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Analytical and experimental investigations of nanoparticles embedded phase change materials for cooling application in modern buildings

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ABSTRACT

This paper presents the analytical and experimental investigations of the phase change heat transfer characteristics and thermodynamic behavior of spherically enclosed phase change material (PCM) with dispersion of nanoparticles for latent thermal energy storage (LTES) system in buildings. In this study, the heat transfer characteristics in terms of the transient temperature variations, moving interface positions, complete rate of solidification and melting were analyzed for the six different PCMs considered in pure form and with dispersed nanoparticles as well. The heat transfer characteristics of the PCMs considered were analytically modeled and experimentally evaluated for the steady state and transient conditions for various heat generation parameters during freezing and melting cycles of the LTES system. The experimental results infer that for the same thermal load conditions the rate of solidification for the PCMs decreased with the increased mass fractions of nanoparticles while compared to the pure PCMs. For the same operating conditions of the LTES system, similar heat transfer characteristics were observed for the six PCMs considered. In this paper, the analytical model solutions and experimental results for the 60% n-tetradecane: 40% n-hexadecane PCM are presented. The solidification time for the 60% n-tetradecane: 40% n-hexadecane PCM embedded with the aluminium and alumina nanoparticles were expected to reduce by 12.97% and 4.97% than at its pure form respectively. Besides, the test results indicate that by increasing the mass fraction of the nanoparticles beyond the limiting value of 0.07 the rate of solidification was not significant further. Furthermore, the rate of melting was improved significantly for the PCMs embedded with the dispersed nanoparticles than the pure PCMs. The analytical solutions obtained for the pure and dispersed nanoparticles based PCMs were validated using the experimental results. The deviations observed between the analytical solutions and the experimental results were in the range of 10%–13%. Based on the analytical and experimental results the present nanoencapsulated LTES system can be regarded as a potential substitute for the conventional LTES system in buildings for achieving enhanced heat transfer characteristics and energy efficiency.

1. Introduction

Increasing energy demands in buildings worldwide evidently indicates the need for redistribution of energy for achieving good comfort conditions in indoor environment without compromising on energy efficiency. This can be achieved through the implementation of thermal energy storage (TES) systems in buildings which can supplement the peak thermal load demand and would enable for achieving effective energy redistribution. In this perspective LTES system offers better capability to store available heating and cooling energy in off-peak load conditions to effectively match the on-peak demand periods. PCMs included in the LHES system are a class of materials that exhibits good phase transformations by undergoing cyclic freezing and melting processes through the influence of heat transfer medium. These materials would ideally undergo phase transition at isothermal conditions which in turn would facilitate the PCMs to capture or release the thermal energy based on the load demand requirements.

Selection of PCMs and their incorporation into LHES system mainly depends on the type of storage (full or partial storage), freezing and melting heat transfer characteristics, cyclic duty, reliability and so on subjected to the cooling or heating load

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Nomenclature

C_p	Specific heat [J kg^{-1} K^{-1}]
F_o	Fourier Number [−]
g	Volumetric heat generation [W m^{-3}]
H	Latent heat of fusion [kJ kg^{-1}]
k	Thermal Conductivity [W m^{-1} K^{-1}]
r	Spatial variable [m]
R	Radius of spherical capsule [m]
s	Dimensionless position of the solid−liquid interface [−]
Ste	Stefan number [−]

Greek Symbols

α	Thermal diffusivity [m^2 s^{-1}]
β	Dimensionless heat generation parameter [−]
γ	Mass proportion of liquid in the mixture [−]
θ	Dimensionless Temperature [−]
σ	Position of interface in spatial variable [m]
φ	Volume fraction of nanoparticles [−]

Subscripts

sol	Complete Solidification
mel	Complete Melting
nf	Nanofluid
f	Fusion
L	Liquid Phase
S	Solid Phase
0	External Fluid

demand in buildings. In recent years, investigations related to the thermal performance and phase change behaviour of PCMs capsulated in either spherical or cylindrical packed bed LHES systems have been performed. As shown in Fig. 1 the spherical capsules called nodules were chosen for the analysis because of their wide ranging applications and higher volume of material and hence higher quantum of energy stored per unit heat transfer area.

In this relation, Ismail and Henriquez [1] simulated a storage system composed of spherical capsules filled with PCM placed inside a cylindrical tank. They used a simplified, transient, one-dimensional model based on dividing the tank into a number of axial layers whose thickness is always equal or larger than a capsule diameter. A model of the moving boundary within the phase change material during the discharging mode, and the influence of the geometry and the Stefan number on the solidification time were investigated [2]. Felix et al. [3] investigated the phase change phenomena of paraffin wax PCM filled inside the spherical capsules of a packed bed latent heat thermal energy storage system integrated with solar water heating system. The numerical investigation performed revealed that the phase change temperature range of the PCM has to be precisely modeled for predicting the thermal performance of the spherical capsules.

Parameshwaran et al. [4] demonstrated the significance of using energy efficient ventilation techniques for improving the performance of the thermal energy storage (TES) system in buildings. The TES system was integrated with a variable air volume (VAV) air conditioning system and the performance of the combined system

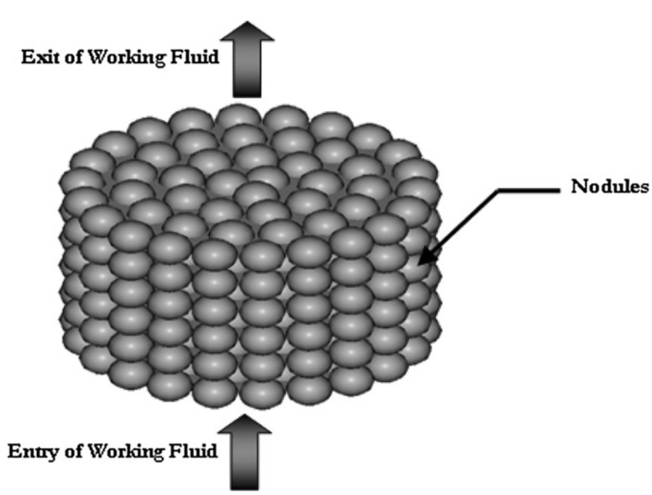

Fig. 1. Arrangement of spherical capsules in LHTES system.

was experimentally investigated for a year-round operating conditions. The experimental results infer that by incorporating the energy efficient ventilation techniques the VAV-TES system was capable of saving the on-peak total energy significantly.

The influence of the length of the tank on the charging and discharging modes of PCM by taking account of undercooling was reported in [5]. Basic correlation for the pressure drop of coolants during charging process and the thermal performance of an encapsulated thermal storage tank was experimentally investigated [6]. Karaipekli and Sari [7] developed a new form-stable PCM for LTES system in buildings and analyzed the thermal properties of the PCM in freezing and melting conditions. The form-stable PCM developed had exhibited increased thermal conductivity and enhanced thermal properties.

Analytical models based on quasi-stationarity for examining the solidification and melting of cylinder with uniform volumetric heat generation was developed by [8]. Heat generated within the PCM is very significant and it has a dominant influence on the heat transfer that occurs during the phase change process [9]. It is inferred that the heat transfer with consideration of conduction and liquid convection is not sufficient to predict the temperatures and the interface positions at various temperatures. Hence, heat generation has to be considered for actual thermal performance predictions pertaining to PCMs. The charging rate of a cylindrical heat storage capsule filled with stearic acid, sliced paraffin and lauric acid as the phase change material was analyzed experimentally [10].

Many research studies were performed numerically and experimentally for determining the thermal properties of the phase change materials used for building space heating and cooling applications [11,12,18]. Parametric studies and experiments were also conducted to predict the heat transfer characteristics of the PCMs inside a spherical encapsulation [12,16,22].

Kalaiselvam et al. [13] evaluated the charging and discharging capabilities of the phase change materials using finned encapsulation for achieving enhanced heat transfer. Numerical analysis of the PCMs encapsulated in spherical and cylindrical modules were performed and the numerical solutions were validated using experimental measurements. The numerical predictions and experimental results suggest that by using the finned configurations the solidification time would be reduced considerably thereby improving the overall performance of the LTES system.

Crank−Nicolson's numerical computational model was used to predict the time and the radial behaviors of the thermal profiles of a composite material [19]. Experiments to investigate the method of enhancing the storage and release capacities of various PCMs for providing better thermal characteristics when introduced into building fabric were also reported. Analytical models for