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Laminar Heat Transfer in a Horizontal Circular Tube with Phase Change Emulsions of Methyl Myristate – An Experimental Study

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Abstract – This work analyzes the thermo-fluidic characteristics of phase change material nanoemulsions (PCMEs) under laminar flow regime in a horizontal circular tube. Oil-in-water nanoemulsions were prepared using an ethylene glycol:water mixture (25:75 by weight) as continuous phase, methyl myristate as phase change material and a mixture of ionic and non-ionic surfactants as emulsifier. In order to obtain stable colloidal dispersions with small droplets, adequate fluidity and reduced subcooling, nanoemulsion composition and formulation conditions were first optimized based on stability and calorimetric analyses. Convective heat transfer coefficients were then investigated under uniform-heat-flux boundary conditions. The disperse phase content (0-10% by weight), the physical state of the emulsified droplets (solid, liquid or melting), as well as the supplied wall heat flux (2000-8000 W/m^2) were used as experimental parameters. When phase change material droplets do not change their solid or liquid state, experimental Nusselt numbers roughly agree with classical Shah-London empirical equation for laminar forced convection. However, at temperatures close to the melting point of dispersed particles, there is a rise in Nusselt number. This behavior is due to the larger apparent storage heat capacity of the samples resulting from the latent heat released during the solid-liquid transition of emulsified droplets. The heat transfer coefficient of PCMEs was also shown to be higher at the bottom of the circular pipe than at the top. This phenomenon may be a consequence of the fact that the droplets near to the heated wall melt first, thus leading to density gradients throughout the section of the tube and possibly secondary convection. As expected, the pressure drop increases with the content of dispersed phases and those rises were larger when dispersed droplets are in solid state. Nevertheless, samples mainly exhibited desirable Newtonian behaviors.

***Keywords*:** Methyl myristate, Phase change nanoemulsion, Heat transfer, Laminar flow, Melting latent heat, Pressure drop.

1. Introduction

The urgent need to tackle global climate emergency has situated the goal of creating and deploying sustainable and energy-efficient technologies as one of the most important challenges for humanity. In this scenario, the development of heat transfer and storage media with enhanced thermal properties is key to improving the thermal performance of conventional facilities and promoting the use of renewables [1]. Among recently proposed solutions, phase change material nanoemulsions, in which a phase change material (PCM) is dispersed as nanometer-sized droplets in a conventional carrier fluid, have attracted increasing interest. This type of two-phase slurries combine the additional latent heat capacity associated to the melting-solidification of dispersed droplets with the better transport properties of the carrier fluid used as continuous phase [2].

Research on PCMEs evidences the potential of these latent functionally heat transfer fluids in a wide range of applications such as heating, ventilation and air conditioning systems (HVAC) or solar-assisted facilities. Thus, Liu et al. [3] proved the efficacy of *n*-hexadecane-in-water nanoemulsions for improving the storage capacity and discharging rate of a pilot-scale thermal energy storage system for room air-conditioning. Likewise, Burgos et al. [1] investigated the photo-thermal performance of aqueous nanoemulsions of hybrid carbon-paraffin and demonstrated that conversion efficiency was

1.5-fold better than water using a solar simulator and 2.7-fold larger when using natural sunlight. However, most current research on PCMEs has focused on the development of the samples and the determination of the thermophysical profile. Since these materials are also expected to work as a heat transfer media, it is essential to experimentally evaluate their flow and heat-transfer characteristics under different operational conditions. Thus, information regarding the heat transfer mechanisms during the phase change of dispersed droplets are of great help when deciding which exchanger geometries are most suitable to fully exploit the stored latent thermal energy, for example. In addition, pressure drop studies are also necessary to estimate pumping power consumption, a factor indispensable to analyze the energetic and economic benefits of replacing convectional heat transfer fluids by PCMEs. When it comes to the hydraulic and thermal performances of paraffin-in-water emulsions under laminar flow regime, it must be highlighted the studies by Ma et al. [4] and Morimoto and Kumano [5]. Authors found that the heat transfer of PCM nanoemulsions was enhanced by the fusion of the dispersed phase, and those improvements were influenced by the wall heat flux and tube diameter due to the fast melting and increased motion of emulsified particles.

2. Nanoemulsion development

PCM nanoemulsions with three different mass concentrations of dispersed phase (2, 6 and 10 wt.%) were prepared by following a solvent-assisted approach. Methyl myristate, also known as methyl tetradecanoate, was used as phase change material, while an ethylene glycol:water mixture (25:75 by weight) was utilized as continuous phase. According to a previous investigation [6], a mixture non-ionic polysorbate 20 (Brij^{TM}S2) and anionic sodium dodecyl sulfate (SDS) at a mass ratio of Brij^{TM}S2:SDS= 39:20 was utilized as emulsifier. In order to ensure that prepared samples shown good stability, appropriate fluidity and reduced subcooling, dispersed phase composition was optimized through visual observations, size and Zeta potential measurements of emulsified droplets based on dynamic light scattering (Zetasizer Nano ZS, Malvern Instruments Ltd., Worcestershire, UK) and analyses of the phase change transitions by means means of differential scanning calorimetry (DSC, Q2000, TA Instruments, New Castle, USA). After different preliminary attempts, a mixture enriched in methyl myristate (90 wt.%) and containing small amounts of methyl stearate (5 wt.%), *n*-nonadecane (2.5 wt.%) and cetyl alcohol (2.5 wt.%) was selected as dispersed phase to prepare the samples. Emulsified droplets exhibited average diameters lower than 180 nm, Zeta potentials stronger than -50 mV and DSC melting peaks mainly at temperatures around 12-14 ºC.

3. Flow and heat transfer performance

3.1. Experimental set-up

In order to investigate the hydraulic and thermal performance of the PCMEs, it was developed a new experimental test rig. The main element of this set-up is the testing section, which consists of a straight stainless-steel tube, with circular section and placed horizontally (Figure 1). A nichrome resistance was continuously wrapped around the central part of the pipe and connected to a power source to supply a uniform heat flux throughout the wall. T-type thermocouples were installed to measure the temperature at the inlet and outlet of the tube, as well as at the three lengths and three angles indicated in the schematics. An entrance region was placed before the heated section to obtain developed flow conditions. The whole channel was thermally insulated to minimize heat losses. In order to measure the pressure drop along the testing section, a differential manometer was also connected to the positions indicated in Figure 1.

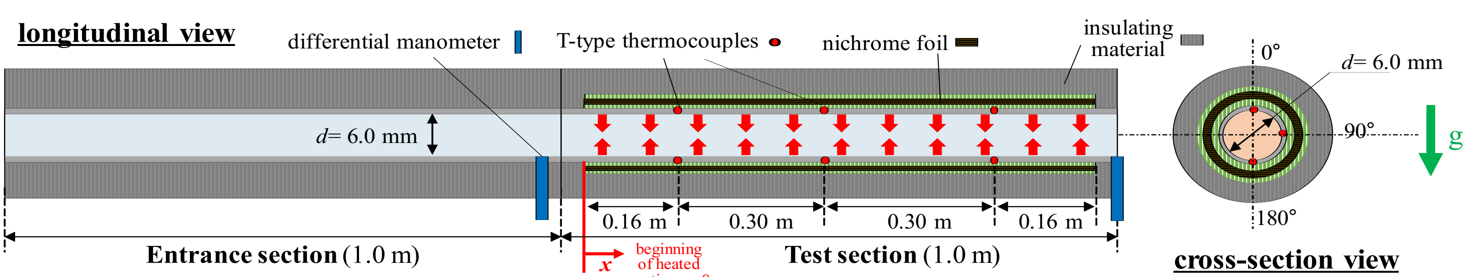

Fig. 1: Longitudinal and cross-section views of the entrance and test sections used to investigate the heat transfer performance.

The investigated thermal fluid is first stored in a reservoir placed in a thermostatic bath to control the inlet temperature. From there, the sample is driven throughout the entrance and testing sections to an outlet reservoir by means of a gear pump and controlling the average fluid velocity using a flow meter. Experiments were performed for the ethylene glycol:water mixture and the three prepared emulsions at three heat fluxes ($\dot{q}$= 2000-8000 W/m^2) and three average fluid velocities (u_m= 0.15-0.35 m/s). Three inlet temperatures were investigated to analyze the effect of the physical state of dispersed droplets: solid (inlet temperature: T_{in}= 2 ºC), melting (T_{in}= 12 ºC) and liquid (T_{in}= 22 ºC).

3.2. Results and discussion

Convective heat transfer coefficients were expressed in a dimensionless way through the Nusselt (*Nu*) and inverse Graetz (x^*) numbers and obtained values were compared with the well-known Shah-London [7] equation for one-phase fluids flowing under laminar regime. As an example, Figure 2 shows the results obtained for the ethylene glycol:water (25:75 by weight) and the emulsion loaded with 10 wt.% of dispersed phase at $\dot{q}$= 4000 W/m^2, u_m= 0.15-0.35 m/s and the three investigated inlet temperatures.

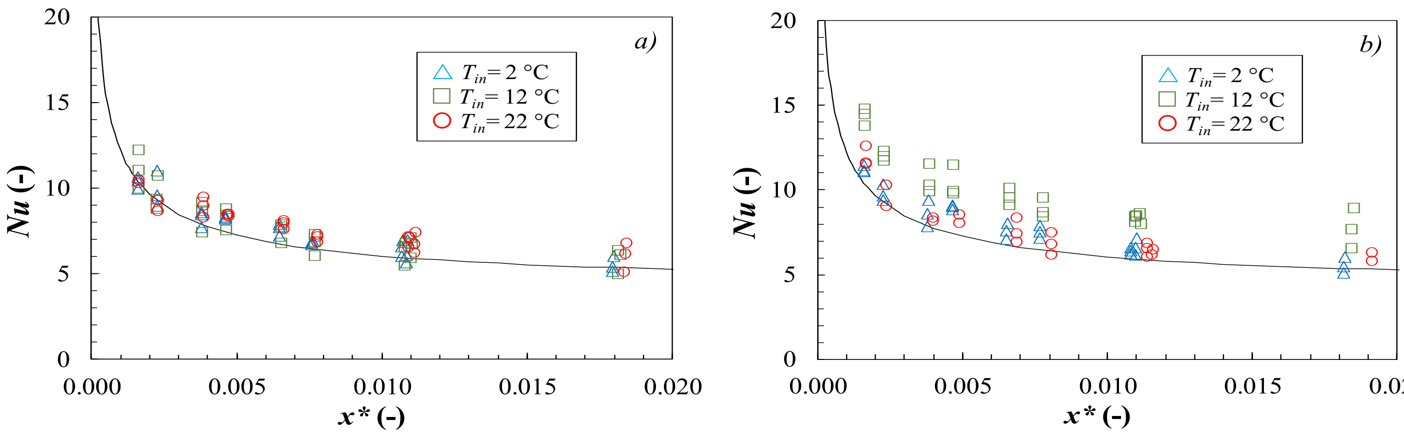

Fig. 2: Comparison between experimental and predicted Nusselt numbers (*Nu*) for the ethylene glycol:water mixture (25:75 wt.%) *(a)* and the 10 wt.% nanoemulsion *(b)* at some representative conditions ($\dot{q}$= 4000 W/m^2, u_m= 0.15-0.35 m/s).

As can be observed, the results experimental determined for the ethylene glycol:water mixture roughly agree with the values predicted by the empirical equation [7], with maximum deviations within 20%. The same finding was obtained for the 10 wt.% emulsion at the inlet temperatures of T_{in}= 2 ºC (dispersed particles are in solid phase) and T_{in}= 22 ºC (liquid dispersed droplets). However, at T_{in}= 12 ºC (when PCM particles are melting), experimental Nusselt numbers are, on average, 30% higher than those measured for the ethylene glycol:water mixture at the same conditions. Also at T_{in}= 12 ºC, Nusselt numbers are larger at the bottom of the tube than at the top. The better heat transfer performance at the lowest part of the pipe, with enhancements that can reach the 70%, may be attributed to a secondary convection in the cross-section of the circular tube. As explained in more detail by Morimoto et al. [5,8], the solid particles near the wall of the heated section undergo melting transition first. Since liquid particles are less dense than solid ones, buoyancy forces move the liquid droplets upward along the tube wall, likely inducing downward flow in the center of the section to satisfy mass conservation.

The pressure drop (Δp) along the test section increases with the content of dispersed phase. As an example, Figure 3 shows the average rises in this property regarding the ethylene glycol:water mixture used as continuous phase without applying any heat flux ($\dot{q}$= 0 W/m^2). Average increases in Δp reach 125% at T_{in}= 2 ºC (dispersed particles are solid) and 56% at T_{in}= 22 ºC (liquid droplets). This can be ascribed to the fact that when dispersed phase is solid, emulsions are known to offer a larger resistance to flow than when dispersed droplets are liquid. Finally, pressure drop results were also used to analyze the (non-)Newtonian behavior of prepared PCMEs. At investigated shear rate conditions, nanoemulsions showed mainly Newtonian viscosities, except for the 10 wt.% sample, for which a slight shear thinning was observed at the lowest inlet temperature (T_{in}= 2 ºC).

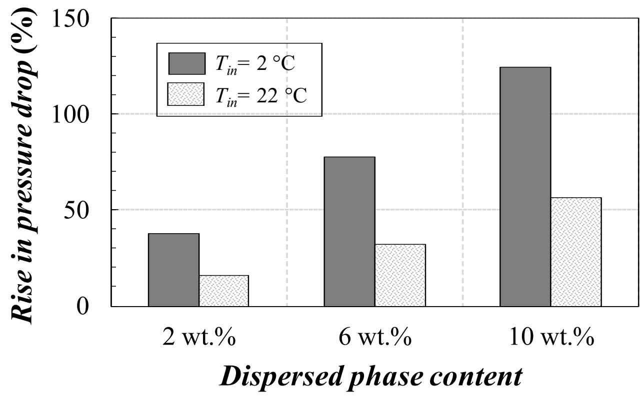

Fig. 3: Average rises in pressure drop regarding the ethylene glycol:water mixture (25:75 by weight) used as continuous phase.

4. Conclusion

At temperatures close to the phase change transition of the emulsified droplets, PCMEs exhibit better heat transfer performance than the ethylene glycol:water mixture (25:75 by weight) used as base fluid. Thus, in the case of 10 wt.% nanoemulsion, the additional latent heat involved in the melting of dispersed particles improves Nusselt number by 30% on average. Higher enhancements in thermal performance (up to 70% better) were measured at the bottom of the tube due to lickely secondary convection. Pressure drop increases with the content of dispersed phase, particularly when emulsified droplets are solid.

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