International Journal of Heat and Mass Transfer 126 (2018) 1168–1176

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Specific heat of aluminum-oxide nanolubricants

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ARTICLE INFO

Article history:
Received 27 March 2018
Received in revised form 13 June 2018
Accepted 14 June 2018

Keywords:
Air conditioning
Density
Lubricant
Nanofluid
Nanoparticles
Specific heat

ABSTRACT

This paper presents specific heat measurements for a synthetic polyolester (POE) based aluminum oxide (Al_2O_3) nanolubricant with a polymeric surfactant over a temperature range from approximately 4 °C to 45 °C. Al_2O_3 nanolubricants with two nominal surface-area-based diameter nanoparticles were investigated: 20 nm and 40 nm. The number-based diameter of the nanoparticles, as determined by dynamic light scattering (DLS), were 112 nm and 148 nm, respectively. The nanoparticle mass fractions were varied from 0.076 to 0.249 for the 112-nm diameter nanolubricant, and from 0.059 to 0.394 for the 148-nm diameter nanolubricant. The measurements showed that the specific heat of the nanolubricant linearly increased with increasing temperature, and linearly decreased with respect to increasing nanoparticle mass fraction. The size of the nanoparticle was shown to have no effect on the magnitude of the specific heat of the nanolubricant. The measurements were compared with two existing models. The mass fraction weighted model exhibited excellent agreement with the measurements (within ±1.01%). In contrast, the volume mass fraction model failed to predict the measurements for most conditions to within ±5%.

1. Introduction

Heating, ventilation, air conditioning and refrigeration (HVAC&R) is a major energy consumption sector for most developed and some developing countries of the world. For this reason, researchers continue the quest for cost effective methods for improving the energy efficiency of HVAC&R equipment. The use of nanolubricants in chillers is a novel technique with the goal of increased efficiency. Compared with the neat lubricant, nanolubricants have beneficial properties that can improve heat transfer [1]. For example, Kedzierski [2] has shown that an aluminum-oxide (Al_2O_3) nanolubricant can improve the pool-boiling heat transfer of a refrigerant/lubricant by as much as 155%. Similarly, Bigi et al. [3] also reported a 35% improvement of the refrigerant/lubricant convective boiling heat transfer coefficient by using Al_2O_3 nanolubricants in place of the base lubricant while having a small effect on pressure drop. In addition, nanolubricants have better tribological performance due to the "ball bearing" effect, thereby leading to a higher compressor efficiency [4,5]. Thus, nanolubricants have a significant potential for increasing the energy efficiency of HVAC&R equipment.

The specific heat (C_p) is a primary thermophysical property for thermal design. For example, the specific heat is essential for calculating single-phase heat transfer rates [6]. Moreover, nearly all turbulent single-phase convective flow and flow-boiling correlations include the Prandtl number ($Pr = \mu C_p/\lambda$), and some include the thermal diffusivity ($\alpha = \lambda/\rho C_p$) [7,8], which both require the C_p. The specific heat can also be used to calculate other properties such as the thermal expansion coefficient and the isothermal compressibility [9]. Therefore, nanolubricant specific heat measurements and corresponding models are required for the application of nanolubricants to HVAC&R equipment and other heat transfer applications.

Unfortunately, the available data for the specific heat of nanolubricants is limited. Only two studies were found in the literature that present measurements for the specific heat of nanolubricants. In the first study, Cremaschi et al. [10,11] measured the specific heat of two Al_2O_3/polyolester (POE) nanolubricants with nanoparticle mass fractions of 10% and 20% for five temperatures ranging from approximately 10 °C to 40 °C. They showed that the specific heat of the nanolubricant increased with temperature, but decreased with nanoparticle mass fraction. The Cremaschi et al. [10,11] study did not report the mass fraction of the surfactant, and was limited to a single base lubricant (RL32H[1]), with the

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[1] Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.077
0017-9310/Published by Elsevier Ltd.

Nomenclature

English symbols

A_n	constants in Table 1, $n = 1, 2$
B_n	constants in Eq. (6), $n = 1, 2, 3, 4, 5$
C_p	specific heat [kJ kg^{-1} K^{-1}]
D_p	nominal diameter of nanoparticles [nm]
D_p0	primary diameter of nanoparticles [nm]
k	ratio of the mass of surfactant to that of nanoparticles
M	molecular mass [kg mol^{-1}]
m	mass [kg]
Pr	Prandtl number
q	heat flow [W]
T	temperature [°C or K]
t	time [s]
$U_\mathrm{r,Cp}$	expanded uncertainty of specific heat [%]
$U_\mathrm{r,xn}$	expanded uncertainty of nanoparticle mass fraction [%]
x	mass fraction

Greek symbols

α	thermal diffusivity [m^2 s^{-1}]
γ	Al_2O_3 nanoparticle crystal phase [–]
δ	Al_2O_3 nanoparticle crystal phase [–]
ρ	density [kg m^{-3}]
ϕ	volume fraction
μ	dynamic viscosity [Pa s]
λ	thermal conductivity [W m^{-1} K^{-1}]

Subscripts

L	lubricant
Ls	lubricant/surfactant mixture
m	mixture
np	nanoparticles
s	surfactant

Abbreviation

DLS	dynamic light scattering
HVAC&R	heating, ventilation, air conditioning and refrigeration
NIST	National Institute of Standards and Technology
POE	polyolester

Al_2O_3 nanoparticles consisting of a single gamma phase. In the second study, Lue et al. [12] measured the specific heat of a Al_2O_3 nanolubricant for vacuum pump applications for five nanoparticle mass fractions ranging from 0.1% to 1.6%. The specific heat of the Al_2O_3 nanolubricant was also shown to decrease with nanoparticle mass fraction. The Lue et al. [12] study limited to a specific vacuum-pump-oil base lubricant and it neglected to report the phase of the Al_2O_3 nanoparticles. Measurements of the specific heat for nanofluids other than nanolubricants are more numerous and have been made with base fluids like water [13–16], water/ethylene glycol [16–19], ethylene glycol [19,20], and molten salt [21,22]. As indicated by the above literature, the specific heat of a nanolubricant can be affected by temperature, nanoparticle mass fraction, and surfactant characteristics.

The objective of the present study is to expand on the specific heat database for Al_2O_3 nanolubricants by measuring the influence of temperature, nanoparticle size and mass fraction, and surfactant properties on the specific heat of several Al_2O_3 nanolubricants for a wide range of test conditions. This was done for a base lubricant and Al_2O_3 nanoparticles that differed from the ones used by Cremaschi et al. [10] and Lue et al. [12]. In addition, the present study reports the mass fraction of the surfactant in the nanolubricants, and the study aims to assess existing predictive methods for the specific heat of the Al_2O_3 nanolubricants.

2. Measurements

2.1. Test nanolubricants

The nanoparticles for the test nanolubricants were Al_2O_3 with crystal phase of 70% δ and 30% γ. The base lubricant for the nanolubricants was RL68H, a synthetic polyolester commercial chiller lubricant. A proprietary polymeric surfactant[2] was used to disperse the nanoparticles in the RL68H. Two different nanoparticle nominal, surface-area based diameters (D_p0) were used, 20 nm and 40 nm, as reported by the manufacturer. For each diameter, a concentrated nanolubricant made by a manufacturer was diluted by adding different masses of neat lubricant to provide five nanolubricants with varied nanoparticle mass fractions. The dilution process was performed by stirring the mixtures along with ultrasonication for approximately 24 h. The ratios of the mass of the surfactant to that of the nanoparticles (k) were approximately 0.3125 and 0.25 for the diameters 20 nm and 40 nm, respectively, and remained constant with the dilution process.

The size of the nanoparticles in the lubricant were measured with a dynamic light scattering (DLS) technique using a number-weighted basis. For spherical nanoparticles, the number-weighted DLS measurement more closely represents the average overall diameter than does the surface-area weighted basis because each nanoparticle diameter is equally weighted [23]. The DLS measurements were performed with a commercial instrument with a reported uncertainty of ±2%. All measurement uncertainties reported in this paper are for a 95% confidence level. The manufacturer's uncertainty was verified by using a NIST-traceable 60 nm ± 2.7 nm nanofluid standard. The measured diameter of the standard with the DLS instrument was 64 nm ± 5 nm, which coincides with the uncertainty range of the standard. Fig. 1 shows the number-weighted size distributions for the two undiluted nanolubricants. The number-weighted size gives each nanoparticle equal weight in determining the average, while the surface-area weighting more heavily weights nanoparticles with larger surface area. The surface-area weighted evaluation is more valuable than the number-weighted evaluation to a manufacturer of dispersions because it gives a better indication for the quantity of surfactant required to cover the surface of all the nanoparticles. The average diameters on number-weighted basis (D_p) were 112 nm and 148 nm, respectively. The width at half of the peak number percentage was roughly 29 nm for $D_\mathrm{p} = 112$ nm (i.e., $D_\mathrm{p0} = 20$ nm), and was 33 nm for $D_\mathrm{p} = 148$ nm (i.e., $D_\mathrm{p0} = 40$ nm). Potentially, a small portion of the difference between the DLS sizing and that of the manufacturer may be due to aggregation.[3] Nevertheless, similar differences between the present investigator's number-weighted measurements and the manufacturer's surface-area based technique have been experienced in previous investigations [23–25].

As reported by the manufacturer, the nanoparticle mass fractions for the undiluted nanolubricants were 0.249 and 0.394 for

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[2] Due to the proprietary nature of the surfactant (Nanophase Technologies R&D product code R1103RL68H), no property information can be provided here.

[3] No particle settling was observed for the approximate month of testing, and the dispersion was believed to be stable based on this observation and the DLS measurements.