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Review of PCM charging in tabular latent heat thermal energy storage systems

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Abstract

This paper includes a review of several previous studies associated with the charging behavior of phase-change materials (PCM) in horizontal and vertical tabular (annular) Latent Heat Thermal Energy Storage (LHTES) units. The effects of various factors on charging, such as heat transfer fluid (HTF) inlet temperature, the eccentricity of the inner tube, the inclination angle of the storage unit (-90°, -60°, -30°, 0°, 30°, 60°, 90°), and the mass flow rate of HTF are investigated. Natural convection controls the charging process in the upper part of the thermal storage unit, while thermal diffusion dominates the melting in the lower part. Also, the HTF inlet temperature has a clear and significant effect on reducing the melting time of PCM. In addition, increasing the inner tube eccentricity results in a reduction in the charging time.

Keywords: PCM, Melting, LHTES, Concentric, Eccentric

1. Introduction

The main challenges of exploiting renewable energy resources are the availability and interruption of these sources. For instance, solar energy exists during the day and is interrupted by the absence of sunlight [1]. Also, there are wind turbines that operate only when the wind blows, etc. A gap or time lag occurs between the source of renewable energy generation and the demand for it. Therefore, energy storage systems are used to prepare energy when natural phenomena are not available to generate that energy. The thermal energy storage systems depend on phase change materials (PCMs) in which sensible and latent energies are stored. Tabular thermal energy storage devices consist of an inner tube that transports the heat transfer fluid, which serves as a source of thermal energy causing the melting of the PCM, an insulated outer shell, and PCM that fills the space between the inner tube and the outer shell. When the HTF begins to circulate in the inner pipe, the PCM receives the thermal energy, causing it to melt, and the process of charging the thermal energy begins as a result of its transformation from the solid state to the liquid state. After the melting is complete and the heat transfer from its source to the PCM stops, the stored thermal energy is released, and the process of solidifying the PCM begins.

2. Melting of PCM in horizontal LHTES units

The PCM charging inside horizontal tabular LHTES systems happens as the PCM receives the heat supplied from hot HTF passing through the inside tube.

Dutta et al. [2] performed a numerical and experimental investigation on the performance of the latent heat storage system during the PCM melting processes Fig. (1). Paraffin wax was used as a PCM material, and the water was used as an HTF. With the application of different heat fluxes, it was concluded that there was an agreement between numerical and experimental results, which indicated that the buoyancy-free convection controlled the charging. Also, a significant effect of the angle of inclination and eccentricity on the PCM melting was observed.

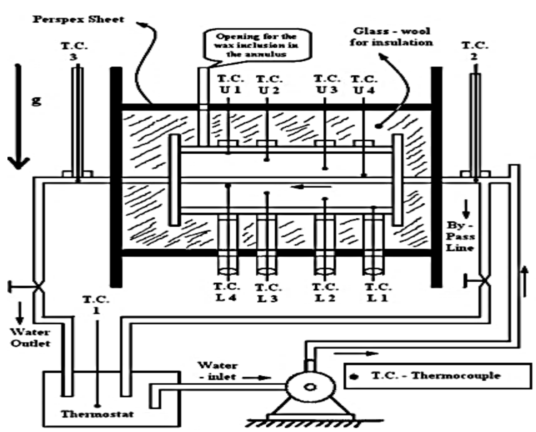

Figure 1. Experimental LHTES unit (Dutta et al. [2]).

Adine and El Qarnia [3] numerically studied the thermal performance of two PCM melting in the tabular heat exchanger Fig.(2). It was found that there is a significant effect of a set of parameters, which are the HTF entrance temperature, HTF mass flow rate, and the length of the storage unit. The efficiency of the heat exchanger is higher as the HTF inlet temperature increases, and a higher mass flow rate is more efficient.

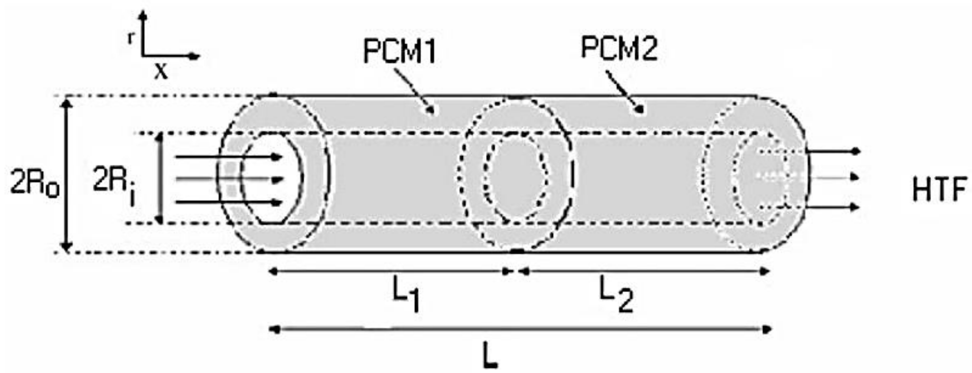

Figure 2. LHTES unit with two PCMs (Adine and El Qarnia [3]).

Ezan et al. [4] experimentally studied ice's charging and discharging process as a PCM inside a horizontal shell and tube LHTES device under the impact of some parameters. The results indicated that natural convection controlled the melting process in the upper section. Also, the inlet temperature of the heat transfer fluid and the amount of flow affected on the melting time. In addition, the impact of the shell size and the inner tube thermal conductivity on the charging process was examined.

Darzi et al. [5] presented numerical research on the properties of melting PCM in horizontal annular storage units with concentric and eccentric arrays of inner tubes Fig.(3). Natural convection controlled the melting in the top part. In contrast, conduction controlled the melting in the lower part. The researchers found that increasing the convection area by using the eccentric case caused an increase in the rate of melting.

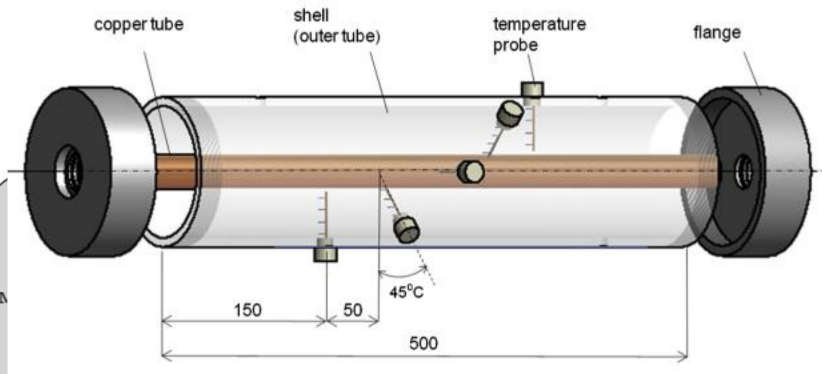

Figure 4. Construction details of the test model (Avci and Yazici [8]).

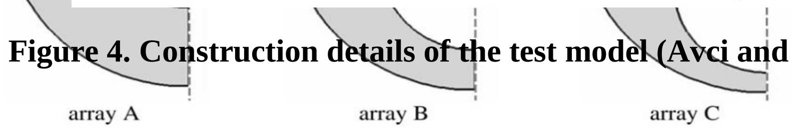

Figure 3. Concentric and eccentric arrays of inner tubes (Darzi et al. [5]).

Hosseini et al. [6] numerically and experimentally examined the impact of buoyancy-driven convection on the PCM thawing within a horizontal thermal storage unit. Also, the impact of the HTF entrance temperature on the melting time was examined. It was inferred that raising the HTF temperature to 80 C^{o} decreased the charging period by 37%.

Wang et al. [7] numerically studied the impact of the HTF's flow rate and inlet temperatures on the PCM melting process placed inside a horizontal LHTES unit. Results indicated that natural convection is the main factor controlling melting, and the HTF entrance temperature significantly impacted the time specified to finish melting. As the water inlet temperature rose, the stored thermal energy increased, and the melting time decreased. Also, the mass flow rate greatly impacted the melting time while it had a low impact on the stored thermal energy. Avci and Yazici [8] presented an experimental study of the thermal properties of a PCM material placed inside a horizontal annular cavity of the LHTES system Fig. (4). Melting of PCM occurred due to natural convection, where the molten material raised to the top due to its melting, leading to the melting of the rest of the solid material. The findings revealed that the buoyancy force controlled the PCM thawing process, and the HTF inlet temperature had a main role in improving the melting process and reducing the time required to complete it.

Agrawal and Sarviya [9] computationally studied the paraffin wax melting in a horizontal tabular LHTES unit. The inner tube was heated and maintained at a constant temperature. A two-dimensional numerical model was used to investigate the thermal behavior of PCM. The results showed a high heat transfer in the upper part due to natural convection. As a result, there was overheating in the upper part while the material remained solid in the lower part. Alshara [10] studied numerically PCM melting in a concentric horizontal LHTES unit whose outer shell is insulated and uses water as the heat transfer fluid. The simulation proved a significant influence of the water inlet temperature on the PCM charging duration. Also, the initial temperature had a small effect on the melting process; thus, it can be eliminated. In addition, reducing the diameter ratio (2) (the distance between the two cylinders) accelerated the melting process.

Dukhan et al. [11] presented an experimental study about the charging of RT42 PCM inside an LHTES device Fig. (5). Water was used as an HTF, while the device was concentric shell-and-tube type. The experimental findings proved that free convection dominated the charging process in the upper portion, while thermal conduction was dominant in the bottom portion. Also, the inlet temperature of HTF had a significant impact on reducing the charging time.

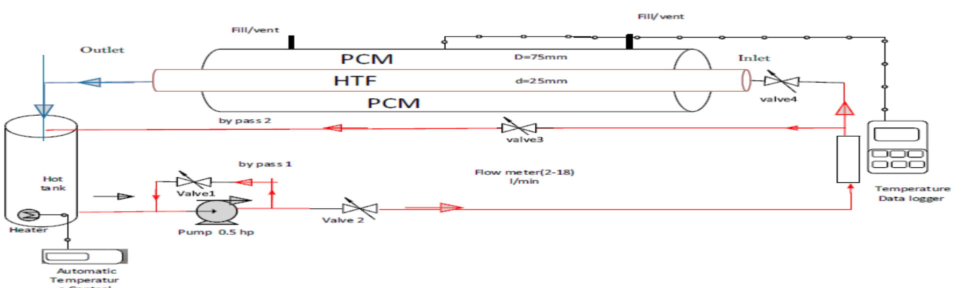

Figure 5. Experimental setup of the LHTES unit (Dukhan et al. [11]).

3. Melting of PCM in vertical LHTES

The PCM charging inside vertical tabular LHTES systems happens as the PCM receives the heat supplied from hot HTF passing through the inside tube.

Akgun et al. [12] conducted experiments to examine the thawing and freezing of PCM, namely paraffin (P1), placed in vertical LHTES Fig.(6). When the HTF (water) circulates, PCM begins to melt. It was observed that tilting the outer shell of the heat exchanger by 5 degrees can improve heat transfer. In addition, increasing the water entrance temperature caused a reduction in the duration required for PCM melting. In order to reduce energy consumption, using a low mass flow rate of water was suggested.

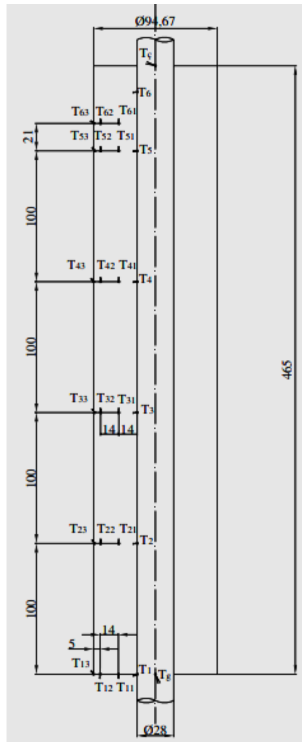

Figure 6. Vertical storage unit (Akgun et al. [12]).

Shmueli et al. [13] presented numerically and experimentally the PCM melting within a vertical LHTES unit Fig. (7) and its thermal behavior. They inferred that diffusion was the essential thermal mechanism that affected the charging process at initial periods. As the process progressed, buoyancy-driven convection was the main factor through which the hotter liquid PCM melted the solid PCM.

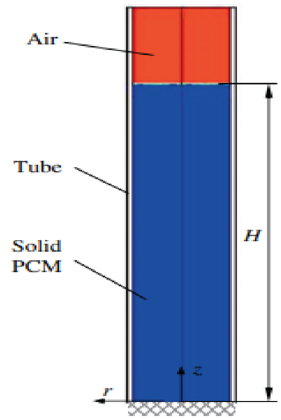

Figure 7. Physical model (Shmueli et al. [13]).

Longeon et al. [14] performed a numerical and experimental study to inspect the influence of the heat transfer mechanism and injection side on the melting and solidification of paraffin RT35 inside the vertical thermal storage system Fig. (8). The impacts of free convection and the HTF flow direction on the melting process were investigated. It was concluded that natural convection controls melting. Moreover, it was recommended that the direction of water flow be from the top in the charging case and from the bottom in the freezing case.

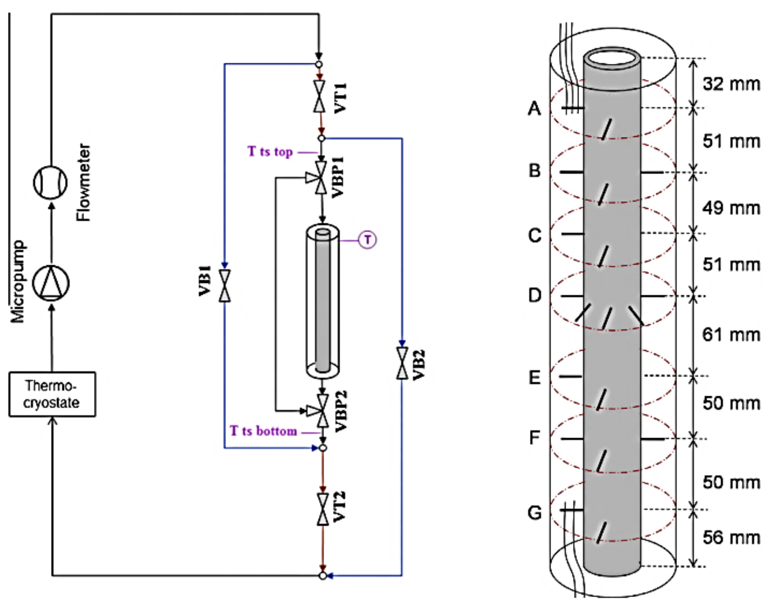

Figure 8. Experimental LHTES unit (Longeon et al. [14]).

Wang et al. [15] experimentally studied the thermal behavior of charging and discharging of the phase change material (erythritol) inside a vertical LFTES unit Fig. (9) which used the air as an HTF. The inner tube diameter (40 mm) and the outer shell diameter (108 mm) and the range of inlet temperatures were 150, 155, and 160 °C. The experimental outcomes showed that buoyancy-driven convection played an essential role in melting by transferring heat from the liquid to the solid region. In addition, raising the HTF inlet's temperature and mass flow rate improved heat transfer and decreased the melting duration.

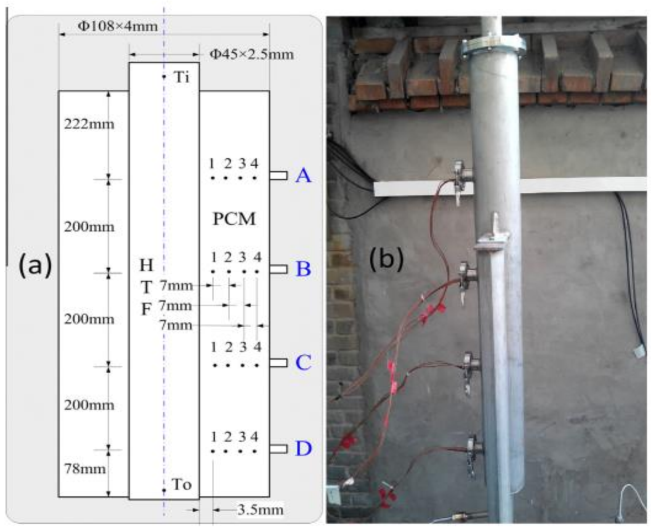

Figure 9. Experimental facilities of thermal storage system (Wang et al. [15]).

Seddegh et al. [16] computationally and experimentally studied the mechanism of heat transfer of PCM charging and freezing in a vertical (LHTES) unit. It was concluded that natural convection is ruling the melting process, the hot HTF inlet temperature greatly affects heat transfer during the charging process, and the HTF flow rate has little effect on both charging and discharging processes.

Seddegh et al. [17] presented experimentally and numerically the mechanism of heat transfer of PCM put in a vertical (LHTES) unit Fig. (10). They studied the impact of the natural convection on this heat transfer. They concluded that buoyance force dominated the charging process, where the molten PCM material with high temperature activated the free convection role to reach the upper solid PCM and melt it.

Figure 10. PCM melting in tabular thermal storage unit (Saeid et al. [16]).

The charging of PCM RT35 within a vertical LHTES unit was experimentally and computationally studied by Ebadi et al. [18]. The PCM melting process was simulated through a numerical model, and information was obtained regarding the thermal behavior of PCM, temperatures, and liquid fraction to compare them with the practical results. The results indicated a significant agreement between the numerical and practical results. Also, it was concluded that thermal diffusion was responsible for transferring thermal energy from the inner pipe wall to the PCM at initial periods of the charging. As the melting progressed, free convection ruled the charging process.

Ali et al. [19] conducted experiments to explore the thermal behavior of PCM charged inside the LHTES device using water as an HTF. The temperature variation between the external shell and inner pipe with different mass flow rates was experimentally calculated. Experimental results showed that raising the HTF inlet temperature resulted in an enhancement in the effectiveness of the energy storage device.

Bechiri and Mansouri [20] computationally studied the PCM RT27 charging in vertical LHTES devices. The PCM was partially placed in the vertical tabular unit, where air filled the upper portion of the unit. The results indicated that free convection varies with the temperature of the cylinder wall, and the initial temperature had an effect on the melting process.

3. Conclusions

The PCM charging in tabular LHTES systems is reviewed. The review of the related experimental and numerical studies presents the following conclusions:

1- Free convection dominated the charging process in the upper part of the LHTES unit, while thermal conduction controlled the melting in the lower part.

2- The HTF inlet temperature had a clear and significant impact on reducing the melting time of PCM and increasing the efficiency of the heat exchanger.

3- The angle of inclination had a significant effect on the PCM melting.

4- Increasing the convection area using the eccentric case caused an increase in the melting rate.

5- The direction of HTF flow is recommended to be from the top in the case of melting and from the bottom in the case of solidification.

6- Raising the HTF flow rate improved heat transfer and decreased the melting duration.

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مراجعة شحن المواد متغيرة الطور في أنظمة تخزين الطاقة الحرارية الكامنة الحلقية

الخلاصة: يتضمن هذا البحث مراجعة للعديد من الدراسات السابقة المرتبطة بسلوك الشحن للمواد متغيرة الطور (PCM) في وحدات تخزين الطاقة الحرارية الكامنة (LHTES) الأفقية والرأسية الحلقية. تم التحقيق في تأثير العوامل المختلفة على الشحن، مثل درجة حرارة مدخل سائل نقل الحرارة (HTF)، وانحراف الأنبوب الداخلي، وزاوية ميل وحدة التخزين (−90°، −60°، −30°، 0°، 30°، 60°، 90°)، ومعدل التدفق الكتلي لسائل نقل الحرارة.يتحكم الحمل الحراري الطبيعي في عملية الشحن في الجزء العلوي من وحدة التخزين الحراري، بينما يسيطر الانتشار الحراري على عملية الذوبان في الجزء السفلي، كما أن درجة حرارة مدخل سائل نقل الحرارة لها تأثير واضح وكبير على تقليل زمن ذوبان مواد متغيرة الطور، بالإضافة إلى ذلك تؤدي زيادة انحراف الأنبوب الداخلي إلى تقليل وقت الشحن.

الكلمات المفتاحية: شحن المواد متغيرة الطور، ذوبان، انظمة خزن الطاقة الكامنة.