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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 the 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 the development of solidified paraffin around tubes and longitudinal fins, the overall thermal resistance is increased and thus, discharging rate is affected. However, by regulating the 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 °C to 5 °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.

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

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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/s. 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/s. 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/s to 0.2 m/s, 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 28–85% 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 h to 3 h and 2.31 h 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.

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