Energy 107 (2016) 482–492

Contents lists available at ScienceDirect

Energy

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

Novel copper – Propylene glycol nanofluid as efficient thermic fluid for potential application in discharge cycle of thermal energy storage

R. Yedhu Krishnan [1], S. Manikandan [1], K.S. Suganthi, V. Leela Vinodhan, K.S. Rajan*

Centre for Nanotechnology & Advanced Biomaterials (CeNTAB), School of Chemical & Biotechnology, SASTRA University, Thanjavur 613401, India

ARTICLE INFO

Article history:
Received 24 December 2015
Received in revised form
31 March 2016
Accepted 9 April 2016
Available online 4 May 2016

Keywords:
Energy recovery
Copper nanoparticles
Nanofluid
Thermal conductivity
Discharge cycle
Constant temperature

ABSTRACT

Nanofluids are promising heat transfer fluids for a wide range of energy management applications. Probe ultrasonication-mediated preparation of copper – propylene glycol nanofluid is accomplished through dispersion of biosurfactant-functionalized copper nanoparticles in propylene glycol. Copper – propylene glycol nanofluids are colloidally stable; retain their thermal conductivity enhancement despite repeated heating–cooling cycles and storage for more than 15 days. These nanofluids exhibit temperature-independent thermal conductivity enhancement, with about ~11% enhancement for 1 vol % nanofluid, attributable to Brownian motion and interfacial layering. The viscosity of nanofluids is lower than that of base fluid (propylene glycol) due to interactions between biosurfactant and propylene glycol. Our data clearly demonstrate that the use of 1 vol % copper – propylene glycol nanofluid as coolant can lead to 13.2% improvement in the rate of energy recovery from a constant-temperature hot bath when the heat transfer resistance in the hot fluid side is low. The results of the present study have implications for energy management in solar thermal systems.

1. Introduction

Heat transfer fluids with higher thermal conductivity, lower viscosity and higher specific heat are required to achieve enhanced heat removal rates from heat sources for energy recovery and sustainable performance of devices. The rate of heat removal from a constant temperature source, as in the case of condensation of vapors and freezing of liquids, depends on the thermophysical properties of the coolant, flow conditions and the geometry of heat exchanger. Latent heat storage using phase change materials is a well-established technique to store abundant solar energy during its availability in the day and utilize the same when the energy demand exceeds solar energy collection [1,2]. The recovery of latent heat stored in phase change materials is accomplished during discharge cycle through the use of a heat transfer fluid. Hence, the efficiency of discharge cycle can be improved through the use of heat transfer fluids with superior thermophysical properties.

Nanofluids are two-phase colloids comprising a nanomaterial with particle size ≤100 nm dispersed in a liquid [3]. Nanofluids are well-known engineered heat transfer fluids [4–6] owing to their improved thermal conductivity. A considerable amount of work has been reported on noble metal-based nanofluids such as silver-based nanofluids [7–11], gold-based nanofluids [12–16] and transition metal based nanofluids such as iron-based nanofluids [17,18], copper-based nanofluids [19–23] and nickel-based nanofluids [24,25]. The thermal conductivity of copper – ethylene glycol nanofluids has been reported [26,27] with varying degrees of thermal conductivity enhancements depending on the nanoparticle size, method of nanoparticle preparation and strategy employed for nanofluid formulation. While 40% enhancement in thermal conductivity was reported at 0.3 vol % of nanoparticles for copper – ethylene glycol nanofluid prepared by one-step method [27], the nanofluid prepared by two-step method using PVP (poly(vinylpyrrolidone)) as surfactant followed by ultrasonication resulted in 50% thermal conductivity enhancement at 0.5 vol % [26]. The use of copper – ethylene glycol nanofluid in solar plate collector has resulted in improvement of solar energy collection efficiency with increasing nanoparticle concentration [28]. It is reasonably well-established that the nanofluids enhance heat transfer through improved thermal conductivity, particle migration and thermal dispersion effects. The use of nanofluids can lead to a reduction in coolant inventory or size of the heat exchanger due to higher heat transfer coefficients and heat transfer rates achievable.

* Corresponding author. Tel.: +91 9790377951; fax: +91 4362 264120.
E-mail address: ksrajan@chem.sastra.edu (K.S. Rajan).

[1] Equal contribution.

http://dx.doi.org/10.1016/j.energy.2016.04.047
0360-5442/

Nomenclature

A	heat transfer area (m^2)
C_p	specific heat (J/kg K)
D_p	particle size (m)
g	acceleration due to gravity (m/s^2)
h	heat transfer coefficient (W/m^2 K)
h_i	test fluid side heat transfer coefficient (W/m^2 K)
h_o	hot fluid side heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/mK)
k_B	Boltzmann constant = 1.381×10^{-23} (J/K)
m	mass of test fluid (kg)
Mo	Mouromtseff number (−)
Nu	Nusselt number (−)
Q	amount of heat transferred (W)
Ra	Rayleigh number (−)
T	temperature of test fluid (°C)
t	temperature of hot fluid (°C)
t_w	wall temperature (°C)
U	overall heat transfer coefficient (W/m^2 K)
U_{pa}	total measurement uncertainty for parameter 'pa'
$U_{pa,A}$	uncertainty in the measurement of parameter 'pa' due to random error
$U_{pa,B}$	uncertainty in the measurement of parameter 'pa' due to systematic error
$\%U_{pa}$	percentage uncertainty for parameter 'pa'
u_B	Brownian velocity (m/s)
u_t	Terminal settling velocity (m/s)
V	volume of test fluid (m^3)

Greek symbols

ϕ	nanoparticle volume fraction (−)
μ	viscosity (mPa.s)
θ	time (s)
ρ	density (kg/m^3)
σ	standard deviation

Subscripts

bf	base fluid
f	fluid
i	inside
n	number of repeated measurements
nf	nanofluid
np	nanoparticle
o	outside
p	particle
pa	any parameter like thermal conductivity, viscosity, etc.
r	ratio

In addition, the use of low-viscous and high-thermal conductivity nanofluids improves heat removal rate and reduces the pumping power, leading to overall increase in energy efficiency. It is relevant to mention that though the use of nanofluids constitutes a passive method of heat transfer intensification, heat transfer performance can be augmented through the use of external fields also. The influence of external magnetic field, electric field and thermal radiation on heat transfer performance of nanofluids has been reported recently through numerical investigations in a variety of geometries, flow and boundary conditions [29–47]. KKL (Koo-Kleinstreuer-Li) correlation has been successfully utilized for estimation of nanofluid thermal conductivity and viscosity in a number of numerical investigations [30,31,33,41,44–46]. Nusselt number has been predicted to increase with increase in nanoparticle concentration [29,31,32,35,39,40,43,45,47] even in the presence of an external magnetic field and thermal radiation. The capability of external magnetic field to influence the flow field has been demonstrated numerically [36]. The application of non-uniform electric field has been shown to augment heat transfer performance of Fe_3O_4-ethylene glycol nanofluid [38]. The numerical study of heat transfer performance of Cu-water nanofluid under natural convection has revealed a reduction in heat transfer enhancement and enhancement of the dimensionless entropy generation number with increase in Rayleigh number [37,44].

Propylene glycol is non-toxic coolant and is considered as an alternative to ethylene glycol. The thermal conductivity of propylene glycol needs to be augmented to overcome its inherent lower thermal conductivity in comparison to that of ethylene glycol. When metal nanoparticles of high thermal conductivity such as copper nanoparticles are dispersed in propylene glycol leading to copper-propylene glycol nanofluid, considerable enhancement in thermal conductivity can be expected. However, there are no reports on transport properties of metal-propylene glycol based nanofluids in literature, despite the significance of propylene glycol for its non-toxic nature and ease of synthesis of metal nanoparticles. Hence, the present work focuses on the preparation, characterization and heat transfer performance of copper-propylene glycol nanofluid. The utilization of functionalized nanoparticles during nanofluid preparation results in nanofluids with long-term stability [48]. Hence, functionalized copper nanoparticles have been used in the present work.

The aspects of the novelty of the present work include (i) the use of biosurfactant for functionalization of copper nanoparticles and preparation of copper − propylene nanofluid thereof, protecting the nanoparticles from aggregation as well as oxidation. Metallic nanoparticles tend to undergo oxidation upon contact with polar liquids. However, the use of biosurfactant has prevented the metallic nanoparticles from undergoing oxidation despite repeated heating and cooling cycles; (ii) the assessment of heat transfer performance of copper − propylene glycol nanofluid under natural convective conditions for heat removal from a constant temperature source. During the discharge cycle of thermal energy storage systems, latent heat removal is accomplished by the phase change material at a constant temperature. The use of copper-propylene glycol as the heat transfer fluid is likely to improve the energy recovery in such systems; (iii) study of the influence of heat transfer resistance of the constant temperature source on the degree of enhancement in energy recovery achievable through use of copper − propylene glycol nanofluid. The constant temperature sources (constant temperature liquid baths) were chosen in such a way that one bath fluid (Therminol 55) has higher heat transfer resistance than propylene glycol and copper − propylene glycol nanofluids while the other (water) has much lower heat transfer resistance. This facilitated the assessment of improvement in energy recovery during the discharge cycle of thermal energy storage systems of different thermophysical properties.

In summary, the uniqueness of the present work stems from the preparation, characterization and assessment of the potential for energy recovery applications of copper − propylene glycol nanofluid, a nanofluid system that has not been studied so far, except for lifetime and corrosion behavior of uncapped copper nanoparticles [49].