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Phenomenological model of binary-series viscosity for analysing rheological properties of a paraffin using validated experiments

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ABSTRACT

This paper presents a theoretical and experimental study on the rheological behaviours of a grade of paraffin that is intended for use in environmental control systems for the purpose of thermal storage. This research concentrates on the paraffin flow properties in a laminar flow. In the experiments, when the paraffin temperature is greater than 291.15 K, the rheological behaviours of the paraffin obey the power-law principles. However, as the paraffin temperature reduces to 291.15 K or lower, the behaviour index tends to decrease with the shear rate, and thus, the rheological behaviours of the paraffin cannot be defined by the power-law model effectively. In the non-power-law phase, the solid properties of the material become increasingly apparent as the temperature gradually reduces. Simultaneously, the paraffin fluidity decreases. Therefore, a new phenomenological model of binary-series viscosity is proposed. The binary model provides an effective definition of the rheological properties of the paraffin in the non-power-law phase (the corresponding material temperatures range from 291.15 K to 288.15 K). In general, the paraffin-specific pressure drop in a horizontal pipe is approximately 1.4–6.0 times that of water at the same temperatures.

Modélisation phénoménologique de la viscosité en série binaire pour analyser les propriétés rhéologiques d'une paraffine en effectuant des expériences validées

Mots clés : Propriété rhéologique ; Modélisation phénoménologique de séries binaires ; Viscosité ; Modélisation en loi de puissance ; Paraffine

1. Introduction

Thermal energy storage is an important method that can be used to bridge the gap between the demand and supply of thermal energy (Cunha and Eames, 2016; Li and Zheng, 2016). Paraffin wax, a typical composite phase-change material (PCM), is recognized as a prospective material for use in environmental control systems (ECSs) (Falco et al., 2016; Moreno et al., 2014). However, an apparent disadvantage of paraffin is its low thermal

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Nomenclature

D	diameter [m]
f	fanning factor [–]
F	function [–]
K	consistency coefficient [kg m^{-1} s^{m-2}]
L	length [m]
m	rheological behaviour index [m = 1/n]
n	rheological behaviour index [n = 1/m]
p	pressure [Pa]; gain factor [–]
r	inner radius [m]
R	inner radius of circular tubes [m]
Re	Reynolds number [–]
t	time [s]
T	temperature [K]
u	flow velocity [m s^{-1}]
U	flow velocity in pipes [m s^{-1}]
V	volume [m^3]

The Greek letters

γ	shear rate [s^{-1}]
Δ	difference value [–]
ε	Newtonian factor [–]
ζ	dimensionless inner radius [–]
η	viscosity [kg^n m^{-n} s^{-2n-1}]
μ	dynamic viscosity of water [kg m^{-1} s^{-1}]
π	circumference ratio [–]
ρ	density [kg m^{-3}]
τ	shear stress [Pa]

Subscripts

p	solid property [–]
y	yielding [–]
∞	infinite [–]
m	mean value [–]
W	wall of tubes [–]
In	inner [–]

conductivity coefficient (Wang et al., 2016). Over the past two decades, several efforts have been made to enhance the thermal conductivity coefficient of paraffins (Li et al., 2016; Sari, 2004; Wang et al., 2016; Zhang and Fang, 2006).

Several scholars have been attempting to improve the heat transfer properties of PCMs through the use of additives like exfoliated/expanded graphite (Sari and Karaipekli, 2007; Tian et al., 2015), graphite powder (Azeem and Abdein, 2012; Li, 2013), carbon fibre (Nomura et al., 2016; Tian et al., 2016), carbon nanotubes (Ji et al., 2012; Xing et al., 2015), graphene (Harish et al., 2015; Park and Kim, 2014), metal foams (Thapa et al., 2014; Xiao et al., 2014), metal nanoparticles (Nemade and Waghuley, 2016; Nourani et al., 2016), and metal salts (Fauzi et al., 2014; Sharma et al., 2011). Furthermore, much research has been focused on the applications of phase change slurries (PCSs) that are prepared from PCMs and carried fluids (Kong et al., 2016; Paloma et al., 2015). In PCSs, both the sensible heat capacity of the carrier fluids (generally water) and the latent heat capacity of the PCMs can be used. Generally, these materials are non-Newtonian fluids. Their flow properties are always determined using the fluid temperatures and mass fraction of the PCMs in the fluids (Huang and Petermann, 2015; Zhang et al., 2016). To ensure desired fluidity of the PCSs, the mass fraction of the PCMs is always maintained in the range of 10–30 wt% (Huang and Petermann, 2015; Huang et al., 2009, 2010).

In 2009, Ho and Gao (2009) prepared a nanoparticle-in-paraffin emulsion by emulsifying alumina (Al_2O_3) and n-octadecane. They investigated its thermo-physical properties and discovered that the measured thermal conductivity and dynamic viscosity for the emulsions showed a nonlinear increase with the increase in the mass fraction of the nanoparticles. In 2010, Huang et al. (2010) presented a paraffin-based emulsion consisting of water as the continuous phase and paraffin as the dispersed phase. Thereafter, they studied its heat capacity in an experimental setup with 30 wt% paraffin (Huang et al., 2010). Recently, it was discovered in an experimental research (Huang and Petermann, 2015) that the PCS viscosity rises rapidly as the dispersed paraffin begins to congeal. In addition, an emulsion containing 30 wt% paraffin would cause 1.5–3 times the pressure drop observed in water at a flow rate of 0.5–1.0 m·s^{-1} in the laminar flow region.

In 2005, Darbouret et al. (2005) detailed the rheological behaviours of a tetra-n-butyl ammonium bromide (TBAB) hydrate slurry, and a Bingham behaviour was observed in the laminar regime. Further, in 2011, Kumano et al. (2011) investigated the flow properties of the slurry. The experimental results indicated that the ratio of the coefficients of pipe friction increased with the increase in the solid fraction, and the rate of increase was high in the case of a low Reynolds number in a laminar flow. Moreover, the flow properties of the measured slurry were determined using the pseudo-plastic fluid model. In 2007, Poole and Ridley (2007) detailed a developing pipe flow of inelastic non-Newtonian fluids obeying the power-law model. The numerical analyses demonstrated that the development length was a function of the power-law index at low Reynolds numbers. Even earlier, in 1998, Royon et al. (1998) studied the thermo-rheological behaviours of a TBAB hydrate slurry. They noticed that the rheological behaviour of the material obeyed a power law model in which the parameters were temperature dependent. More importantly, the temperature dependence of the viscosity exhibited a slight increase near 282.65 K, corresponding to the phase-change temperature. The authors attributed the deviation to the variation in the particle state near the phase-change temperature. In 2012, Kumano et al. (2012) observed two constant coefficients of pipe friction and heat transfer in experiments. The values thus obtained were the same as those for the turbulent flow of the TBAB solution in the low solid-fraction region. For the high solid-fraction region, however, a laminarization phenomenon occurred, and both the flow and heat transfer characteristics could be estimated from the laminar flow of the hydrate slurry. Moreover, the laminarization point for the solid fraction could be predicted using the apparent Reynolds number.

Nevertheless, in a pumped system, both the phase separation and demulsification of the PCSs occur after multiple circulations. In general, these degradations are irreversible, and the PCSs become unsuitable for thermal energy storage and release. Hence, this paper presents a new approach with the use of a PCM (paraffin only, without water) to only transfer and store (release) thermal energy. Parts of the latent heat capacity