portion of thermal energy discharge. The total solidification time for paraffin at inlet temperature of 15 ^{o}C is 1.38 hr. However, a higher temperature gradient can be generated by decreasing the inlet temperature of HTF. Therefore, the discharging rate is increased by 9.01 % and 17.43 % as the inlet temperature is decreased from 15 ^{o}C to 10 ^{o}C and 5 ^{o}C, respectively. Moreover, it can be observed that after solidification, the sensible portion of thermal energy discharge behave differently to varied inlet temperatures of HTF.

The influence of inlet temperature of HTF on transient temperature response of paraffin at central position at zone B and zone D are illustrated in **Fig. 6 (B)** and **Fig. 6 (E)**. It is evident that before solidification, the sensible portion of thermal energy discharge is almost identical for all inlet temperatures of HTF. However, the latent portion of thermal energy is discharged at higher rate by decreasing inlet temperature of HTF. The total solidification time required to discharge the latent portion of thermal energy at central position at zone B is 0.76, 0.88 and 1.06 hr for inlet temperature of 5 ^{o}C, 10 ^{o}C and 15 ^{o}C, respectively. Likewise, the discharging rate at central position at zone D is increased by 23.58% and 48.11% as the inlet temperature is decreased from 15 ^{o}C to 10 ^{o}C and 5 ^{o}C, respectively**.** After solidification, a linear identical decline in temperature profile is noticed. It shows that conduction is a dominant mode of heat transfer at central position of LHS unit.

Likewise, paraffin at top position at zone C indicates a significant enhancement in discharging rate, as shown in **Fig. 6 (D)**. It can be noticed that the discharging rate is increased by 20.36% and 32.95% as the inlet temperature is decreased from 15 ^{o}C to 10 ^{o}C and 5 ^{o}C, respectively. Likewise, paraffin at bottom position at zone D displays a significant reduction in solidification time, as presented in **Fig. 6 (F)**. The total solidification time is reduced by 9.18% and 16.41% as the inlet temperature is reduced to 10 ^{o}C and 5 ^{o}C, respectively. Similarly, paraffin at top position at zone E exhibits improvement in discharging rate, as shown in **Fig. 6 (G)**. It can be noticed that an enhancement of 12.37% and 28.04% is recorded by decreasing inlet temperature to 10 ^{o}C and 5 ^{o}C, respectively. The total solidification time of paraffin at various positions in LHS unit at varied inlet temperatures are presented in **Table 3**.

Inlet temperature of HTF has a notable impact on outlet temperature of HTF, as shown in **Fig. 6 (H)**. Due to decrease in inlet temperature of HTF, the temperature gradient between paraffin and HTF is magnified and therefore an enhanced discharge rate is obtained, which results in high temperature output of HTF for a short interval of time. However, with an increase in inlet temperature of HTF, the temperature gradient is reduced and thus a high temperature output is generated for a long period of time. Therefore, it can be predicted that by further increasing the inlet temperature of HTF during discharging cycle, a high temperature output of HTF can be achieved for a longer span of time, which can be utilised for number of domestic or commercial applications.

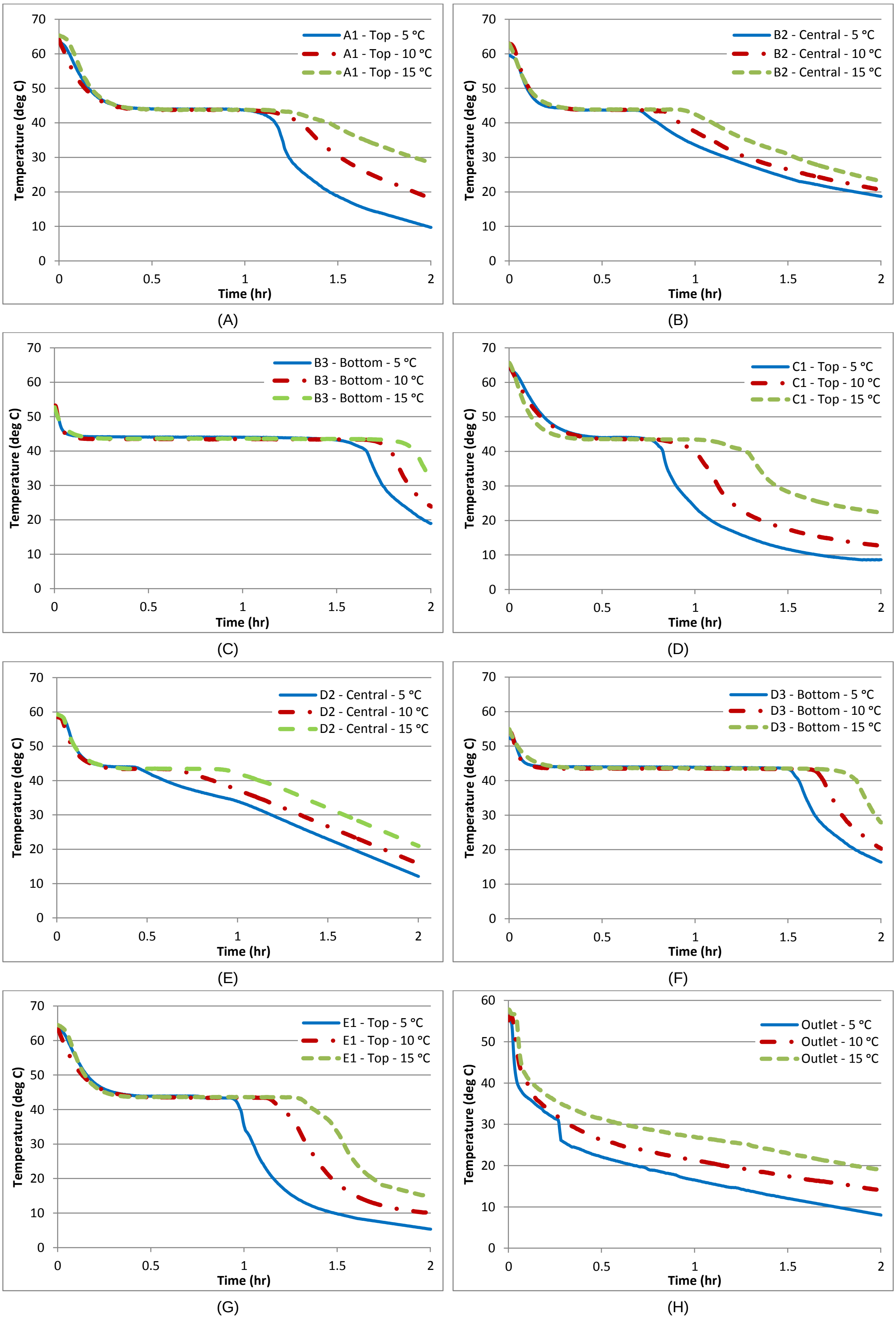

Fig. 6 Time-wise variation in temperature profile registered at top position (zone A, C and E), central position (zone B and D), bottom position (zone B and D) and outlet of LHS unit during discharging cycles at various inlet temperatures (5 ^{o}C, 10 ^{o}C and 15 ^{o}C) and constant volume flow rate of 1.5 l/min.

Table 3
Total solidification time recorded for varied inlet temperatures

Fig. No	Thermocouple		Inlet Temperature		
	Zone	Position	5 ^{o}C	10 ^{o}C	15 ^{o}C
Fig. 6 (A)	A	Top	1.14 hr	1.26 hr	1.38 hr
Fig. 6 (B)	B	Central	0.76 hr	0.88 hr	1.06 hr
Fig. 6 (C)	B	Bottom	1.63 hr	1.76 hr	1.89 hr
Fig. 6 (D)	C	Top	0.81 hr	0.97 hr	1.21 hr
Fig. 6 (E)	D	Central	0.55 hr	0.81 hr	1.06 hr
Fig. 6 (F)	D	Bottom	1.54 hr	1.68 hr	1.84 hr
Fig. 6 (G)	E	Top	0.97 hr	1.18 hr	1.35 hr

3.3 Influence of Flow Rate

To examine the influence of volume flow rate of HTF on heat transfer rate and solidification time of paraffin in LHS unit, experimental tests are conducted at constant temperature of 10 ^{o}C and four varied volume flow rates of 1.5, 2, 2.5 and 3 l/min. The time-wise variations in temperature profiles are obtained from thermocouples installed at top position at all five zones and outlet of HTF from LHS unit, as illustrated in **Fig. 7**.

As discussed in **section 3.1**, the discharging cycle of paraffin is composed of three phases. In initial phase, the sensible portion of thermal energy is discharged rapidly due to higher temperature gradient between HTF and paraffin. Natural convection is dominating the initial stage of discharging cycle and thus, the temperature drop of paraffin is fast. In second phase, the latent portion of thermal energy is discharged at almost isothermal temperature. During this phase, the phase transition from liquid to solid takes place and thus, the natural convection is weakened and conduction is the dominant mode of heat transfer. However, due to formation of solidified paraffin around tubes and longitudinal fins, the overall thermal resistance offered by paraffin is increased which effects the heat transfer rate. Therefore, it is noticed that latent portion of thermal energy is gradually discharged. In third phase, the sensible portion of thermal energy in solid phase is discharged which is dominated by conduction heat transfer. Similarly, it can be noticed from **Fig. 7** that initial sensible phase of thermal energy discharge is not affected by volume flow rate. However, the latent portion of thermal energy discharge is noticeably influenced.

Paraffin at top position at zone A has demonstrated an obvious enhancement in discharging rate and reduction in solidification time, as presented in **Fig. 7 (A)**. The total solidification time is reduced by a fraction of 9.03%, 14.98% and 28.19% as the volume flow rate is increased from 1.5 l/min to 2, 2.5 and 3 l/min, respectively. Likewise, paraffin at top position at zone B has illustrated an increase in discharge rate by a fraction of 7.16%, 11.55% and 21.01%, as shown in **Fig. 7 (B)**. Similarly, the solidification time for paraffin at top position at zone C is reduced by 11.04%, 21.22% and 27.32% as the volume flow rate is increased from 1.5 l/min to 2, 2.5 and 3 l/min, as presented in **Fig. 7 (C)**. Also, an enhancement in discharging rate is noticed for paraffin at top position at zone D, as illustrated in **Fig. 7 (D)**. The discharging rate is improved by a fraction of 10.72%, 16.52% and 27.76% as the volume flow rate is increased. Moreover, the improvement in heat transfer rate is observed for paraffin at top position at zone E, as shown in **Fig. 7 (E)**. Due to enhanced heat transfer rate, the solidification time is reduced by 6.76%, 13.05% and 19.81%, respectively.

It is evident that in case of constant inlet temperature of HTF, the heat transfer rate can be significantly influenced by varying volume flow rate of HTF and consequently, the discharging rate of paffin in LHS unit can be influenced. With an increase in volume flow rate of HTF, the discharging time is reduced. It is due to the fact that by increasing volume flow rate, the amount of thermal energy carried away by HTF is also increased. Therefore, the rapid decline in output temperature of HTF is noticed, as shown in **Fig. 7 (F)**. However, in order to maintain a higher outlet temperature of HTF for longer period of time, a small volume flow rate is recommended. In practical applications, the volume flow rate should be regulated to application based demands of outlet temperature and duration of discharge time.

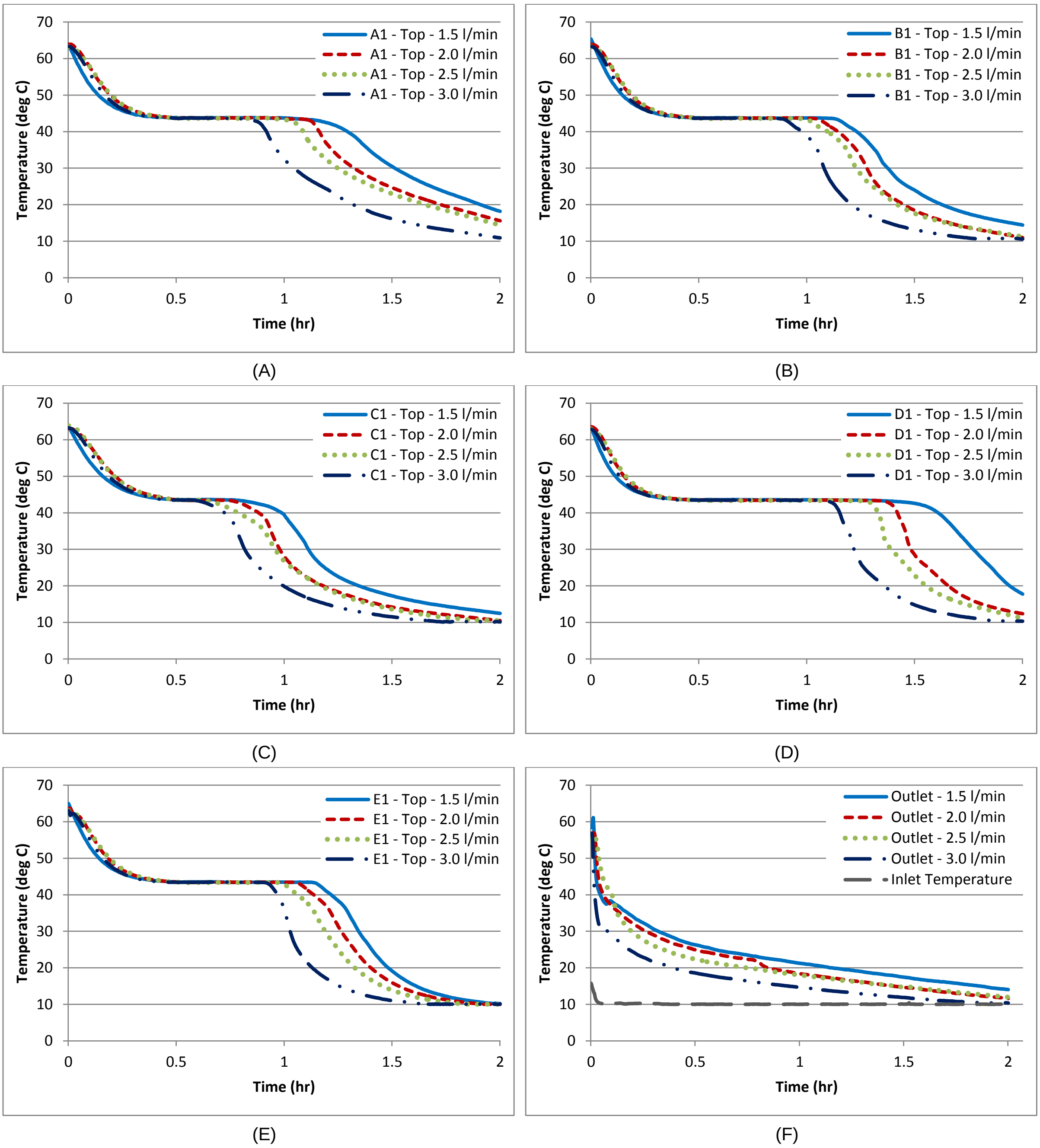

Fig. 7 Transient temperature variations recorded at top position at all five zones and outlet of LHS unit while conducting discharging cycles at four varied volume flow rates of 1.5, 2.0, 2.5 and 3.0 l/min and constant inlet temperature of 10 °C.

3.4 Energy Discharge and Mean Power

In order to investigate the thermal performance of paraffin in longitudinal fins based LHS unit during discharging cycles, the accumulative thermal energy discharge to HTF and mean discharge power of LHS system are calculated. To calculate thermal energy discharge by paraffin to HTF and mean discharge power, the following relations are implemented:

$$Q_{dis} = \sum \rho_{avg} \left(\frac{c_{p,in} + c_{p,out}}{2} \right) \left(T_{HTF,out} - T_{HTF,in} \right) \dot{V} \Delta t \quad (1)$$

$$P_{dis} = \frac{Q_{dis}}{t_{dis}} \quad (2)$$

where Q_{dis}, ρ_{avg}, c_p, T_{HTF}, $\dot{V}$ and Δt represent the measure of thermal energy discharge to HTF (kJ), average density of HTF (kg/m^3), specific heat capacity of HTF (kJ/kg. K), temperature of HTF (^{o}C), volume flow rate of HTF (m^3/sec) and time interval to record temperature data (sec), respectively. Likewise, P_{dis} represents the mean discharge power of LHS unit (kW) and t_{dis} is the total time elapsed by discharging cycle (sec).

Transient variations in thermal energy discharge to HTF is registered by conducting discharge cycles at constant inlet temperature of 10 ^{o}C and varied volume flow rates of 1.5, 2, 2.5 and 3 l/min, as illustrated in **Fig. 8**. It can be observed that volume flow rate has a significant impact on discharging rate of thermal energy to HTF. Due to higher temperature gradient at start of discharging cycle, the rate of accumulative thermal energy gain by HTF is higher. However, the temperature gradient is reduced owing to extraction of thermal energy from paraffin. Hence, the rate of accumulative thermal energy gain by HTF is affected. Despite that, with an increase in volume flow rate of HTF, the resistance to convective heat transfer in HTF can be decreased and thus, the discharging rate can be enhanced. It is noticed that after 1.5 hr of discharging cycles, the accumulative thermal energy discharge to HTF is recorded as 10604.41 kJ, 11150.88 kJ, 11521.10 kJ and 12055.03 kJ for volume flow rate of 1.5, 2, 2.5 and 3 l/min, respectively. Similarly, in order to discharge equal amount of thermal energy (12094.34 kJ), the required time is reduced by 24% as the volume flow rate is increased from 1.5 to 3 l/min.

The impact of inlet temperature and volume flow rate on mean discharge power of LHS unit is illustrated in **Fig. 9**. It can be observed that during inlet temperature of 15 ^{o}C, the increase in mean power is almost linear with an increase in volume flow rate. The discharge power is enhanced by 18.24%, 33.58% and 49.75% by increasing volume flow rate from 1.5 to 2, 2.5 and 3 l/min, respectively. Likewise, for inlet temperature of 10 ^{o}C, the discharge power is increased by 6.85%, 13.47% and 26.49%, respectively. Similarly, for inlet temperature of 5 ^{o}C, the discharge power is improved by 7.31%, 17.98% and 33.70%, respectively. Moreover, it can be noticed that inlet temperature also significantly influences the mean discharge power. For instance, at constant volume flow rate of 1.5, the discharge power is increased by 28.39% and 36.05% as the inlet temperature is decreased from 15 ^{o}C to 10 ^{o}C and 5 ^{o}C, respectively. Similarly, at flow rate of 3 l/min, the discharge power is increased from 1.959 kW to 2.125 and 2.38 kW, respectively. By regulating inlet temperature and volume flow rate of HTF, the desired output temperature and power demand can be achieved in practical applications.

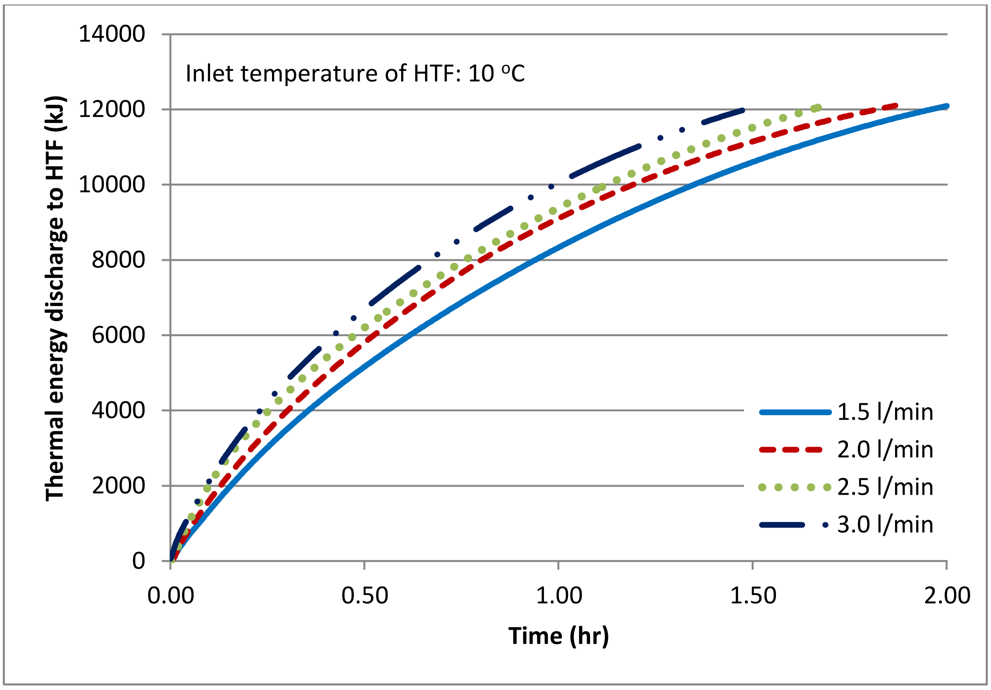

Fig. 8 Transient variation in accumulative thermal energy gain by HTF during discharging cycles at constant inlet temperature of 10 ^{o}C and four different volume flow rates of 1.5, 2.0, 2.5 and 3.0 l/min.

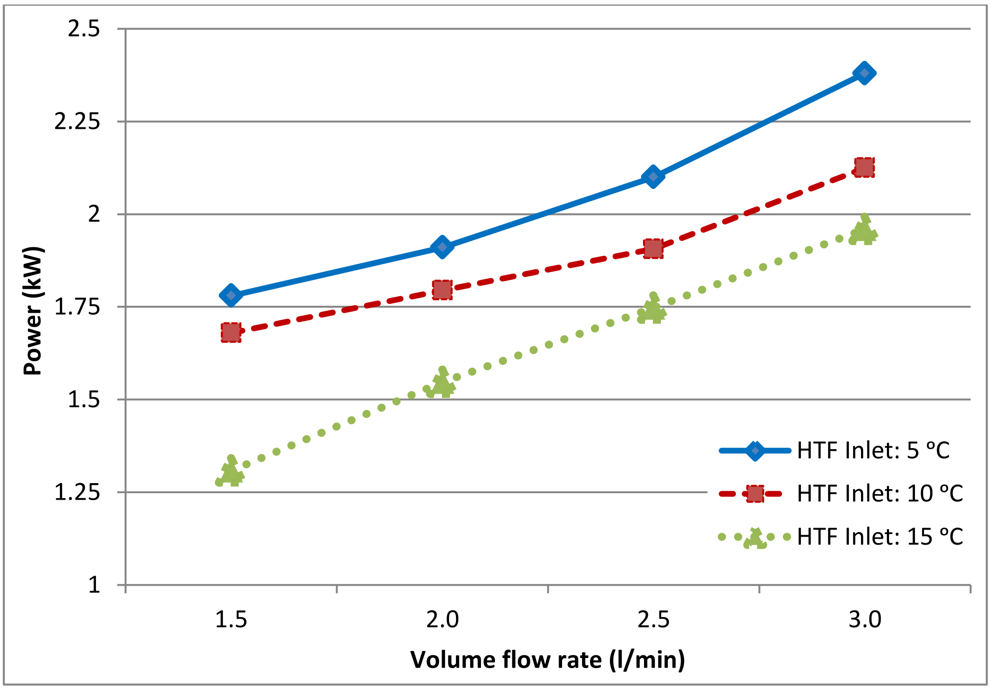

Fig. 9 Influence of volume flow rate and inlet temperature of HTF on mean discharging power of LHS unit.

Furthermore, the results indicate that the discharge rate, accumulative thermal energy discharge and mean discharge power of our proposed LHS system is considerably higher as compared to LHS systems discussed in previous literature, as presented in **Table 4**. It can be noticed that none of the previously reported models could match the rapid solidification time (1.5 hr), accumulative thermal energy discharge (12 MJ) and mean discharge power (2.125 kW) of our proposed LHS system.

Table 4
Comparative thermal enhancement achieved by present study

	Discharge		
Ref No.	Time (hr)	Energy (kJ)	Power (kW)
[24]	12.5	575	-
[28]	8.67	772.4	0.025
[30]	0.56	80	-
[31]	18.35	1200	0.02
[32]	0.506	490	0.269
[33]	4.2	-	0.325
[40]	2.31	-	1
[41]	22	7500	0.1
[42]	1.67	7293.1	-
[42]	2.167	8813.1	-
Present study	1.5	12000	2.125

4. Conclusions

In this article, the experimental investigations of discharging cycles of paraffin in LHS unit are presented. LHS unit is comprised of shell and tube with longitudinal fins based heat exchanger and paraffin as thermal storage material. Water is employed as HTF and is channelled to pass through the tubes of LHS unit to extract thermal energy from paraffin. The discharging cycles are conducted at various operating conditions of inlet temperature and flow rate of HTF. The following conclusions are drawn from experimental investigations of discharging cycles:

- Due to inclusion of longitudinal fins, the effective surface area for heat transfer is enhanced and hence the impact of low thermal conductivity of paraffin on discharging cycle of LHS unit is significantly decreased. Consequently, the discharging rate is significantly improved. The novel geometrical orientation of shell and tube with longitudinal fins based LHS unit qualifies as an efficient and responsive thermal energy storage/discharge device. For instance, the novel LHS unit can discharge 12 MJ of thermal energy to HTF in 1.5 hours when it is discharged at inlet temperature and volume flow rate of 10 ^{o}C and 3 l/min, respectively.
- It is noticed that natural convection has minimal impact on discharging rate. However, due to presence of extended surfaces via longitudinal fins, conduction heat transfer is dominant mode for thermal energy discharge. Moreover, it is noticed that conduction is more prominent at central positon as compared to top and bottom positions of LHS unit. Heat transfer rate is relatively weaker at bottom position and therefore, the solidification time for paraffin at bottom position is higher as compared to central and top position.
- Discharging cycle involves three phases of paraffin. Initially, the sensible portion (liquid phase) of thermal energy is rapidly discharged due to higher temperature gradient. Secondly, during latent portion of thermal energy discharge, a rather steady and gradual reduction in temperature

is noticed due to high latent heat capacity of paraffin. Likewise, the formation of solidified paraffin around tubes and longitudinal fins increase the overall thermal resistance, which affects the discharging rate. Finally, due to low temperature gradient, the sensible portion (solid phase) of thermal energy discharge is relatively slow as compared sensible portion of liquid phase.

- It is observed that inlet temperature and volume flow rate of HTF have significant influence on latent portion of thermal energy discharge. The influence of an increase in overall thermal resistance can be controlled by adjusting inlet temperature or volume flow rate of HTF. It is noticed that as the inlet temperature of HTF is decreased from 15 ^{o}C to 5 ^{o}C, the mean discharge power is enhanced by 36.05%. This is due to the fact that with an increase in temperature gradient, the conduction heat transfer overcomes the overall thermal resistance of paraffin. Likewise, with an increase in volume flow rate from 1.5 l/min to 3 l/min, the solidification time at constant inlet temperature of 10 ^{o}C is reduced by 24% to discharge same amount of thermal energy 12.09 MJ. Moreover, in case of constant inlet temperature as 5 ^{o}C and 15 ^{o}C, the mean discharge power can be enhanced by 33.70% and 49.75% by increasing volume flow rate from 1.5 l/min to 3 l/min, respectively.
- It is deduced that by adjusting inlet temperature and volume flow rate, the required output temperature and mean power can be achieved in practical applications. Likewise, the novel LHS unit offers time, spatial and economic benefits. Moreover, in order to meet application based energy demands, the mean power and thermal storage capacity can be augmented by connecting several LHS units in parallel. Therefore, the LHS unit can be perfectly employed in various domestic and commercial applications such as heating, ventilation and air conditioning (HVAC) systems, water heating systems, waste heat recovery and solar power plants etc.

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