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A Review Study on the Gradient Tree Shaped Fins Employed for Enhancing Latest Heat Storage Systems

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ABSTRACT

Thermal energy storage systems have become more significant in utilizing solar energy effectively. Latent heat thermal energy storage systems play a prominent role in various applications of storage and cooling systems. This study is compiled from the various results obtained from the researchers on latent heat systems using tree shaped fins for enhancement of performance. Among the uniform and gradient tree shaped fins, the later one provides better solidification, melting rates and higher heat transfer rates. The gradient tree-fin LHS unit possesses stronger temperature uniformity, faster solidification rate, and higher energy discharge rate Compared to the uniform fin layout, the gradient tree-shaped fins effectively increase the melting rate, shortens the melting duration by 9%, and further improve the overall temperature uniformity of LHS units.

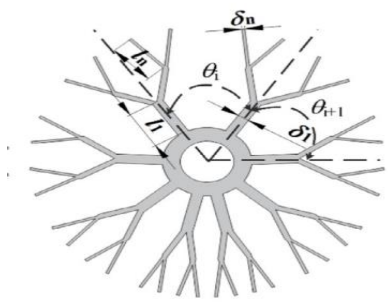
Keywords: Phase Changing Material (PCM), Solidification, Melting, Gradient Tree shaped fins.

1.INTRODUCTION

Thermal energy storage is a way of storing and managing renewable heat energy when needed. Thermal energy storage helps in efficient use of thermal energy in energy crisis. The different kinds of thermal energy storage can be divided into three separate categories: sensible heat, latent heat, and thermo-chemical heat storage. Each of these has different advantages and disadvantages that determine their applications. Because latent heat storage (LHS) is associated with a phase transition, the general term for the associated media is Phase-Change Material (PCM). TES systems offer the possibility to store high amounts of thermal energy, especially the latent heat thermal energy storage (LHTES) system at a constant or near constant temperature depending on the temperature difference of the phase-change material (PCM). It requires a smaller weight and volume of material for a specific amount of energy, compared with the conventional sensible heat thermal energy storage (SHTES) system. The PCM loaded in LHTES systems have low thermal conductivity ($k \leq 0.2$ W/m K), which drastically affects thermal performance of these systems. The low thermal conductivity influence reflected during energy retrieval or withdrawal with an appreciable temperature drop during the process [1], During these transitions, heat can be added or extracted without affecting the material's temperature, giving it an advantage over SHS-technologies. Storage capacities are often higher as well. Latent heat storage (LHS) is of great interest in a wide range of technical applications for the fossil and renewable energy systems, including solar energy collection[2][3],Different techniques are adopted to improve the thermal performance of LHTES systems, such as using an extended surface or fins, utilizing multiple families of PCM, thermal conductivity improvement, and micro-encapsulation of PCM [4], The applications embedded in the PCM, such as longitudinal, circular/annular, plate, and pin fins, represent the base of most extended surface or fin heat-transfer enhancement techniques, especially the techniques based on plate finned heat exchangers [5], pin fin heat sinks [6,7], and tree-shaped fins [8]. Zhang et al. [9] and Zheng et al. [10] analyzed the solidification mechanism of LHS units equipped with tree-shaped fins through numerical simulations and optimized their spatial layout by parametric analysis. Besides, Safari et al. [11] investigated the melting performance in concentric and eccentric heat exchangers by experimental and numerical comparison. Their results indicated that eccentric heat exchangers using tree-shaped fins shortened the melting duration by 85%. The available literature [9,10] shows that a multi-level tree-shaped fin (i.e., branch level n> 1) can significantly enhance the radial heat transfer characteristics of horizontal LHS units.

This review paper mainly focuses on the role of gradient tree shaped fins in enhancing thermal performance of the LHTES system over uniform tree shaped fins and rectangular fins. Further the gradient tree shaped fins are optimized considering the length and width index.,

Uniform tree-shaped fin



Gradient tree-shaped fin

2. STORAGE MEDIUM OF LHTES(PCM)

PCM is used as a storage medium for storing heat energy in the latent heat thermal energy systems (LHTES). PCM helps to store more thermal energy in lesser volumes of storage and provides compactness to the system. The phase-change material (PCMs) can be classified into three categories: solid-solid, solid-liquid, and liquid-gas. Among these categories, solid liquid of the PCM is the most suitable for the LHTES system. It can be divided into organic compounds, such as paraffin and fatty acids; inorganic compounds, such as salt hydrates and metallic; and eutectics, such as organic-organic, inorganic-organic, and inorganic-inorganic. The advantages and disadvantages of these classifications are compared and presented in Table 1 [1].

Table1: Comparison of Advantages and Disadvantages

Type of PCM	Advantages	Dis-advantages
Organic	Large temperature range. High latent heat. No super-cooling. Chemical stable. Good compatibility with other materials.	Low thermal conductivity. Relative large volume change. Flammability.
Inorganic	High heat of fusion. High thermal conductivity. Low volume change. Available in low cost.	Super-cooling. Corrosion.
Eutectics	Sharp melting temperature. High volumetric thermal storage density.	Lack of currently available test data of thermos-physical properties.

Among the different PCM's lauric acid(organic) is used as storage medium and aluminum 6061 is used as fin material for the study. The thermophysical properties of lauric acid and aluminum are given in the Table 2[1].

Table2: Thermophysical properties of PCM and fin material

Material	Thermo-physical properties	Value	Unit
Lauric acid	Phase-transition temperature	42–44	°C
	Special heat	1690 (solid); 2400 (liquid)	$J \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$
	Heat conductivity	0.24 (solid); 0.15 (liquid)	$W \cdot m^{-1} \cdot {}^{\circ}C^{-1}$
	Specific latent heat	173.8	$kJ \cdot kg^{-1}$
	Thermal expansion index	0.000615	K^{-1}
	Density	874 (solid); 769 (liquid)	$kg^{-1} \cdot m^{-3}$
6061 aluminum alloy	Heat conductivity	202.4	$W \cdot m^{-1} \cdot {}^{\circ}C^{-1}$
	Special heat	871	$J \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$
	Density	2719	$kg^{-1} \cdot m^{-3}$

Table3: Dimensions of the fins.

Type	Height H/mm	Level n	Length l/mm	Width δ/mm	Angle gradient $\Delta\theta$/°
Uniform rectangular fin	210	/	44	4.18	0
Uniform tree-shaped fin	210	0	14.01	4	0
		1	15.41	2	
		2	16.95	1	
Gradient tree-shaped fin	210	0	14.01	4	10
		1	15.41	2	
		2	16.95	1	

3. CONFIGURATION OF FINS

Most PCMs have low thermal conductivity, which represents the biggest challenge in the design of PCM-LHTES systems. Hence, various enhancement techniques have been proposed to overcome this drawback. Most of these techniques are based on the fins embedded in the PCM, such as longitudinal, circular/annular, plate, and pin fins. A few cases of fins in a new design and configurations have been reported by authors, as an efficient method to enhance the charge and discharge performance of LHTES systems [1] Sciacovelli et al. [13] simulated the use of two-kinds of tree-shaped fins including: a single bifurcation and a double bifurcation configuration, to optimize and accomplish the maximum performance of the LHTES system. The results indicated that the discharge efficiency increases to 24% when the optimal fins with two-bifurcations are used. The optimal fin design also depends on the operating time of this system; a short operating time of the Y-shaped fins with wide angles between the branches are preferable. Huang et al. [12] used three horizontal LHS units (see Fig. 3a), including the traditional LHS unit with uniform rectangular fins, fractal LHS unit with uniform tree-shaped fins, and gradient LHS unit with gradient tree-shaped fins (i.e., the angle between the main bifurcations of adjacent tree-shaped fins gradually increases from top to bottom with a constant angle gradient ($\theta i+1-\theta i = \Delta\theta$). Fig. 3b draws the cross-section of three different fins. And the detailed dimensions of these fin configurations are given in Table 3.

Zhang et al. [9] proposed a tree-shaped metal fin to enhance solid-liquid phase change heat transfer. Considering the inherent advantage of heat flow between a point and an area, the fin is laid out in a point-area fashion with multiple bifurcations and embedded inside a shell-tube LHS unit as seen in the fig (4). The LHS unit is composed of M tree-shaped fins, which develop in an annular fashion inside the shell tube LHS unit.

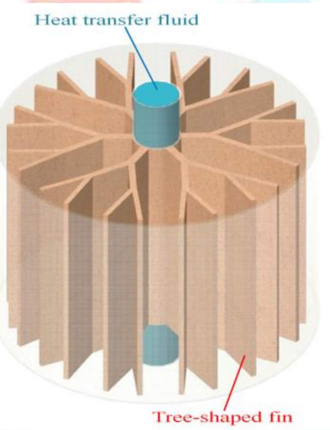


Fig 4: Tree-Shaped fin

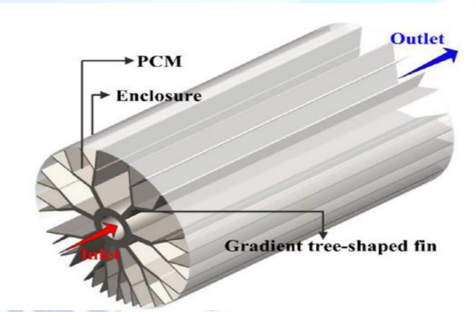


Fig 5: Gradient tree shaped fin

4. RESULTS AND DISCUSSION

The gradient tree shaped metal fin is embedded in the LHS unit to accelerate the heat transfer rate of the solidification process. The contact area between the fin and PCM is greatly extended owing to the dendritic distribution of the tree shaped metal fins and energy discharge of PCM is also increased due to the gradient tree shaped fins.

(a) Solidification Process:

The presence of tree-shaped fins induces variation of the heat transfer path during the energy discharge process and hence affects the transient temperature distribution and solidification phase change. The liquid PCM in LHS units with the trees shaped progresses through the pre-sensible cooling stage, the solidification stage, and the post-sensible cooling stage during the energy discharge process.

The cooling rate of the tree-shaped is greater than that of the PCM under the cooling effect of the central tube owing to the high thermal conductivity of the metal fins. As times proceeds, the energy discharge process enters the solidification stage. During the solidification stage, the sensible and latent heat releases coexist inside the LHS unit, in which the latent heat release is dominant over the sensible heat.

It is seen that the tree-shaped fins divide the PCM region into several independent, relatively small regions of different sizes. The size of an individual PCM region and its distance away from the cold surface has an important effect on the solidification process.

The dendritic configuration of the gradient tree shaped metal fins helps to collect the heat stored in the PCM efficiently from periphery to the center.

Thus, the tree-shaped fin significantly improves the solidification performance.

(b) Melting Process

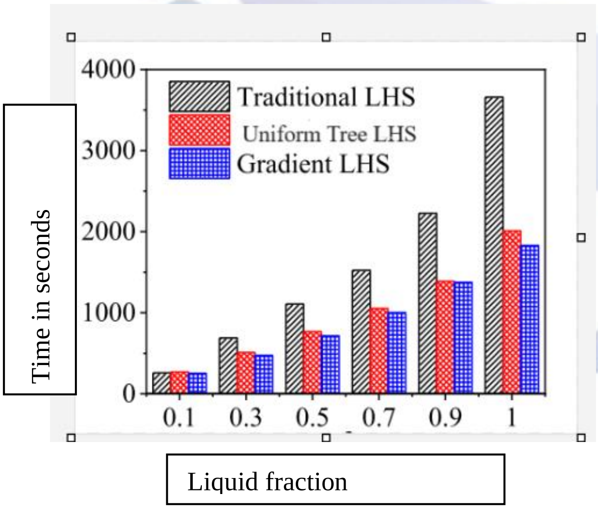


Fig 6: Variation of liquid fraction with time

The gradient LHS unit intensifies the heat conduction of the lower PCM while prolonging the natural convection duration of the upper PCM over this stage, thus completing the melting process first.

To quantitatively compare the performance of three LHS units, Fig.6 compares the liquid fraction variation over the melting processes.

Obviously, the gradient LHS unit has the fastest increase in the liquid fraction, while the traditional LHS unit has the slowest liquid fraction increase. More importantly, the gradient LHS unit has a 9% reduction in the total melting duration compared to the uniform tree shaped LHS unit.

5. CONCLUSIONS

The gradient tree-fin LHS unit possesses stronger temperature uniformity, faster solidification rate, and higher energy discharge rate. The gradient tree-shaped fin provides maximum access for the heat flow in a point-area fashion and hence maintains high efficiency during the whole solidification process.

During the melting process, the thermal transport mechanism is heating conduction in the early stage, after which natural convection gradually dominates the middle stage. In the late melting stage, the natural convection decays and heat conduction becomes dominant again. Compared to the other LHS units, the prolonged natural convection in the gradient LHS unit and its coupling with the heat conduction contributes to the enhancement in the late melting stage. However, natural convection exerts its influence only in the initial solidification stage, and conduction is the primary thermal transport mechanism for most solidification duration.

The gradient tree shaped fins facilitate the heat diffusion from point to area, breaking the heat transfer hysteresis in traditional LHS units, thus accelerating the melting/solidification rate. Compared to uniform tree-shaped fins, the gradient tree-shaped fins accelerate the melting rate of LHS units, reducing the total melting time by 9%, but they weaken the solidification efficiency, extending the solidification duration by 57.4%.

The length and width distribution of the gradient tree shaped fins also affects the characteristics of LHTES units and length distribution should be larger and width distribution should be shorter for achieving more success in LHTES units.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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