Renewable and Sustainable Energy Reviews 75 (2017) 1239–1253

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Experimental studies of nanofluid thermal conductivity enhancement and applications: A review

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ARTICLE INFO

Keywords:
Nanofluids
Conduction
Measurement
Enhancement
Applications

ABSTRACT

In many applications, there is a critical need for enhancing the poor thermal conductivity of conventional fluids in order to develop efficient heat transfer fluids. This requirement can be met through dispersing nanometric particles in a given base fluid such as water, ethylene glycol, oil or air. The resulting nanofluids enhanced thermal conductivity of the base fluids. In order to evaluate this enhancement, nanofluid thermal conductivity is required to be measured. Several methods and techniques are covered in the present contribution. In addition, enhancements recorded experimentally are reviewed and summarized. Different parameters affecting on such enhancement are covered, including: nanoparticle concentration, size, shape and thermal conductivity. In addition, base fluid type, nanofluid bulk temperature and dispersion techniques are also covered parameters. However, nanofluids have the potential to contribute in several practical applications including solar thermal, transportation, electronic cooling, medical, detergency and military applications. In the present work, a brief overview of evolution in the use of nanofluids in some applications has been presented. According to this contribution, there is a critical need for further fundamental and applications of nanofluids studies in order to understand the physical mechanisms of using nanofluids as well as explore different aspects of applications of nanofluids.

1. Introduction

Heat transfer is one of the most important processes in many industrial and consumer products. For more than a century, scientists and engineers have made great efforts to enhance the inherently poor thermal conductivity of conventional fluids [1,2]. In 1873, Maxwell [3] proposed an idea of using metallic particles to enhance the electrical or thermal conductivity of matrix materials. He presented a theory for effective conductivity of slurries, by dispersing millimeter- or micrometer-sized particles (typically have size between 0.1 and 100 μm [4]) in liquids. However, major problems such as sedimentation, erosion, and high pressure drop prevented the usual micro-particle slurries to be used as heat transfer fluids. Nanofluids, which is a dilute suspension of nanometer-size particles or fibers (typically less than 100 nm) dispersed in a fluid such as water, oil, and ethylene glycol (EG) [5], have emerged as a potential candidate for the design of heat transfer fluids [6]. According to their potential applications in the heat transfer field, nanofluids have been a subject of intensive investigation [7–12].

According to the definition of micro- and nano-particles size, nanoparticles have surface/volume ratio 1000 times larger than that of microparticles [13]. This in turn, allows improving thermal properties of nanofluids rather than microparticles-colloidal suspensions, since heat transfer occurs on the surface of the particle [14]. Compared with microparticles, nanoparticles stay suspended much longer in base fluids, with very little settling under static conditions, unlike micron-sized suspensions [15]. However, strong van der Waals interactions generate an aggregation tendency between nanoparticles [16]. Therefore, different techniques are utilized to minimize long-term particles aggregation. This process is quite critical in preparation of nanofluids as particles clustering has been reported as features increasing thermal conductivity of nanofluids [17–19]. Moreover, the number of atoms present on the surface of nanoparticles is very large, as opposed to the interior [20]. These unique properties of nanoparticles can be exploited to develop nanofluids with an unprecedented

Abbreviations: BG, BioGlycol; CNF, Carbon nanofiber; CTAB, Hexadecyltrimethylammonium bromide; DE, Decene; DI, Deionized water; DWCNT, Double-walled carbon nanotubes; DOl, Diathermic oi; EG, Ethylene glycol; EO, Engine oil; HTF, High-temperature heat transfer fluid; HTO, Heat transfer oil; MEG, Mono ethylene glycol; MO, Mineral Oil; MWCNT, Multi-wall carbon nanotube; NSAQ, Nanosperse AQ; OAK^+, Potassium oleate; PO, Pump oil; TH66, Therminol 66; CSP, Concentrated Solar Power; FRS, Forced Rayleigh scattering; THW, Transient hot wire; TL, Thermal-lensing

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http://dx.doi.org/10.1016/j.rser.2016.11.111
Received 11 January 2015; Received in revised form 11 July 2016; Accepted 4 November 2016
Available online 23 November 2016
1364-0321/

Nomenclature

k_{bf}	Base fluid thermal conductivity, W/m K
k_{nf}	nanofluid thermal conductivity, W/m K
q	heat flux, W/m^2
r	radial coordinate, m
T	temperature, K
t	time, s
α_{nf}	nanofluid thermal diffusivity, m^2/s
ω	electric current frequency, Hz

combination of the two features most highly desired for heat transfer systems: extreme stability and ultrahigh thermal conductivity. Furthermore, because the nanoparticles are so small, they may reduce erosion and clogging dramatically. Other benefits envisioned for nanofluids include decreased demand for pumping power, reduced inventory of heat transfer fluid, and significant energy savings [21].

This discovery brought about a wave of studies in this area, predominantly experimental confirmation of the huge potential of nanofluids as well as efforts to theorize the phenomenon. In this paper, various techniques used to measure thermal conductivity are covered. Then, experimental work carried on studying the thermal conductivity enhancement of nanofluids against their base fluids is reviewed. This review aims to define parameters investigated experimentally through the literature in order to find out points of agreement and conflict in the obtained results to understand the thermal behavior of nanofluids. Moreover, different applications using nanofluid is also reviewed.

2. Thermal conductivity measurement techniques

Measuring the thermal conductivity of nanofluids can be carried out with different methods. The most common techniques for this purpose are the transient ones including: transient hot-wire method [22–37], temperature oscillation method [38,39], and 3-ω method [40–42]. Some other methods such as steady-state parallel-plate technique, micro-hot strip method, and optical beam deflection technique have also been utilized by some researchers [43–45].

2.1. Transient hot-wire method

The transient hot-wire (THW) method is the most widely used experimental technique for measuring fluids thermal conductivity, as it is an easy and low cost method to be implemented. It is a standard transient dynamic technique based on the measurement of the temperature rise in a defined distance from a linear heat source (hot wire) embedded in the test material. A hot wire is placed in the fluid, which functions as both a heat source and a thermometer [46–48]. The ideal mathematical model of the method is based on Fourier's law, assuming the hot wire as an ideal, infinite thin and long heat source in an infinite surrounding from homogeneous and isotropic material with constant initial temperature. According to Fourier's law, when the wire is heated, fluid of higher thermal conductivity corresponds to a lower temperature rise.

The mathematical model which describes the relation between thermal conductivity k_{nf} and measured temperature T using the THW method is explained and summarized as follows [47]. Assuming a thin, infinitely long line source dissipating heat into a fluid reservoir, the energy equation in cylindrical coordinates can be written as:

$$(1/\alpha_{nf})(\partial T/\partial t) = (1/r)\partial[r(\partial T/\partial r)]/\partial r \quad (1)$$

The initial condition can be written as shown in Eq. (2):

$$T|_{t=0} = T_0 \quad (2)$$

while the boundary conditions are defined by Eqs. (3) and (4) as follows:

$$\lim_{r\to 0}(r(\partial T/\partial r)) = (q/2\pi)(1/k_{nf}) \quad (3)$$

and

$$(\partial T/\partial r)|_{r=\infty} = 0 \quad (4)$$

If the temperatures of the hot wire at times t_1 and t_2 are T_1 and T_2, then by neglecting higher-order terms, the thermal conductivity can be approximated as [5]:

$$k_{nf} = (q/4\pi)\ln(t_1/t_2)/(T_1 - T_2) \quad (5)$$

Therefore, in order to determine k_{nf} experimentally using THW method according to Eq. (5), a constant electric power supply is used to heat the wire with a constant heat flux, q, at a time step, t. A Wheatstone-bridge circuit is used to determine the temperature increase of the wire from its change in resistance. Although the THW is an easy, fast response and low cost method; its accuracy can be affected by nanoparticle interactions, sedimentation and/or aggregation, and natural convection during extended measurement times. In addition, the assumptions of an infinite wire-length and the ambient acting like a reservoir may also introduce errors [42,49].

2.2. Temperature oscillation method

This method is based on the oscillation method proposed by Roetzel et al. [50] and further developed by Czarnetzki and Roetzel [38]. Applying this method requires measuring the temperature response of the nanofluid sample when a temperature oscillation or heat flux is imposed. The measured temperature response of the sample is an indication of averaged or localized thermal conductivity in the direction of sample chamber height [51]. The experimental set up of this method is explained in details by Paul et al. [42].

2.3. 3-ω method

The 3-ω method is quite similar to the THW method, as it uses a radial flow of heat from a single element which acts both as the heater and the thermometer. However, the main major difference is the use of electric current frequency dependence response instead of the time dependent response which is utilized by the TWH method. When a sinusoidal current at frequency, ω, passes through the metal wire, a heat wave can be generated at a frequency of 2ω, which is deduced by the voltage component at frequency 3ω. More details about this method are available in [42,52].

2.4. Other thermal measurement methods

The short-hot-wire method is an improved design of the hot-wire method, in which boundary effects can be taken into account, It has been applied by [53,54]. Another modification of THW is carried out by Mintsa et al. [55], who inserted a mixer into his THW experimental devices to avoid nanoparticle aggregation/deposition in the suspensions. In order to avoid interference between the detector and heater, Ali et al. [56] separated them by combining the THW method with a laser beam displacement method.

2.5. Optical measurement methods

In order to improve the thermal conductivity measurement accuracy, optical measurement techniques have been proposed as non-invasive methods [57–61]. The accuracy improvement resulted from separating detector and heater from each other avoiding the unavoidable interference between them in the THW method. In addition, optical techniques provide faster measurement, within a few micro-