Preliminary study to determine the maximum settling velocity and model parameter of Cu nanoparticle by settling method

Azraf Azman¹,²,a), Mohd Zamri Yusoff¹, Mohd Zaid Hassan², Hafizal Yazid², Prem Gunasegaran¹, KC Ng³

¹UNITEN, Jalan IKRAM-UNITEN 43000 Kajang Selangor, Malaysia.
²Malaysian Nuclear Agensi, Bangi 43000, Kajang Selangor, Malaysia.
³University of Nottingham Malaysia Campus, Jalan Broga,43500 Semenyih, Selangor Malaysia.

a azraf@nuclearmalaysia.gov.my

Abstract. Nanoparticle suspensions also known as nanofluids are often polydisperse and tend to settle with time. Its settling process is very challenging and quite complex to understand. In this study, Copper (Cu)nanoparticles were dispersed in base fluid (water) and the settling behaviour were examined to obtain the settlement parameter. A series of experiments adopted from sludge settling methods were conducted and the results were analysed. Based on the experiments, the settling curve was successfully established.

1. Introduction

Nanofluids are colloidal suspensions composed of nanoparticles with the size of less than 100 nm which are dispersed in a carrier fluid. These nanoparticles act as an additive material for carrier fluid to obtain a better thermal conductivity enhancement. Nanofluids are a topic of great interest due to its physical properties. These materials has significant feature in many fields such as aerospace, biomedicine and thermal engineering.

In the field of thermal engineering, nanofluids has shown a significant improvement in flow and heat transfer of the liquids/fluids. However, its practical application remains as a significant issue due to instability of the nanoparticle in the solution/fluid. The nanoparticles tend to agglomerate once in suspension. The agglomeration results in sedimentation and this will decrease the efficiency of nanofluids thermal conductivity.

Sedimentation is the tendency of particles in suspension to settle out of the fluid in which they are entrained and come to rest against a barrier. These particle move from relatively higher density through a less dense fluid. This is due to their motion through the fluid in response to the forces acting on them such as gravity, centrifugal acceleration, or electromagnetism. This process is relevant for a wide range of natural and industrial processes such as waste water treatment [1], the fouling of heat transfer surfaces [2], stability of dust clouds [3], sedimentation in natural waters, such as in rivers, lakes and oceans [4], and metallurgy [5].

Sedimentation in a field of gravity is well studied for cases where the sedimenting material (dispersed phase) is sufficiently diluted to make its volume fraction much lower than that of the continuous phase. According to [3], these particles move uniformly downward with their constant terminal sedimentation velocity. This is due to the different nature of the sedimentation components (carrier fluid, nanoparticle, particle properties) and the concentration at which these compounds occur. Buoyancy-gravitational flow instabilities may occur in the continuous phase when the solid particles
are settled or when the solid particles settling process is completed [7]. In reality, the volume of nanofluids settling will depend on both its hindered settling and compression behaviour. These two factors, are both influenced by the composition of the nanoparticle size distributions, surface properties, rheology, carrier fluid, etc.

According to [8], instability issues always exist after nanofluids were formed. The settling of nanoparticles can be neglected in forced flow compared to nanofluids natural convection. However, it may not be practical to ignore/neglect these issues in nanofluids natural convection due to temperature driven velocity is too small. In extreme cases, the sedimentation or settling issues of nanofluids need to be treated using stabilizers. It is a significant topic for nanofluids natural convection and nanoparticles sedimentation. To the best of the authors’ knowledge, no correlative works have been reported yet.

Therefore, in this work, the method to obtain the settling velocity and settlement parameter for Cu nanoparticles is adopted according to secondary sludge settlers design. Generally it involves two steps: (1) settling at low concentrations (including discrete and flocculent particle settling), and (2) settling at high concentrations (including hindered and compression settling) [9]. Detailed information on the settling behaviour of a nanofluids sample can be obtained from a batch of settling and hindered settling curve [10].

2. Materials and methods

2.1. Preparation of nanofluids

The black colour, spherical shape Cu nanoparticles were purchased from the Sigma Aldrich, USA (concentration%). The physical and chemical properties are summarised in Table 1. The nanoparticles were in a dry state properties in as in Figure 1. In order to study the instability of suspension, five samples with different concentrations were prepared which is 0.5%, 1%, 2%, 3% and 4%.

Table 1. Physical properties of Cu nanoparticles.

| Nanoparticle | Size          | Density, ρ | Colour  |
|--------------|---------------|------------|---------|
| Cu           | 60 – 80 nm    | 8933       | Black   |

Figure 1. Cu nanoparticle powder.
Figure 2. Scanning Electron Microscopy (SEM) image of typical Cu nanoparticle morphology.

The mass of the nanoparticles for different concentrations were estimated using the weight percent ratio. The nanoparticles with different weights (x,y,z,g) were mix with 20 mL deionized water(DW). The mixture was ultrasonicated for two hours to break any possible agglomeration of nanoparticles.

Figure 3. Preparation of Cu nanofluidswith different concentrations.

2.2. Experimental setup
The experiment to determine the gravity settling velocity of the Cu nanoparticle suspension was carried out using a digital web camera. Then the vials were placed in front of a white colored cardboard in an enclosed compartment. A usb led light bar was placed at upper and behind the sample vial. The white background and a led lighting were applied for better photographic effect and contrast. The digital web camera captured the dynamic events of the suspension and showed the movement of the solid-liquid interface with time.
3. Result and discussion
The experiments demonstrated that the unstable suspensions settle rapidly during the first minutes of the experiment. The change of the interface height slows down the settling of nanoparticles considerably. The liquid above the interface becomes more transparent when most of the larger particles have settled out. However, there are still small particles that remain for a period of time as observed from the liquid phase is not completely clear. Based on [10] in Figure 5, there are four different phases in a unhindered settling curve or batch settling curve. However, batch settling curve only indicate information on the settling behaviour at the suspensions interface.

Figure 5. Four different phases in batch settling curve (Experimental Methods in Wastewater Treatment, 2016).
Figure 6. Batch settling curve of various concentration of Cu nanofluids.

In Figure 6, the 0.5% and 4% Cu nanofluid concentrations showed the slowest and fastest settling time respectively. This suggest that there are some large object/particles or clustered forms due to instability of charge present in the suspension. Cu nanofluids with 4% concentrations settles less then 20 minutes while the 0.5% concentrations settles over 60 minutes. Figure 7 showed that the hindered settling velocity settles rapidly with higher nanofluid concentrations compared to lower concentrations. Note that the velocity of the particles with concentrations of 4% is ~4.8m/s compared to ~1.2m/s for 0.5% concentrations. Referring to sludge settling test, the relation between the particle concentration and the zone settling velocity can be described as an exponential decaying function as shown by Vesilind, 1968.

\[ V_{hs}(X) = V_0 \cdot e^{-rV \cdot XTSS} \]  

where \( V_{hs} \) is the hindered settling velocity, \( V_0 \) is terminal velocity, \(-rV\) is the settling parameter and \( XTSS \) is the nanoparticle concentration.

However, from Figure 7, the settling of Cu suspensions shows that the relation between concentration and zone settling velocity can be described as an inverse to exponential decay or a logarithmic function as followed.

\[ V_{hs}(X) = V_0 \cdot (1 - e^{-rV \cdot XTSS}) \]
Figure 7. Hindered settling velocity of Cu nanoparticles.

The hindered settling velocity increase at higher concentrations, and it is assume that there are some large object or clustered forms due to instability of charge present in the suspension. Note that in Figure 6, the settling pattern shows the settling time of the nanoparticles became faster with respect to concentrations.

In Figure 8, the circles represent measured settling velocities and the line is the calculated settling velocities logarithmic function as followed in Eq.2. From the calculated equation the terminal velocity of Cu is estimated at $V_0$, 7.62e-05 m/s from the settling function. The dashline shows the 95% confidence intervals of the estimated parameters for the settling function. In accordance with the results, sedimentation will occur in suspensions after the preparations.

Figure 8. Settling velocity as a function of solid concentration.
4. Conclusions
Nanofluids based on Cu nanoparticles were prepared at various/different concentrations using water as a base fluid. In accordance with the preliminary results, settling of Cu nanoparticles was slower with lower concentrations. Observation within 24 hours of nanofluids settling prepared via the two-step method, revealed that settling and agglomeration depends on the size and concentration of nanoparticles. The higher the particle concentration in the fluid, the smaller the inter-particle distance between the particles. As a result, the probability of agglomeration to occur is higher due to Vander Waals attraction. These phenomena will also exert a negative influence of the heat transfer performance of nanofluids, which requires complementary studies on the determination of sizes and concentrations of nanoparticles in a suspension.

5. References
[1] Diehl S 1997 Continuous sedimentation of multi-component particles. Math. Meth. in the Appl. Sci. 20 p 1345–1364.
[2] Brahim F, Augustin W, Bohnet M 2003 Numerical simulation of the fouling process. Int. J. of Thermal Sci. 42:323–334.
[3] Goossens D 2006 The granulometrical characteristics of a slowly-moving dust cloud Earth Surf. Processes and Landforms 10 p 353–362.
[4] van Maren D S 2007 Grain size and sediment concentration effects on channel patterns of silt-laden rivers Sedimentary Geol. 202 p 297–316.
[5] Holbeach J W, Davidson M R 2009 An Eulerian-Eulerian model for the dispersion of a suspension of microscopic particles injected into a quiescent liquid Eng. Fluid Appl. of Comp. Mech. 3 p 84–97
[6] Di Felice R 1999 The sedimentation velocity of dilute suspensions of nearly monosized spheres Int. J. of Multiphase Flow 25 p 559–574.
[7] Bergantz G W . Ni J 1999 A numerical study of sedimentation by dripping instabilities in viscous fluids Int. J. of Multiphase Flow 25 p 307–320.
[8] Meng X, Zhang X, Li Q 2016 Numerical investigation of nanofluid natural convection coupling with nanoparticles sedimentation Appl. Thermal Eng. 95 p 411–420
[9] Zhang Y, Wang H, Qi L, Liu G, He Z, Jiang S 2016 Simple model of sludge thickening process in secondary settlers. Front. Environ. Sci. Eng. 10(2) p 319-326.
[10] Experimental Methods in Wastewater Treatment 2016 EISBN: 9781780404752
[11] Akhatov J S, Juraev ET, Juraev TI, Avdievich VN 2018 Study of sedimentation process in nanofluids with various concentrations of SiO₂ and Al₂O₃ nanoparticles, Appl. Solar Ener. 54(6) (Allerton Press, Inc.) p 428–432

Acknowledgements
The author would like to thank all research officers from Agensi Nuklear Malaysia (ANM) and from Jabatan Perkhidmatan Awam Malaysia for their supports and helps in completing this work.