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Measurement of heat transfer enhancement in melting of n-Octadecane under gravitational and electrohydrodynamics (EHD) forces

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ABSTRACT

Organic Phase Change Materials (PCMs) have been studied extensively in literature for their use in latent heat thermal storage applications. This is mainly due to their chemical stability, high latent heat of fusion and low melting point which makes them a good candidate for space heating applications. However, one of the main drawbacks is their low thermal conductivity $\kappa \leq 0.6$ W/mK, which poses a negative impact on the maximum allowable heat transfer rates that can be achieved which in turn puts a restriction on the geometry of the PCM modules.

A novel heat transfer enhancement technique recently discovered employing the application of a high voltage within the PCM to introduce Electrohydrodynamic (EHD) forces which increases the melting process rate. The melting of paraffin wax under EHD forces was previously investigated and it was found that a reduction of the melting time by 40% can be achieved [5].

In this paper, a novel experimental methodology to quantify the heat transfer augmentation in melting of Octadecane under gravitational and EHD forces is presented. The developed experimental method allowed for the study of the EHD heat transfer enhancement under different parameters: electric potential, wave-form, temperature gradient and various aspect ratios. It is found that Coulomb forces are the main driving mechanism of enhancement in the melting of Octadecane and that a heat transfer augmentation up to 8.6 folds can be reached by using EHD.

1. Introduction

Thermal energy storage systems are an enabling technology towards more sustainable and energy efficient communities. They are often used in conjunction with thermal systems subjected to prolonged times of mismatch between the thermal supply and the consumer thermal demand. These mismatched conditions are, for example, highly pronounced in solar thermal systems, combined heat and power plants (CHP) and waste heat recovery systems. In such systems, thermal storage acts as a buffer and provides an efficient solution for the mismatch problem.

Latent Heat Thermal Storage (LHTS) systems are one type of system in which thermal energy is stored in the form of latent heat of fusion. The Phase Change Material [PCM] is transformed from solid state to liquid state during energy storage and the reverse during energy recovery. This type of storage is widely investigated and encouraged in industry owing to their high thermal storage density compared to other types of storage. However, the PCMs operating under low temperature heating applications (below 85 °C) are often characterized by very poor thermal conductivity ($0.1 \rightarrow 0.6$ W/mk) [1]. These poor thermal properties hinder the heat transfer process and limit the system storage capacity for a given charging period.

Several heat transfer enhancement techniques were investigated to overcome the thermal conductivity problem. These techniques varied from using passive techniques to active heat transfer enhancement techniques. The widely used passive techniques are the use of fins, metal additives of high thermal conductivities and microencapsulating the PCMs. A summary of recent progress in the passive heat transfer enhancement techniques used in the latent thermal storage systems can be found in review articles [2,3].

The studies conducted on using active techniques are very limited and mainly only two types were investigated to the best of our knowledge. These two types are the use of ultrasonic vibrations [4] and Electrohydrodynamics (EHD) [5] in enhancing the melting rate for organic PCMs.

EHD has been studied extensively in the field of heat transfer enhancement and was found to be one of the least power consumptive active enhancement techniques. It has proven to work in both single

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and multi-phase systems [6].

EHD enhancement technique occupies less volume compared to the passive techniques that rely on adding foreign material in the PCM. This makes EHD a good alternative candidate in applications where space is more valuable or in micro-gravity conditions [7] or under Nano-scale applications [8].

The EHD mechanism of heat transfer enhancement can be attributed to the additional electric body forces imposed on the dielectric fluid. The EHD body forces $\left(\vec{f_e}\right)$ acting on a dielectric fluid as formulated by Chu [9].

$$\vec{f_e} = \rho_q \vec{E} - \frac{1}{2}E^2\nabla\varepsilon + \frac{1}{2}\nabla\left(\rho E^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T\right) \tag{1}$$

The first term is called Coulomb force and it arises from the presence of free charge carriers (ρ_q) in the bulk of the dielectric fluid, and it acts in the same direction as of the electric field ($\vec{E}$). The second term is called dielectrophoretic forces or polarization forces and it appears whenever a spatial gradient in permittivity ($\nabla\varepsilon$) does exist, either from temperature gradients or at an interface between two different phases. The third component is called electrostrictive force and it is a gradient of a scalar and is usually neglected for incompressible fluids.

The recent study by Nakhla et al. [5], discovered that EHD can significantly reduce the melting time of paraffin wax by 40%. The study showed that EHD forces acted on both the bulk of the molten wax and on the solid/liquid interface. The EHD forces induced convective cells inside the liquid wax and acted on the interface pulling the solid dendrites from the mushy zone. These findings were the first in the field of thermal storage systems. The author examined the melting performance under constant heat flux boundary conditions and for paraffin wax as the PCM.

In this paper, the previous work is expanded to investigate the behavior of melting under constant temperature boundary conditions, while using Octadecane ($C_{18}H_{38}$) as the PCM. A novel experimental facility was built, which can accurately quantify the electric Nusselt number at different stages during the melting process. The electric Nusselt number is defined as the ratio between the augmented heat transfer by EHD forces to the heat transfer by conduction only.

The experimental work was conducted under different temperature boundary conditions, voltages and wave-forms as well in order to understand the possible mechanisms lying behind the EHD heat transfer augmentation in melting of PCMs.

2. Methodology

2.1. Experimental setup

The experimental test facility was designed to be able to quantify the heat flux through the solid PCM. Octadecane was chosen as the PCM because of its well-known thermo-physical properties in the literature of phase change materials [10]. Octadecane also has a relatively low melting point (28 °C) which is favorable for minimizing heat losses to the surroundings. Finally, Octadecane is an organic dielectric material, with properties similar to those of paraffin's which are widely used as common PCMs for low temperature range (<70 °C) applications.

The design of the experimental facility relies on testing key parameters of the melting process, which is a transient phenomenon in nature, under a quasi-steady environment. The experimental facility controls the movement of the melt front to a specified thickness which can help understand the heat transfer enhancement mechanism induced by EHD for a range of melt thicknesses.

A specified melt thickness is achieved by using simultaneous controllable heating and cooling loops. The PCM is encapsulated between two heat exchangers, the top heat exchanger has water running at a temperature (T_h) which is higher than the melting temperature (T_m) of the PCM, while the bottom heat exchanger has water running at a temperature (T_c), which is lower than that of the PCM melting point [Refer to Fig. 1]. One side is acting as a heat source for melting and the other side acts as a heat sink for solidification. The simultaneous heating and cooling from both sides made it possible to control the location of solid/liquid interface and to achieve steady state.

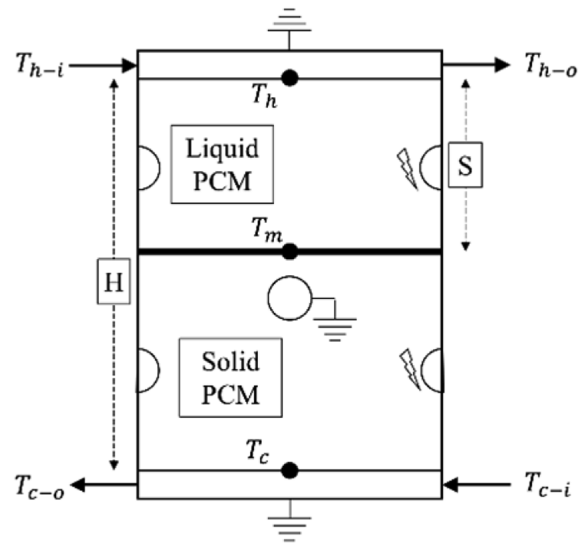

Fig. 1. A schematic section of the test cell.

Upon reaching steady state, the heat flux through the solid and the liquid PCM can be quantified through the solid phase, owing to the fact heat conduction is the only mode of heat transfer through the solid PCM.

Applying high voltage to the cylindrical electrodes embedded into the PCM induces EHD body forces in the liquid phase and at the solid/liquid interface which in turns enhances the heat transfer in the liquid PCM and an increase in the melt thickness and a new steady state can be achieved.

By comparing the two-steady state cases the dimensionless Nusselt number can be quantified for a base case and for the EHD case.

Fig. 2 shows the experimental apparatus used. The experimental facility consists of a polycarbonate test section, encapsulating the phase change material [Octadecane]. The container had internal dimensions of 40 mm in height, 50 mm in depth and 156 mm long. The walls of the container are made of 0.5-inch polycarbonate sheets. Two heat exchangers are fastened to the top and bottom of the test section. These heat exchangers provide the heat sources and sinks for the experiments. The heat exchangers are designed to use water as the working fluid; the water passes through internal channels which were machined into the aluminum heat exchangers. A flat surface on the heat exchanger was used to heat and cool the phase change material.

The two heat exchangers are connected to a controlled thermal bath with a reported temperature stability of ± 0.01 °Cto maintain a constant temperature boundary condition for each heat exchanger. The hot heat exchanger is connected to Neslab RTE-10 thermal bath and the cold heat exchanger is connected to Neslab RTE-7 thermal bath. The mass flow rates through both the hot and the cold heat exchanger are kept high enough to ensure a maximum temperature difference between the inlet and the outlet of each heat exchanger at 0.3 °C. Each heat exchanger has eight thermocouple slots, uniformly located, to assess the temperature uniformity of the surface in contact with the PCM. The thermocouples are type-T thermocouples and they were calibrated to an accuracy of 0.25 °C. The thermocouples' signals are read by data acquisition card (NI-DAQ 9213) that is connected to the computer station for real time monitoring and logging of temperature data.

The amount of melt thickness and thus the location of the solid