International Communications in Heat and Mass Transfer 90 (2018) 73–84

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Experimental and numerical study of solidifying phase-change material in a triplex-tube heat exchanger with longitudinal/triangular fins

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ARTICLE INFO

Keywords:
Phase-change material
Triplex-tube heat exchanger
Triangular fins
Longitudinal fins
Solidification time

ABSTRACT

Latent heat thermal energy storage (LHTES) system uses a large triplex-tube heat exchanger (TTHX) with internal longitudinal fins incorporating phase-change material (PCM) was experimentally designed, tested, and evaluated. The PCM was entirely solidified using the both-sides freezing, as a main method under the influence of average discharging temperature was at 65 °C. The changes in the mass flow rates of 16.2, 29.4, and 37.5 min/kg were investigated. The solidification rate increased, as the mass flow rate increased, therefore the mass flow rate at 37.4 kg/min consumed a short time, compared with the 16.2 and 29.4 kg/min. Furthermore, the PCM completely solidified, as fast as at position B than position A from the entrance of the HTF-tube because of temperature variations in axial and angular direction during discharging process. Two types of extended surfaces, namely the longitudinal and triangular fins in various configuration were numerically studied. A significant enhancement was observed using internal, internal-external, and external triangular fins at 14%, 16%, and 18% respectively, compared to longitudinal fins configuration. Consequently, the external triangular finned tube has been considered the most efficient for the brief solidification PCM (630 min). The total energy released for the both types of fins were compared. The simulation results were agreed well with the experimental results.

1. Introduction

Solar energy is considered, as one of the most prospective sources of energy in many parts of the world. The characteristics of solar energy, such as being abundant and freely available, easily and directly utilizable, renewable and has continuity, and safe and environmentally friendly, make solar energy an attractive alternative to fossil fuels. However, the continuous increase in the level of greenhouse gas emissions and the depletion of fossil fuels are identified, as the main driving forces behind the efforts to effectively utilize different sources of renewable energy. Solar energy systems require thermal energy storage (TES) to eliminate the mismatch between energy supply and demand. Considerable emphasis is placed on continuous power generation during cloud transients and non-daylight hours for solar device applications.

Most phase-change materials (PCM) that are used, as storage media in TES systems suffer from a low thermal conductivity ($k \leq 0.2$ W/m K), which results in an incomplete melting and solidification process, and a significant temperature difference within the PCM that can cause material failure and system overheating. Enhancing the thermal performance of TES systems is necessary in employing a PCM to various engineering applications, such as building heating, water heating, solar systems, electronic cooling, drying technology, refrigeration and cold storage, air conditioning, and waste heat recovery [1]. Furthermore, few attempts have been made to optimize the fin design for maximizing the performance of latent heat thermal energy storage (LHTES) systems. The fin design optimization presents two intrinsic difficulties. First, fin design optimization problems result in expensive computational costs. Second, an intrinsic difficulty emerges from the transient behavior of a PCM-LHTES system.

Many researchers studied the performances of different kinds of heat exchangers used in LHTES systems with a PCM, such as concentric-cylinder, shell and tube, and triplex-tube heat exchanger (TTHX), and their applications in melting and solidification process [2,3]. Abdulateef et al. [4] have reviewed geometric and design parameters of the various fins employed for enhancing thermal energy storage systems. Three configurations experimentally compared by Agyenim et al. [5], a concentric tube system with no fins and increased with circular, and

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https://doi.org/10.1016/j.icheatmasstransfer.2017.10.003

Table 1
Thermos-physical properties of the PCM.

Properties	PCM (RT82)
Density, solid, ρ_s (kg/m^3)	950
Density, liquid, ρ_l (kg/m^3)	770
Specific heat, C_{pl}, C_{ps} (J/kg K)	2000
Latent heat of fusion, L (J/kg)	176,000
Dynamic viscosity, μ (kg/m s)	0.03499
Melting temperature, T_m (K)	350.15–358.15
Thermal conductivity, k (W/m K)	0.2
Thermal expansion coefficient (1/K)	0.001

Table 2
Latent heat of fusion and melting temperature of PCM (RT82) for 10 tests by DSC.

Test	Melting process			Solidification process		
	Onset point (°C)	Peak point (°C)	Heat of fusion (kJ/kg)	Onset point (°C)	Peak point (°C)	Heat of fusion (kJ/kg)
1	75.13	83.51	192.22	81.79	78.48	203.18
2	69.81	82.03	198.82	81.78	78.34	202.98
3	70.22	82.13	202.02	81.82	78.38	207
4	69.77	82.13	204.36	81.84	78.04	208.65
5	70.08	82.23	203.02	81.9	78.04	209.01
6	70.12	82.3	198.87	81.94	78.08	209.41
7	70.22	82.2	204.28	81.88	78.05	209.8
8	70.57	82.23	202.71	81.89	78.08	209.05
9	75.5	82.1	200.96	81.92	78.11	209.76
10	70.23	82.16	199.07	81.84	77.98	209.23
Average	71.165	82.302	200.633	81.86	78.158	207.807

longitudinal fins resulted in high efficiency at a minimum volume. The system with longitudinal fins showed the best performance with increasing thermal response of PCM during charging, and reduced subcooling during discharging. Abdulateef et al. [6] also simulated two types of extended surfaces, namely the longitudinal and triangular fins. A significant enhancement in PCM melting was accomplished using internal, internal-external, and external triangular fins at 11%, 12%, and 15% respectively, compared with the longitudinal fins cases. Experimentally, the PCM melting for both-sides heating was successfully achieved at 90 °C. However, the changes in the mass flow rates of 16.2, 29.4, and 37.4 min/kg on the PCM average temperature in the axial direction were investigated. Tay et al. [7] indicated the plain tubes, which contained the heat-transfer fluid (HTF) modified to accommodate the techniques of the pin and the circular fins attached to the tube. Comparisons were conducted based on the solidification process. The finned tube was found to yield better average effectiveness and shorter phase-change duration (25% faster in terms of the phase-change duration) because of the large heat-transfer area of the finned tube design, compared with the pinned tube. Manish and Jyotirmay [8] experimentally examined the enhancement in the heat-transfer for melting and solidification of the PCM in a shell and tube with three longitudinal fins installed on the HTF tube. Solomon and Velraj [9] experimentally studied the heat-transfer enhancement of the PCM used in free-cooling application during outward cylindrical solidification in a double pipe heat exchanger, in which the PCM was filled in the annulus along with eight longitudinal uniformly spaced copper fins of different heights and air, as the HTF passes through the inner tube. The solidification time was decreased because of the utilization of longitudinal fins. Castell et al. [10] conducted a solidification process in the LHTES system with vertical external longitudinal fins. Heat-transfer enhancement achieves by the vertical fins on the HTF-side significantly promote the nature convection within the HTF. Celador et al. [11] presented

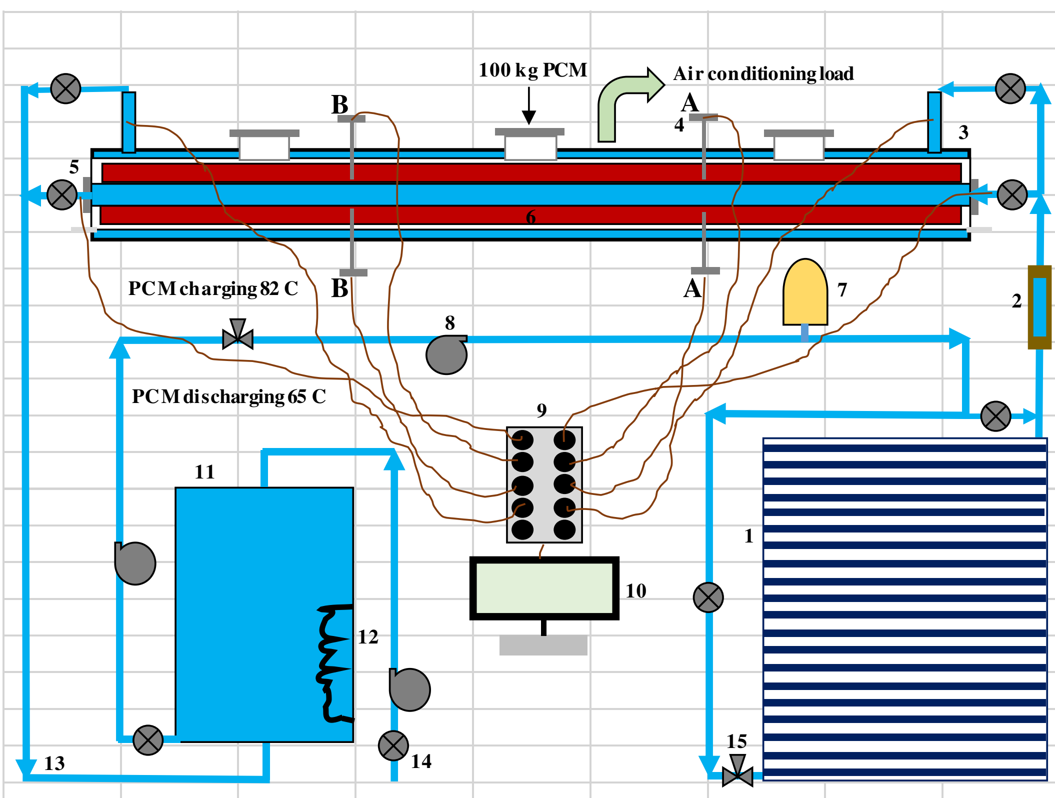

Fig. 1. Schematic of the experimental apparatus of the LHTES system. It includes: 1. Evacuated tube solar collectors, 2. Flow meter, 3. TTHX, 4. T-type thermocouple, 5. J-type thermocouple (water), 6. Internal longitudinal fins, 7. Pressure vessel tank, 8. Pump, 9. Data logger, 10. Computer, 11. Water storage tank, 12. Electrical heater, 13. Pipes, 14. Valve two-ways, 15. Valve three-ways.