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A NON-DIMENSIONAL HEAT TRANSFER ANALYSIS OF PCM SOLIDIFICATION

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1. ABSTRACT

The present experimental investigation analysed the non-dimensional heat transfer study for the phase-changing phenomena during the phase change material (PCM) solidification. Thermal performance is characterized by measuring the degree of subcooling through solid Stefan number and by measuring superheating of the PCM at the onset of freezing through liquid Stefan Number. Meanwhile, a parameter termed as the dimensionless temperature is included to represent the instantaneous bulk-to-fusion temperature difference concerning Fourier number. It is found to be an inverse function of the initial Stefan Number.

2. INTRODUCTION

Chilled water and ice thermal storage are the principal cold thermal energy storage technologies. These are also categorized by storage time. For short-term storage, chilled water systems use nighttime chilling to provide daytime cooling [1,2]. Chilled water thermal storage systems have been utilized for the cooling of buildings and to reduce the energy demand when the national consumption rate is at its peak by Sebazali et al. [3]. Browne & Bansal [4] used a ε-NTU technique based on physical principles and heat transfer coefficients for a vapour-compression liquid chiller. Although cost-effective, the chilled water unit performs best when storage space is not constrained [5], limiting its use in tiny storage systems. With the energy crisis and renewable energy efforts, thermal storage technologies that store cold energy such as snow and ice for cold applications have gained popularity. The basic attributes of both chilled water and ice thermal storage systems are in Table 1.

Table 1. Comparison of Chilled water and Ice storage systems[6]

	Chilled water	Ice Thermal Storage
Specific heat (kJ/kg K)	4.19	2.04
Chiller type	Standard water	Low-temperature secondary coolant
Latent heat of fusion (kJ/kg)	-	334
Tank volume (m^3/kWh)	0.089–0.169	0.019–0.023
Storage installed cost per kWh ($)	8.5–28	14–20
Chiller cost per kW ($)	57–85	57–142

For small spaces, ice thermal storage systems are popular. It is commonly used in official buildings, which are used for various times. Despite the many benefits of ice-bank systems over chilled water, they require a lower evaporation temperature, which lowers their COP and increases their energy consumption per cooling effect. Heat transfer decreases as solidification progresses. The non-dimensional transient analysis of heat transfer performance must be predicted to estimate the ice-cold thermal storage system's performance under varying heat loads. In this current study, the evolution of different non-dimensional parameters related to PCM solidification is witnessed under different operating and locations with PCM.

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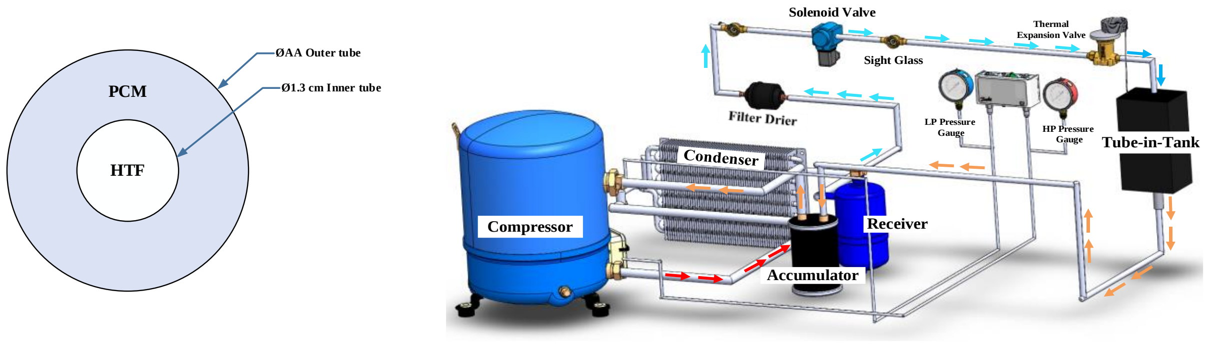
3. EXPERIMENTAL SETUP



a) b)

Fig. 1. Cross-sectional view of LHTS and Experimental Setup

The cross-sectional view of the tube in tube latent heat thermal storage (LHTS) is shown in Fig.1(a) and the VCRS system for the discharging process and the installed LHTS is displayed in Fig.1(b). To test on different Stefan Numbers, the PCM temperature has been operated at different ranges including 20 °C, 15 °C and 5 °C. The test is performed for different axial and radial locations with the PCM enclosed in the annular region of the LHTS. The PCM is water.

4. DATA REDUCTION

In this study, dimensionless parameters are used to describe LHTES solidification performance thermally. The liquid PCM absorbs sensible heat during freezing and latent heat when it reaches its fusion temperature. Dimensionless Stefan number measures sensible heat absorbed by solid or liquid PCM on latent heat. Thus, solid-phased Stefan number Ste_s and liquid-phased Stefan number Ste_l are evaluated in the study as given below:

$$Ste_s(t) = C_s(T_m - T_{ice}(t))/L \quad (1)$$
$$Ste_l(t) = C_l(T_{bulk}(t) - T_m)/L \quad (2)$$

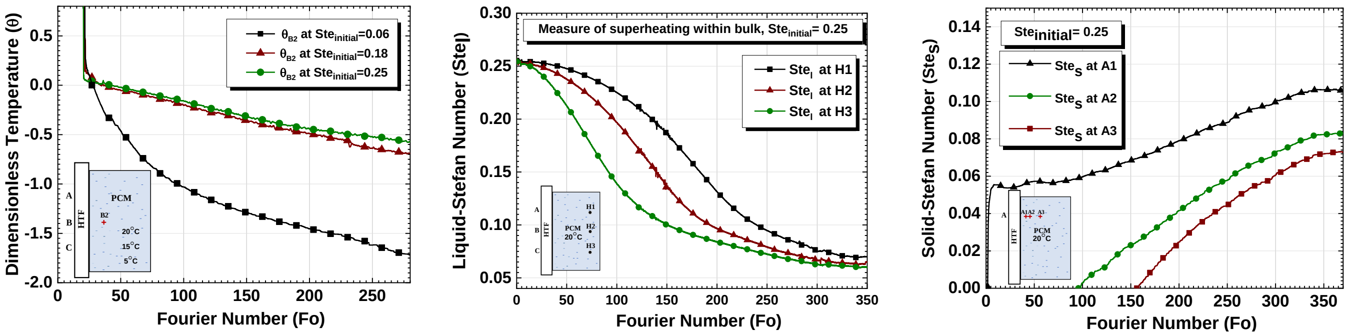
Here T_m and T_{ice} refer to fusion and ice temperature, respectively. L is the latent heat of fusion whereas C_s and C_l are the solid and liquid-specific heat of PCM. The temperature of the frozen PCM layer at a specific location is presented as the ratio of the instantaneous ice-to-fusion temperature normalized by the initial superheat. At any axial or radial location in the solid PCM layer, θ is given as:

$$\theta = \frac{T_{ice}(t) - T_m}{T_{bulk_i} - T_m} \quad (3)$$

Where T_{bulk_i} is the initial bulk temperature.

5. RESULTS AND DISCUSSION

The variation of different dimensionless heat transfer parameters is discussed in this section. It includes the evolution of Stefan number during the solid and the liquid phase of the PCM during the solidification phenomena. The evaluation uses liquid and solid phase Stefan numbers and dimensionless temperature under different operating conditions. The time-wise variation of parameter dimensionless temperature, θ is analysed for a specific position with PCM at different Stefan numbers in Fig.2(a). It can be seen that the θ declines with the Fourier number which represents the time factor. It is maximum during the onset of the phase changing phenomena and the highest for the lower Stefan Number of 0.08. However, a slight difference can be achieved in the θ for higher Stefan number such as for 0.18 and 0.26. Thus, the dimensionless temperature, θ is found be an inverse function of the initial Stefan Number. Fig. 2(b) and (c) represent the variation in the liquid and solid phased Stefan number within bulk and solidified PCM, respectively. The liquid Stefan number measures superheating in the liquid PCM based on the bulk temperature while the solid-phased Stefan number measures subcooling across the frozen PCM layer. The variation is investigated at different axial and radial locations with the PCM. Fig. 2(b) displays the measure of superheating in the bulk liquid PCM while Fig.2(c) shows the solid Stefan number at the freeze layer of PCM. A faster drop in superheating is achieved at the higher position of H_1 as the Stefan number is higher for this position whereas the liquid Stefan number is highest for the nearest position representing maximum subcooling in the nearest position.



a) Dimensionless temperature b) Liquid Stefan number c) Solid Stefan number

Fig.2. Timewise variation of studied parameters

6. CONCLUSIONS

The non-dimensional investigation on the thermal performance of a water-based PCM thermal energy storage system is evaluated based on two kinds of Stefan Numbers related to liquid and solid PCM. Parameter dimensionless temperature is evaluated under different initial Stefan numbers at a specific position with the PCM. It is found that it is an inverse function of the initial Stefan number. Meanwhile, a higher liquid Stefan number evolution is perceived for the top position within PCM whereas the solid Stefan number is highest for the nearest location.

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