International Journal of Heat and Mass Transfer 126 (2018) 390–399

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental investigation of the effects of mass fraction and temperature on the viscosity of microencapsulated PCM slurry

Krzysztof Dutkowski, Jacek Jan Fiuk *

Faculty of Mechanical Engineering, Koszalin University of Technology, ul. Raclawicka 15-17, 75-620 Koszalin, Poland

ARTICLE INFO

Article history:
Received 30 January 2018
Received in revised form 28 May 2018
Accepted 30 May 2018

Keywords:
Experimental research
Viscosity
mPCM slurry
Micronal® DS 5039 X
Steady state
Non-steady state

ABSTRACT

The use of microencapsulated phase change materials (mPCM) is one of the most efficient ways of storing thermal energy. Microencapsulated phase change slurry (mPCM slurry) is formed when the microencapsulated phase change material is dispersed into the carrier fluid. The mPCM slurry can be used as a heat transfer medium.

This paper details an experimental study that was performed to investigate rheological properties of microencapsulated phase change slurry (Micronal® DS 5039 X – water). Six samples of mPCM slurry were prepared with different mass ratios of mPCM to water, namely: 10:90, 30:70, 50:50, 70:30, 90:10, 100:0 (pure Micronal® DS 5039 X). The dynamic viscosity-shear rate curves were obtained for spindle speeds from 0.01 to 100 rpm (shear rate 0.0132–132.00 s^{-1} respectively). The steady state measurement of viscosity was carried out when the slurry reached constant temperatures, namely: 10.0; 15.0, 17.5, 20.0, 22.5, 25.0, 27.5, 30.0, 40.0 and 50.0 °C.

The dynamic viscosity of slurries increases with the mPCM concentration in dispersion rises. Only the sample of 10% mPCM may be considered as a Newtonian fluid within the test range (shear rate 0.0132–132.00 s^{-1}). Increasing the shear rate ultimately causes viscosity to decrease down to the Newtonian plateau, where it seems to be constant. The higher the temperature of the slurry, the lower the shear rate value, after which the viscosity characteristic becomes linear or constant. The same principle applies to mass ratio. In vicinity of the melting point (about 25 °C) the phase change process of mPCM slurry does not influence the viscosity-shear rate characteristic behavior when steady state conditions are preserved.

The non-steady state condition was also examined, more specifically, the temperature of the sample was increased continuously at a steady pace from 16 °C to 29 °C. This stage took 17 min with each data point collected at 15 s intervals. During a non-steady state temperature increase, near melting point, the viscosity of the slurry clearly departed from those values observed in steady states. It can therefore be concluded that around the melting point temperature, the phase change process of mPCM slurry influences the viscosity.

1. Introduction

With the increasing ecological awareness of society, there is a growing interest in obtaining energy from renewable sources such as wind or solar energy. A characteristic feature of these sources is the limited availability in terms of time (day and night cycle, low wind periods). Extensive work has been done on the efficient storage of energy both in the form of electricity and heat. One of the ideas behind heat accumulation is the utilization of latent heat in phase-change materials (PCM), which are characterized by a high value of phase heat transfer. When converting from a solid to a liquid state, the PCM material receives heat. This heat is released during re-conversion, i.e. from the liquid to the solid state. Large tanks filled with variable-phase material are used for the storage of heat (heat accumulators). The disadvantages of large heat accumulators are the non-uniform front of the moving phase boundary and the inability to uniformly melt the material throughout its volume. In addition, during heat transfer, the PCM undergoes solidification on the heat exchange surface, making it difficult for heat exchange to occur through the liquid material away from the exchanger walls. This problem was partly solved in the 1940s [1] when, at the National Cash Register Corporation, an attempt was made to place phase-change material inside capsules. The use of a medium in which the capsules were suspended enabled a more uniform heat transfer and phase-change processes.

---

* Corresponding author.
E-mail address: jacek.fiuk@tu.koszalin.pl (J.J. Fiuk).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.158
0017-9310/© 2018 Elsevier Ltd. All rights reserved.

In this manner, the heat exchange surface between the heat accumulator filling and working medium is increased. In addition, capsules made from natural or synthetic polymers comprise a coating that protects against chemical interaction between both the PCM material and the material from which heat exchangers and heat storage units are built. The closing of the phase-change material into capsules limits changes in volume due to temperature or concentration changes and prevents the formation of undesirable effects such as foaming, sedimentation or coagulation.

1.1. Microencapsulated phase change material slurry (mPCM slurry) as a latent functional thermal fluid

Technological advancements have made mass production of capsules with a diameter of the order of micrometers available today. Hence, flow is possible not only for an intermediary fluid, but the whole dispersion of base fluid and microcapsules filled with phase-changing material. Intensive research has been undertaken to determine the thermal properties and flow characteristics of microencapsulated Phase Change Material Slurries (mPCM slurry), which are classified as Latent Functional Thermal Fluid (LFTF) [2]. LTFT is a two-phase working fluid used in heat exchange systems and is characterized by a greater heat transfer capacity (by latent heat in the phase transition temperature range) compared to conventional single-phase fluids. In addition to mPCM slurry, LFTF may include, but is not limited to, ice slurries or emulsions consisting of PCM particles added directly to the base fluid. For example, correlations for calculating flow resistance and heat transfer coefficient based on the results of our own experiments regarding the flow of ice suspension in a horizontal pipe length of 4.596 m and an inner diameter of 24.0 mm are described in [3]. The effect of the ice fraction and Reynolds number on the local velocity distribution in the rectangular channel were the subject of the research described in [4]. The effect of the mass fraction of ice in an inner channel of 7.5 mm in diameter and 1 m in length is described in [5]. In their work, Wang et al. [6] presented a mathematical model for calculating the pressure drop of heterogeneous ice slurry flow in horizontal pipes. To verify the model, they used results of the experimental studies of other authors. Thermophysical properties, such as viscosity and heat of fusion for emulsion consisting of organic PCM (RT10) and water, are described in a research paper by Shao et al. [7]. The thermophysical properties of nano-sized particles of tetradecane, hexadecane and octadecane as the dispersed PCM in water were the subject of the work of Kawanami et al. [8]. Paraffin flow properties in a laminar flow and the phenomenological model are presented in [9]. Delgado et al. [10] show that the measured heat transfer coefficient was about 3.5–5.5 times higher when a speed of 290–600 rpm is used in a PCM emulsion. The thermal and rheological properties of emulsion consisting of n-octadecane as PCM nanoparticles with the mass ratio to water and surfactant: 10:90:2, 20:80:2, 30:70:2, 40:60:2 were measured by [11], while shear thinning behavior was clearly observed. In another study [12], the method of preparation and the results of research on the thermo-physical and transport properties of emulsions containing nano-sized PCM (n-hexadecane and n-octadecane) have been described. Moreover, the viscosity, phase change temperature and latent heat of five types of hydrocarbon and wax phase slurries have been tested by Chen et al. [13].

MPCM slurries offer many advantages and can be used either as thermal storage materials or heat transfer fluids due to: (1) their high storage capacity during phase change; (2) the possibility of using the same medium either to transport or to store energy, as these slurries are pumpable (thus reducing heat transfer losses); (3) heat transfer at an approximately constant temperature; (4) a high heat transfer rate due to the elevated ratio surface/volume; (5) a lower pumping power, as a consequence of the reduction in mass flow due to the higher heat capacity; (6) a better heat exchange than conventional heat transfer fluids, due to the decrease in fluid temperature as a consequence of the higher heat capacity. Furthermore, these novel fluids have a more advantageous thermal energy storage density than conventional systems of sensible heat storage in water, and can compete with macroencapsulated PCM tanks. Moreover, the response time may be shorter using these PCM emulsions or mPCM slurries as a storage material than with macro-encapsulated PCM. The tanks will be simpler as there is no need to macroencapsulate, thus conventional tanks can be used [14].

1.2. Previous study on mPCM slurry viscosity

Chen et al. [15] developed a slurry containing 5-μm-sized n-eicosane particles and water. This slurry, with a melting temperature of 36.4 °C, was made with low-weight ratios, i.e., 10% and 20%. The dedicated viscosity measurement indicated that the slurry behaved as a Newtonian fluid [16].

Both experimentally and numerically, Zeng et al. [17] investigated the convective heat transfer characteristics of mPCM slurry flowing in a circular tube. The mPCM slurry was made of microencapsulated 1-bromohexadecane (C16H33Br) and pure water. The mass fraction of mPCM was 5.0, 10.0 and 15.8% respectively. Viscosity was measured by a rheometer (MCR300 SN357142). The mPCM slurry (5.0 wt% and 10.0 wt%) can be considered as a Newtonian fluid along with the mPCM slurry (15.8 wt%) after the 600 s^{-1} shear rate because the dynamic viscosity values are constant as the shear rate changes.

Zhang and Zao [18] experimentally investigated the thermal and rheological properties of a series of prepared mPCM slurries fabricated by dispersing microencapsulated PCM into water with an appropriate amount of surfactant. The mass ratio of mPCM to water and surfactant was 10:90:1, 25:75:1, 35:65:1, respectively. The mPCM slurry can be considered as a Newtonian fluid when the shear rate is higher than 200 s^{-1} and the PCM microcapsules' mass fraction lower than 35 wt%. The viscosity was higher for larger particle slurries.

Delgado et al. [14] experimentally investigated the microencapsulated PCM slurry with three different PCM mass fractions (14, 20 and 30%). The studied mPCM slurry consisted of microcapsules of paraffin coated by a polymer and dispersed in water through detergents. These PCM microcapsules had a diameter range from 1 to 20 μm. The viscosity–shear rate curves using a control stress rheometer were obtained through a shear sweep from 0.001 to 1000 s^{-1} and at a constant temperature ($T = 27\ °C$). The equation that best predicts the shape of the flow curve for the three mPCM slurries is the non-Newtonian model, namely the Carreau model.

Allouche et al. [19] investigated the 45% w/w aqueous dispersion of RT15 paraffin microcapsules supplied by CIBA chemicals (UK) while a rheological rotational rheometer (UM/MC 100 PHYSICA) was used. Experiments were performed applying constant shear rates from 10 to 500 s^{-1}. Tests were repeated in a temperature range of 7–20 °C. The rheological study revealed a non-Newtonian fluid behavior of the PCM for different temperature settings.

Kong et al. [20] used mPCM slurries produced by Thies Technology Inc. as heat transfer fluids. The phase change material (PCM) used in the study was butyl stearate. Each microcapsule was made by encapsulating the PCM using polyurea as a shell material, which made up about 35% of the total volume of each microcapsule. The MPCM particle size range used in the experiments was between 5 and 10 μm in diameter. The apparent viscosity of mPCM slurries was measured using a coaxial rotating drum viscometer from Brookfield Engineering Laboratories Inc. Microencapsulated PCM