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Heat transfer analysis of microencapsulated phase change material slurry flow in heated helical coils: A numerical and analytical study

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In this paper, numerical simulations and analytical analysis of the flow of a blend of microencapsulated phase change material (MPCM) in water, so called MPCM slurry (MPCMs), through a heated helically coiled heat exchanger were performed and data are presented and discussed. The numerical simulation results have been validated using experimental heat transfer data. Analysis of the numerical and analytical results reveal that the radius of curvature of the helically coiled heat exchanger have a direct effect on velocity profile and heat transfer rate of MPCMs flows. The results also indicate that MPCMs at low concentrations can be treated as homogenous heat transfer fluids.

1. Introduction

Energy consumption in cooling and heating systems in residential and commercial buildings has grown rapidly. The large volume of heat transfer fluid (HTF) that needs to be pumped in energy systems reduces the efficiency and increase the cost of such systems. One way to reduce the energy and cost associated with the pumping of HTFs in energy systems is to improve their thermal properties (e.g., thermal capacity). Microencapsulated phase change material (MPCM) is composed of phase change materials (PCMs) in the core and a solid shell material that encapsulate the PCM. Microencapsulated phase change material slurries (MPCMs) proved to be an enhanced heat transfer fluid due to the large heat carrying capacity exhibited during their phase change temperature range. The PCM can absorb and release a large amount of thermal energy when they change from solids to liquids and from liquids to solids, respectively. The blend of MPCM and base fluid (a.k.a., MPCMs) yields an enhanced heat carrying capacity that enables less pumping power to deliver the same amount of heat compared with traditional base fluids.

Helical coil heat exchangers are widely utilized in residential and industrial applications including heating, ventilation, and air conditioning (HVAC) systems, combined heat and power systems, and power generation. Helically coiled heat exchangers are considered compact heat exchangers with large surface-to-volume ratio that can fit small spaces and deliver large heat transfer rates.

The effect of curvature on fluid flow has been studied by numerous researchers. Guan and Martonen [1] modeled the flow in curved tubes and observed flow axial and secondary motions in the developing and fully developed regions of the flow. Dean [2] mathematically modeled a constant-radius curve duct to explore the secondary flow in the pipes. Ho and Wijeysundera [3] considered the spiral coil thermal performance where they numerically computed the enthalpy effectiveness of spiral coil heat exchangers in a cooling process. Naphon [4] numerically and experimentally explored the heat transfer and flow structures of a turbulent fluid flow in a spiral coil tube where he revealed the significant roles of centrifugal force on the temperature distribution and heat transfer rate enhancement.

MPCM has been used in experiments and modeled extensively in the past decade by various researchers. Alvarado et al. [5] used microencapsulated n-tetradecane slurry with tetradecanol as a nucleating agent to conduct pressure drop and heat transfer experiments in a horizontal circular tube under turbulent flow conditions. Their results showed that MPCMs behave similarly to a Newtonian fluid at mass fractions below 17.7%. They observed that the pressure drop of 5.9 wt% MPCMs was smaller than that of

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water because of possible drag reduction effects. They further reported that the phase change process significantly increased the effective heat carrying capacity of MPCMs when compared with water. Yamagishi et al. [6] conducted an experimental study on pressure drop and heat transfer characteristics of MPCMs having octadecane as a PCM in a straight tube. They found that the heat transfer coefficient of MPCMs decreased with MPCM concentration increase at the same fluid velocity due to a suppression of turbulence intensity. Sabbah et al. [7] performed a numerical study to characterize the thermal boundary layer growth where they studied the influence of MPCM on the growth of the boundary layer at the thermal entry length extension. In another study by Kurnia et al. [8], a computational analysis of coiled square tubes was explored. They simulated laminar flow of MPCMs through a square cross section of straight, conical spiral, in-plane spiral, and helical coils. Higher heat transfer performance due to the use of MPCM when compared to water was observed in this computational study.

Numerous studies have been performed to experimentally investigate the effects of the curvature on the fluid flow's pressure drop and heat transfer characteristics. Srinivasan et al. [9] studied the pressure drop of water and oil flowing through the coils with curvature ratios from 0.0097 to 0.135. Their experimental results showed that pressure drops in the coils were greater than those in the straight tubes due to increased flow resistance near the tube walls. They postulated a correlation for estimating the friction factor of fluids flowing through the coils as a function of Dean number and curvature ratio. Mori and Nakayama [10] studied a fully turbulent fluid flow in coils using theoretical and experimental methods. They derived a Nusselt number correlation for Newtonian fluids flowing through the coils in terms of Reynolds number, Prandtl number and curvature ratio, which was validated by their experimental results. They observed that Nusselt numbers in the coils were greater than those in the straight tubes due to the curvature effects. Seban and McLaughlin [11] performed an experimental study on heat transfer characteristics of water in the helical coils under turbulent flow conditions. The experimental results showed that the heat transfer coefficient on the outer surface was always higher than that on the inner surface. Rennie and Raghavan [12] conducted an experimental study on the heat transfer characteristics of a coaxial heat exchanger. They found that the overall heat transfer coefficients increased with Dean number.

Kong et al. [13] characterized the effects of using MPCMs containing methyl stearate as a PCM on thermal performance of a commercial coil heat exchanger where they showed that, when compared to water, MPCMs enhanced the overall heat transfer coefficients and the heat exchanger effectiveness due to the latent heat of fusion of PCM. Later, Kong [14] and Kong et al. [15] performed experimental tests to investigate the flow and heat transfer characteristics of MPCMs as an enhanced heat transfer fluid in a fully instrumented heated helically coiled tube. Different mass fractions of MPCMs were tested and correlated using the Dean number. Their results showed that although heat transfer enhancement is restricted due to high viscosity and low latent heat of fusion of PCM materials used in MPCMs, MPCMs still shows heat capacity improvements when compared to its base fluid, water.

Various attempts have been made to model the MPCMs flow through circular tubes. Charunyakorn et al. [16] used a source term to account for the amount of heat absorbed or released during the phase change process. This model assumed that the MPCM particles consisted entirely of the phase change material, neglecting the shell material. Roy and Avanic [17] modeled the phase change using a temperature-dependent specific heat function. They explored various shapes (i.e., triangular, rectangular, or sinusoidal profile) of the specific heat functions and concluded that the shape was not a sensitive parameter in establishing the heat performance of MPCMs. They used the effective heat capacity method to model the convective and phase change process in which the tube was split into three regions as suggested by Choi et al. [18].

In this paper, we investigate the fluid dynamics and heat transfer characteristics of MPCMs flow through helical coiled heat exchangers using numerical and theoretical analyses to address the knowledge gap that exists between the experimentally observed phenomena and micro-level analysis. Understanding how fluid conditions affect the fluid dynamics and heat transfer behavior of the MPCMs through the curved path could eventually lead practical utilization of MPCMs in industrial applications.

2. Numerical analysis

In the current study, a two-turn helically coiled tube (made of copper, 2.6 m length, inner pipe diameter of 10.2 mm, and inner coil diameter of 0.414 m) was modeled using ANSYS Fluent, as shown in Fig. 1(a). A fully developed turbulent flow is defined, and the prescribed inlet velocity and a constant heat flux on the outer wall of the coil are assumed. The steady state flow condition and the no-slip velocity condition on the wall are applied to the model.

The prism layers were applied in the fluid region near the wall to create finer mesh cells in that region, Fig. 1(b). The boundary conditions applied to various concentrations of MPCMs (5.9%, 10.9%) and water (base fluid) are shown in Table 1.

The Reynolds number and heat flux used in this study are defined as Eqs. (1) and (2), respectively

$$Re = \frac{\rho u d}{\mu} \tag{1}$$

$$q'' = \frac{\dot{m} c_p \Delta T}{A_s} \tag{2}$$

where u, $\dot{m}$, c_p, and A_s are fluid velocity, mass flowrate, and surface area of the heat exchanger, respectively. The 2.5 m/s inlet velocity with fully developed turbulent flow condition is considered at the inlet. The MPCMs properties were evaluated and shown in Table 2. The MPCMs density can be evaluated by measuring the mass and volume of several samples for different concentrations. Using the Maxwell equation [19], the thermal conductivity is calculated by Eq. (3):

$$k_{MPCMs} = k_w \left[\frac{2k_w + k_{MPCM} + 2MF(k_{MPCM} - k_w)}{2k_w + k_{MPCM} - MF(k_{MPCM} - k_w)} \right] \tag{3}$$

where k_w, k_{MPCM}, and MF are water thermal conductivity, MPCM thermal conductivity, and MPCM mass fraction in the slurry, respectively.

The specific heat capacity of the MPCMs can be divided into two main sections, one during phase change (a.k.a., effective specific heat), and one without phase change. Using Eq. (4), specific heat of MPCMs can be calculated based on specific heat of water ($c_{p,w}$) and MPCM ($c_{p,MPCM}$) without the phase change process:

$$c_{p,MPCMs} = MF \cdot c_{p,MPCM} + (1 - MF) \cdot c_{p,w} \tag{4}$$

To estimate the specific heat during phase change, the latent heat of PCM fusion is considered in the heat transfer rate ($\dot{Q}$). Therefore, the specific heat can be obtained using Eq. (5):

$$c_{p,MPCMs} = \frac{\dot{Q}}{\dot{m}_{MPCMs} \Delta T_{MPCMs}} \tag{5}$$

where $\dot{m}_{MPCMs}$ denotes the MPCMs mass flow rate and ΔT_{MPCMs} represents the MPCMs temperature difference of inlet and outlet. The HTF (MPCMs and water) viscosity is obtained using Eq. (6), [14]: