Applied Thermal Engineering 128 (2018) 973–981

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

# Experimental study and Taguchi Analysis on alumina-water nanofluid viscosity

Elif Begum Elcioglu [a,b], Almila Guvenc Yazicioglu [a,*], Alpaslan Turgut [c], Ahmet Sermet Anagun [d]

[a] Middle East Technical University, Department of Mechanical Engineering, 06800 Ankara, Turkey
[b] Eskisehir Osmangazi University, Sivrihisar Vocational School, Mechanics Program, Sivrihisar, Eskisehir, Turkey
[c] Dokuz Eylul University, Department of Mechanical Engineering, Tinaztepe Campus, 35397 Buca, Izmir, Turkey
[d] Izmir University of Economics, Department of Industrial Engineering, 35330 Balcova, Izmir, Turkey

## HIGHLIGHTS

- Temperature, nanoparticle fraction and diameter dependent nanofluid viscosity data.
- Experiments were planned and data were analyzed using Taguchi Method.
- Temperature & concentration interaction effect is significant on nanofluid viscosity.

## ARTICLE INFO

*Article history:*
Received 9 December 2016
Revised 21 July 2017
Accepted 3 September 2017
Available online 9 September 2017

*Keywords:*
Nanofluids
Viscosity
Alumina-water
Taguchi Method
Design of experiments

## ABSTRACT

Nanofluids as dispersions of fine particles within industrial fluids have potential in thermal applications due to their improved thermal characteristics. On the other hand, their viscosity may be a limitation for forced convective heat transfer, since increase in viscosity increases the pump power requirement. In this study we report experimental results for alumina-water nanofluid viscosity at different temperatures, for different nanoparticle fractions and diameters. Experimental data were collected based on a Taguchi experiment design (L8). Statistical analyses via Taguchi Method were done to determine the effects of experiment characteristics on nanofluid viscosity and relative viscosity. The viscosity of nanofluids decreased sharply with temperature (20–50 °C); increased with nanoparticle fraction (1–3 vol%), and increased slightly with nanoparticle diameter (10 ± 5 nm, 30 ± 10 nm). Taguchi Analysis revealed that the importance of the parameters on nanofluid viscosity can be sorted from lower to higher sequence as temperature, nanoparticle fraction, and nanoparticle diameter; and they were all statistically significant on nanofluid viscosity. One novel conclusion is that the interaction effect of temperature and nanoparticle volumetric fraction was significant on nanofluid viscosity at $\alpha = 5\%$, thus the effect of nanoparticle fraction was different at different temperatures, and vice versa. This interaction effect appeared in the developed nanofluid viscosity equation with a novel term, the product of temperature and nanoparticle fraction. This result may be beneficial for hydrodynamic applications, where the thermal aspects and flow characteristics need to be considered simultaneously.



## 1. Introduction

Nanofluids can be defined to be engineered materials composed of nanoparticles, base fluid(s), and optional dispersants/surfactants. Choi and his co-workers defined nanofluids as innovative new class of fluids combining metallic nanoparticles and conventional heat transfer fluids [1]. Improvements obtained in the convective heat transfer coefficient of nanofluids has directed their use primarily in heat transfer applications, but nanofluids still hold potential for use in other fields. Similar to the increments heat transfer coefficient, viscosity of nanofluids is shown to be greater than those of the base fluids. For the analysis of nanofluid flow, hydrodynamic nature of the flow must be considered along with the thermal aspects. For a fully developed laminar flow in a circular tube, from an axial position of $x_1$ to $x_2$, the pressure drop, $\Delta p$ [2] can be defined with Eq. (1).

$$\Delta p = p_1 - p_2 = f\frac{\rho u_m^2}{2D}(x_2 - x_1) \quad (1)$$

* Corresponding author.
*E-mail addresses:* yalmila@metu.edu.tr (A. Guvenc Yazicioglu), sanagun@gmail.com (A.S. Anagun).

https://doi.org/10.1016/j.applthermaleng.2017.09.013
1359-4311/

## Nomenclature

| | |
|---|---|
| $D$ | tube diameter [m] |
| $f$ | oscillator vibration frequency [Hz] |
| f | friction factor |
| $h$ | inter-particle spacing [m] |
| $F$ | force driven by the electromagnetic unit [N] |
| $K_B$ | Boltzmann's constant |
| $p$ | pressure [Pa] |
| $P$ | pump power requirement [W] |
| $R_s$ | nanoparticle radius [m] |
| $R_z$ | mechanical impedance received by the oscillator [N s m$^{-1}$] |
| $t$ | time [s] |
| $u$ | velocity [m s$^{-1}$] |
| $V$ | vibration velocity [m s$^{-1}$] |
| $\dot{\forall}$ | volumetric flow rate [m$^3$ s$^{-1}$] |
| $w$ | angular vibration frequency [Hz] |
| $x$ | axial position [m] |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | level of significance |
| $\rho$ | density [kg m$^{-3}$] |
| $\mu$ | viscosity [mPa s] |
| $\eta$ | intrinsic viscosity |
| $\varphi$ | nanoparticle volumetric fraction |

*Subscripts*

| | |
|---|---|
| *coded* | equations in the coded form |
| $f$ | (base) fluid |
| $m$ | mean |
| $nf$ | nanofluid |
| $p$, $s$ | nanoparticle |
| $r$ | relative |
| *uncoded* | equations in the uncoded form |

The friction factor f is constant for fully developed flow, and is defined as:

$$\text{f} = \frac{64}{Re_D}, \quad \text{where } Re_D = \frac{\rho u_m D}{\mu} \tag{2}$$

The friction factor and the pressure drop depend on working fluid viscosity. Pump power requirement is also correlated to working fluid viscosity (Eq. (3)). This may be a limitation for convection heat transfer, as increased pump power requirement may increase the operation cost.

$$P = \Delta p \cdot \dot{\forall} = \frac{32\mu}{D^2} u_m (x_2 - x_1)\dot{\forall} \tag{3}$$

Viscosity of nanofluids thus may be regarded as a challenge for convection heat transfer, and considerable research has been conducted on this property. A review on recent developments on the viscosity of nanofluids was presented in [3], and it was stated that the difficulty in estimating standards on nanofluid viscosity was due to the inconsistencies in literature results. The increment ratio obtained in nanofluid (effective) viscosity in comparison to the base fluid viscosity is called the relative viscosity, and defined in Eq. (4).

$$\mu_r = \mu_{nf} / \mu_{bf} \tag{4}$$

In Eq. (4), $\mu_r$, $\mu_{nf}$, and $\mu_{bf}$ stand respectively for the relative, nanofluid, and base fluid viscosities. Some commonly used classical models for the viscosity of nanofluids are presented in Table 1.

As it is seen in Table 1, most of the classical models relate nanofluid viscosity only with nanoparticle fraction, $\varphi$, while a few of them consider other particle-related effects. On the other hand, these equations have not been successful in predicting the viscosity of nanofluids due to the lack of agreement between their assumptions (e.g., dilute/moderate concentration, perfectly spherical shaped and non-interacting particles, etc.) and the complex nature of nanofluids. A review of experimental nanofluid viscosity literature was done in [6]. The general conclusion of that work was the increase in nanofluid viscosity with increasing nanoparticle fraction and decreasing temperature (as can be deduced from both the classical and empirical models; for instance Einstein Model for nanoparticle fraction dependence, and the equation reported in [7] for temperature dependence), and the need for the consideration of a larger number of parameters when correlating nanofluid viscosity more sensitively. This conclusion was one of the motivations for this study.

Viscosities of different types of nanofluids are reported in the literature. $Al_2O_3$ (alumina) nanoparticles have been widely investigated, and alumina-water nanofluids have been one of the most commonly studied type of nanofluids [8]. As indicated in [8], one

**Table 1**
Classical models for the description of nanofluid viscosity.

| . | Equation | | Assumptions |
|---|---|---|---|
| Einstein Model | $\mu_{nf} = \mu_{bf}(1 + 2.5\varphi)$ | (5) | Dilute suspension of non-interacting spherical particles [4] |
| Brinkman Model | $\mu_{nf} = \mu_{bf}(1 - \varphi)^{2.5}$ | (6) | Modified Einstein model for moderate concentrations [4] |
| Batchelor Model | $\mu_{nf} = \mu_{bf}(1 + 2.5\varphi + 6.5\varphi^2)$ | (7) | Brownian motion of particles is considered with ($\varphi^2$) term [4] |
| Lundgren Model | $\mu_{nf} = \mu_{bf}\left(1 + 2.5\varphi + \frac{25}{4}\varphi^2 + f(\varphi^3)\right)$ | (8) | Taylor series in $\varphi$ [3] |
| Frankel and Acrivos Model | $\mu_{nf} = \mu_{bf}\frac{9}{8}\left(\frac{(\varphi/\varphi_m)^{1/3}}{1-(\varphi/\varphi_m)^{1/3}}\right)$ | (9) | $\varphi_m$ to be determined experimentally [3] |
| Graham Model | $\mu_{nf} = \mu_{bf}\left\{1 + 2.5\varphi + 4.5\left[\frac{1}{\left[\frac{h}{dp}\left(2+\frac{h}{dp}\right)\right]\left[1+\frac{h}{dp}\right]^2}\right]\right\}$ | (10) | Generalized version of Frankel and Acrivos [3,4] |
| Koo and Kleinstreuer Model | $\mu_{nf} = \mu_{bf}(1 - \varphi)^{-2.5} + 5.10^4\lambda\varphi\rho_f\sqrt{\frac{K_B T}{2\rho_s R_s}}\xi(T, \varphi)$ | (11) | Equation has a conventional static part and a dynamic part originating from the Brownian motion of nanoparticles [5] |
| Krieger and Dougherty Model | $\mu_{nf} = \mu_{bf}\left(1 - \frac{\varphi}{\varphi_m}\right)^{-\eta\varphi_m}$ | (12) | Power-law model. $\varphi_m$ = 0.495–0.54, $\eta$ = 2.5 (for mono-dispersed suspensions of hard spheres) [4] |

*$\varphi_m$: maximum packing fraction, $\lambda$ and $\zeta$ are the modeling functions in Koo and Kleinstreuer Model.