Energy 89 (2015) 1065–1086

Contents lists available at ScienceDirect

Energy

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

Review

A comprehensive review of thermo-physical properties and convective heat transfer to nanofluids

K.H. Solangi [a,*], S.N. Kazi [a], M.R. Luhur [b], A. Badarudin [a], A. Amiri [a], Rad Sadri [a], M.N.M. Zubir [a], Samira Gharehkhani [a], K.H. Teng [a]

[a] Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] Department of Mechanical Engineering, Faculty of Engineering, QUEST Nawabshah, Sindh Pakistan

ARTICLE INFO

Article history:
Received 26 February 2015
Received in revised form
8 June 2015
Accepted 28 June 2015
Available online 27 July 2015

Keywords:
Nanofluids
Heat transfer
Stability
Thermal conductivity
Rheological properties

ABSTRACT

Nanofluids are fluid nanoparticle suspensions that exhibit enhanced properties at modest nanoparticle concentrations. Nanofluids have unique heat transfer properties and are utilized in high heat flux systems (e.g., electronic cooling systems, heat exchanger liquids, solar collectors, and nuclear reactors). However, suspension stability is critical in the development and application of these heat transfer fluids. Reynolds number, mass concentration, and particle size control the heat transfer behavior of fluids. Sedimentation and agglomeration of nanoparticles in nanofluids and their dispersion have rarely been investigated. Therefore, this paper explains the parameters that affect the stability of nanofluids and the different techniques used to evaluate the stability of nanofluids. This paper also presents an updated review of properties of nanofluids, such as physical (thermal conductivity) and rheological properties, with emphasis on their heat transfer enhancement characteristics. Studies on zeta potential as a function of pH are discussed and extended further to identify opportunities for future research.

1. Introduction

Nanofluids are suspensions obtained from dispersing different nanoparticles in host fluids to enhance thermal properties [1–5]. Nanofluids are next-generation heat transfer fluids that are used as heat exchanging fluids. Nanofluids have better thermal properties than conventional heat transfer fluids [6–10]. Over the past two decades, nanofluids have exhibited remarkably improved thermal conductivity, stability, and heat transfer coefficients as well as reduced overall plant consumption and costs. Nanofluids have great application potential in several fields. Nanofluids are increasingly utilized in different heat exchangers to optimize energy consumption [3]. Hence, discovering suitable nanofluids with improved heat transfer properties and high thermal conductivity has become challenging [4,11–16]. Several studies have reported the results of thermal conductivity of oxide nanofluids [e.g., aluminum oxide (Al_2O_3), SiO_2, TiO_2, and cupric oxide (CuO)] in the last decade. These studies explored the evolution of thermal conductivity with solid content. Thermal conductivity enhancement of nanofluids depends on adding nanoparticles and the nanoparticle aspect ratio [17]. However, adding nanoparticles increases viscosity of nanofluids which limits the thermal benefits of nanofluids through enhanced pumping power in the systems. Along with the thermal behavior of nanofluids, the most important issue is the stability of nanofluids; achieving the desired stability remains challenging today [3]. Most investigations have focused on the suspension stability of nanofluids with no conclusive results. Several researchers have investigated the addition of gum arabic, gum tragachan, CTAB (cetyl trimethylammonium bromide), and SDBS (Sodium Dodecyl Benzene Sulphonate) surfactants as well as controlling pH suspension [18–20]. Adding surfactants and modifying nanoparticle surfaces effectively improve stability of the nanofluids based on steric hindrance and electrostatic repulsion among nanoparticles [21–23]. Adding surfactants is simple and convenient and is thus attractive in practical applications. Unfortunately, maintaining long-term stability of nanofluids with increasing concentrations becomes difficult because steric hindrance and electrostatic repulsion lose their effects when the distances among nanoparticles become small [24–27]. Decreasing NF (Nanofluid) concentration is the best approach to maintain good fluidity. This paper reviews the enhancement of stability of nanofluids and the different parameters that influence NF properties.

* Corresponding author. Tel.: +60 172515435.
E-mail address: solangi.quest@gmail.com (K.H. Solangi).

http://dx.doi.org/10.1016/j.energy.2015.06.105
0360-5442/

The physical and rheological properties and current trends in formation of nanofluids are discussed in detail. This paper investigates challenging issues (e.g., economy, thermal achievement, availability, and environmental impact) that need to be solved for future research on nanofluids as well as proposes suggestions that can ensure the preparation of nanofluids that remain stable over a long period with negligible agglomeration and without chemically changing the fluid properties.

2. Development of nanofluids

Norio Taniguchi first used the term “nanotechnology” in 1974. He described nanotechnology as technology that engineers materials at the nanometer size. Choi [28] coined the term “nanofluid” in 1995 to describe this combination. The main focus of nanofluid research since then has been to develop superior heat transfer fluids [12,29]. Nanofluids have become established in the history of nanoscience and have therefore attracted the attention of researchers around the globe. Nanofluid research has expanded over the years, as evidenced by the fact that studies numbered only 10 research papers in 2001 and grew to 175 in 2006 and 700 in 2011 [30–33].

Modern nanotechnology has enabled the production of average-sized (below 100 nm) metallic and nonmetallic nanoparticles. The mechanical, optical, electrical, magnetic, and thermal properties of nanoparticles are better than those of conventional bulk materials with coarse grain structures [34,35]. Recognizing the opportunity to apply nanotechnology in thermal engineering, Stephen Choi and his colleagues at the ANL (Argonne National Laboratory) proposed the concept of nanofluids in 1994 and investigated issues related to fundamentals and applications of nanofluids. Researchers from Japan and Germany also published articles that describe fluids that resemble the concept of nanofluids developed at ANL. Researchers from Japan [36] dispersed Al_2O_3, SiO_2, and TiO_2 by adding acid (HCl) or base (NaOH) [37–39] to base liquids. Abrasion-related properties are more favorable than conventional solid/fluid mixtures. Successful employment of nanofluids supports the current trend toward component miniaturization by enabling the design of small and light heat exchange systems. Yu [40] discussed the properties of nanofluids and future challenges. Keblinski et al. [41] studied the heat flow in nanoparticle suspensions. The research showed that the nanofluids exhibit high thermal conductivity even at low concentrations of suspended nanoparticles. For example, the experiments exhibited an increase in thermal conductivity by dispersing less than 1% volume fraction of copper (Cu) nanoparticles or CNT (carbon nanotubes) in ethylene glycol or oil by 40% and 150%, respectively [10,42]. The research also showed that nanofluid technology provides opportunities for developing nanotechnology-based coolants for various innovative engineering and medical applications [10,43].

3. Preparation of nanofluids

Preparation of nanofluids is the first step in experimental studies of nanofluids. Nanofluids are primarily prepared via two processes: two-step preparation and one-step preparation.

3.1. Two-step method

Several researchers employ the two-step method to prepare nanofluids [5,6,24,44–67]. The method utilizes nanoparticles, nanofibers, nanotubes, and other nanomaterials, which are initially produced as dry powders via chemical or physical methods.

The method is extensively used in synthesizing nanofluids by mixing base fluids with commercially-available nanopowders obtained from different mechanical, physical and chemical routes (e.g., milling, grinding, and sol–gel and vapor phase methods). Ultrasonic vibrators or high shear mixing devices are generally used to stir nanopowders with host fluids. Frequent use of ultrasonication or stirring decreases particle agglomeration [68]. Agglomeration is a major issue in synthesizing nanofluids [69]. The two-step method is the most economical method for large-scale production of nanofluids because nanopowder synthesis techniques have already been scaled up to industrial production levels [39,44]. Nanoparticles tend to aggregate because of high surface area and activity [3]. Researchers suggest [70] that the two-step method is more suitable for preparing nanofluids with oxide nanoparticles than those with metallic nanoparticles. Stability is a significant issue for this method as the powders aggregate easily because of the strong van der Waals force among nanoparticles. Despite its disadvantages, the method is recognized as the most economical process for producing nanofluids [33]. Fig. 1 shows the two-step method.

Preparation of stable nanofluids is an important area in nanofluid research and application [71]. Eastman et al. [70] employed the two-step method to prepare nanofluids and observed that nanometer-sized Cu particles dispersed in ethylene glycol have higher effective thermal conductivity than those dispersed in pure ethylene glycol. The method may be economical, but it presents drying, storage, and transportation issues. Issues in agglomeration and clogging also decrease the thermal conductivity of nanofluids. The advantage of this method is that the nanofluids could be prepared on a large scale. However, nanoparticle aggregations are difficult to break up under ultrasonication or stirring. Thus, stability and thermal conductivity of nanofluids prepared through dispersion are usually not ideal [72].

3.2. One-step method

Advanced techniques are developed to produce nanofluids via a one-step method because of the difficulty in preparing stable nanofluids via the two-step method. The one-step method includes the direct evaporation and condensation method, SANSS (submerged-arc nanoparticle synthesis system), and laser ablation methods [72–74], in which metals are vaporized using physical technology and cooled into liquids to obtain nanofluids. These physical methods have excellent control over particle sizes and produce stable nanofluids.

The one-step method involves simultaneously producing and dispersing particles in fluids [39]. The method includes the chemical liquid deposition method and vapor deposition method. Several researchers have used this method to prepare nanofluids [60,66,75–79]. Drying, storage, transportation, and nanoparticle dispersion are avoided in this method to minimize nanoparticle agglomeration and increase fluid stability. The method prepares uniformly dispersed nanoparticles, which are stably suspended in

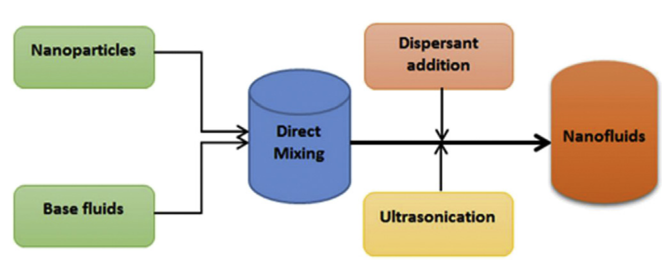

Fig. 1. Two-step preparation process of nanofluids [33], reproduced with permission from principal author and publishers IOSR JMCE.