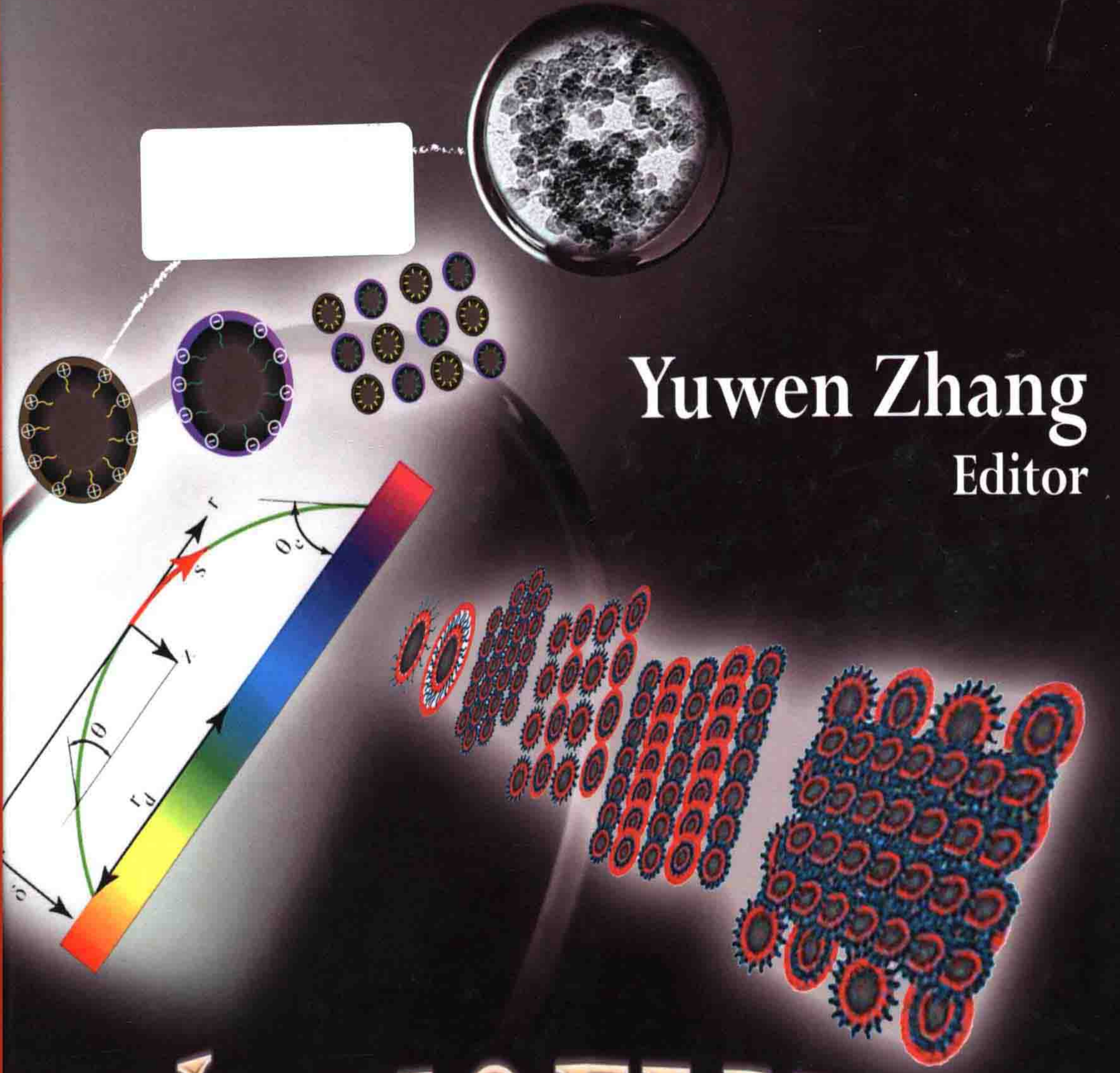
Yuwen Zhang
Editor



NANOFLUIDS

Research, Development and Applications

Nanotechnology Science and Technology

NOVA

NANOTECHNOLOGY SCIENCE AND TECHNOLOGY

NANOFLUIDS

RESEARCH, DEVELOPMENT AND APPLICATIONS

YUWEN ZHANG
EDITOR

nova publishers
New York

For permission to use material from this book please contact us:
Telephone 631-231-7269; Fax 631-231-8175
Web Site: http://www.novapublishers.com

NOTICE TO THE READER

Additional color graphics may be available in the e-book version of this book.

Library of Congress Cataloging-in-Publication Data

Nanofluids (Nova Science Publishers)
Nanofluids : research, development and applications / [edited by] Yuwen Zhang (Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia, MO, USA).
pages cm
Includes bibliographical references and index.
ISBN 978-1-62618-165-6 (hardcover)
1. Nanofluids. I. Zhang, Yuwen, 1965- editor of compilation. II. Title.
TJ853.4.M53N36 2013
620.1'06--dc23

2013005761

Published by Nova Science Publishers, Inc. † New York

NANOTECHNOLOGY SCIENCE AND TECHNOLOGY

NANOFLUIDS

RESEARCH, DEVELOPMENT AND APPLICATIONS

NANOTECHNOLOGY SCIENCE AND TECHNOLOGY

Additional books in this series can be found on Nova's website under the Series tab.

Additional e-books in this series can be found on Nova's website under the e-book tab.

PREFACE

This book presents current research related to the synthesis, characterization, and heat transfer of nanofluids. Nanofluids are stable colloidal suspensions of solid nanomaterials in base fluids. While nanoparticles were first added to base fluids to obtain nanofluids; other nanomaterials, like nanorods, nanotubes, nanowires, nanofibers, nanosheets, or other nanocomposites, are used to synthesize the nanofluids. The types of base fluids cover a wide range of liquids that include water, oil, ethylene-glycol (automotive antifreeze), refrigerants, polymer solutions, or even bio-fluids. The special properties of nanomaterials and their interactions with base fluids lead to substantially different properties of nanofluids compared with that of base fluids. Significant physical insights into complex physical phenomena in nanofluids are gained via the utilization of advanced theoretical tools and state-of-the-art experimental measurement techniques.

Chapter 1 – The objective of this chapter is to present critical research issues and application potentials of selected nanofluids, as related to the research accomplished and a number of hypotheses posed by different investigators – the goal is to shed some light on the subject as opposed to merely "generating heat." There are significant discrepancies among the experimental data available, as well as between the experimental findings and the theoretical model predictions, related to nanofluids thermo-physical characteristics. Oddly, there are more hypothetical theories proposed than reliable experimental results to verify those theoretical models. The nanofluids were hyped-up in the past, but it would be a mistake to hype-down nanofluids now and make premature judgments based on inconsistent and incomplete research to-date.

Regardless of ever-increasing number of research studies in this area, the basic research of convenience (repetition of similar experimentation with unstable nanofluids) remains in the initial stage; the promising nanofluids are still to be developed and results are still to be experimentally re-confirmed and established.

Development of many industrial and new technologies is limited by existing thermal management, and need for enhanced heat transfer and high-performance cooling. Nanofluids, stable colloidal mixtures of nanoparticles (including nanorods, nanofibers, nanotubes, nanosheets, and functional nanocomposites, even nano-droplets and nano-bubbles) in common fluids, have a potential to meet these and many other challenges. Colloidal nano-mixtures with functionally-stable and active-like nanostructures that may self-adjust to the process conditions, require systematic surface-chemistry study and enhancements (coatings with functional layers, surfactants, etc.), in addition to investigation of thermo-physical characteristics and phenomena.

A comprehensive, systematic and interdisciplinary experimental research program is necessary to study, understand and resolve critical issues in nanofluids research to date. The research must focus on both, synthesis of nanofluids and a careful exploration and optimization of thermo-physical characteristics. Development of new-hybrid, drag-reducing nanofluids may lead to enhanced flow and heat transfer characteristics. The nanoparticles in these fluids yield increased heat-transfer while the long-chain polymers are expected to enhance flow properties, including active and functional interactions with nanoparticles, thus providing potential for many applications yet to be developed and optimized.

Chapter 2 – Over the past decade, research in heat transfer enhancement using nanofluids – suspensions of nanometer-sized solid particles in a base liquid – has received considerable attention all over the world. However, the value of thermophysical properties of suspensions and heat transfer characteristics reported in literature by several authors are in disagreement. Several theoretical works to predict the mechanism of heat transfer enhancement, the effective thermophysical properties of the suspension as well as convective heat transfer, range from a homogeneous model to complex two-phase flow models have been proposed. Validation of theoretical studies with good experimental data is essential for proper understanding of the phenomena. This chapter provides insight into the recent development of nanofluids from preparation, characterization to theoretical aspects and ways to improve nanofluid stability so as to be able to commercialize and implement potential applications.

Chapter 3 – In this chapter, the formulation of nanofluids and experimental investigations on thermophysical properties together with the mechanisms proposed for the alteration in their values or characteristics due to the addition of nanoparticles are discussed. This chapter describes the two kinds of methods which have been frequently employed in producing nanofluids namely single-step method and the two-step method. Important thermophysical properties of nanofluids like thermal conductivity, viscosity, density, specific heat capacity and surface are also explained in this chapter.

Chapter 4 – The empirical correlation shows that the base fluid temperature plays an important role for effective thermal conductivity enhancement of nanofluids with decreasing nanoparticle sizes. Furthermore, it shows that the Reynolds number, function of temperature, has a more dominant role than other factors such as base fluid thermal conductivity, particle size, and diffusivity. Despite that the Brownian velocity of nanoparticles has been traditionally used for the Reynolds number in modeling, it is too slow to properly describe the effective thermal conductivy enhancement of nanofluids for many cases. The more comprehensive model based on a faster heat transfer velocity, in the same order as the speed of sound, agrees better with wide range of experimental data.

Chapter 5 – Innovative designs of different kinds of stable ferrofluids (magnetic or ferroelectric nanoparticles (NPs) dispersed in a suitable carrier liquid) are described in this chapter with well-known chemical synthesis routes, and basic physics underlying behind tailoring functional properties for medicals, biosensors and other applications. Common nanostructured flocculates described in this chapter include magnetic oxides such as γ-Fe_2O_3, Fe_3O_4 and spinel ferrites AB_2O_4 or perovskites ABO_3, A = a divalent cation and B = a tri or tetravalent cation in general. Surface modified NPs dispersed and immobilized in different polymer and ionic fluids give a road map of understanding the formation and properties of different ferrofluids with stable properties at elevated temperatures for applications. The most fascinating properties of a practically useful ferrofluid are its stability and rheology with self-adjustable magneto-viscosity and magnetic/ferroelectric features upon perturbations at moderate magnetic or electric fields. Applications of ferrofluids primarily depend on the basic properties such as ability to manipulate the parent features subject to an applied perturbation field (such as magnetic, electric, optical, etc.), rheology, absorption capacity of electromagnetic energy at selective frequencies and heating-up, thermal conductivity, magnetocalory, biological activities, ferroelectrics, light-energy transfer, magnetic switching, and other perturbation sensitive features. Those cover diversified fields such as chemical and biochemical separations, magnetic target drug delivery, magnetic resonance imaging contrast agents, hyperthermia therapy, disease diagnosis, chromatography, electrochemical biosensors, optical detection and luminescence detection, heat sinker and dampers, multicolored pigments, magnetic switches and valves, phosphors, and many more in the time to come in the near future.

Chapter 6 – Nanofluids, as alternate heat transfer fluids, have gained enormous attention from research laboratories and industries in recent times. The thermophysical properties and the overall convective heat transfer performance of nanofluids have been investigated extensively. This chapter aims to review the methodologies adopted for quantification of the forced convection behavior of oxide-based nanofluids. The factors that lead to the enhancement of heat transfer in nanofluids are also discussed. The influence of the two major thermophysical properties, the thermal conductivity and the dynamic viscosity are discussed. The effects of parameters like inertia, Brownian diffusion, thermophoresis, diffusiophoresis, Magnus effect, fluid drainage and gravity are also brought out. Apart from the literature review, results from experiments at the authors' laboratory on forced convection experiments at high pressure loops are also presented, which show a moderate increase in heat transfer coefficient at pressures as high as 5 bar.

Chapter 7 – Jet impingement cooling is a vital technique for thermal management of electronic devices of high heat flux by impinging fluid on a heater surface due to its high local heat transfer rates. One may find plenty of publications on the heat transfer characteristics of jet impingement cooling technique such as the distance between the jet outlet and the heated surface, the magnitude of the jet velocities, turbulence intensity, the angle of impingement, the array of jets and the roughness of the heater surface. But little attention is paid to the effect of the thermal properties of the impingement fluid, which may be another way to further improve the heat transfer performance of the jet impingement. With development of enhanced heat transfer techniques in conventional systems, the conventional working fluid with low thermal conductivity turns into a bottleneck factor for promoting the performance effectiveness of thermal systems. Improvement of the thermal properties of impinging fluids may become a promising trick of augmenting heat transfer process in the jet impingement cooling system.

Recent advances in the nanotechnology have permitted the creation of a new and special class of fluids, named 'nanofluids'. The thermal conductivity and heat transfer performance of nanofluids are superior to those of the original pure carrier fluids because the suspended nanoparticles remarkably improve energy transport capability of the suspensions. Nanofluid offers the exciting possibility of increased heat transferability of jet impingement.

In this current study, experiments were conducted to investigate the heat transfer enhancement of the nanofluid in the impinging jet cooling system. Two types of nanofluids were used as the working fluid. Cu-water nanofluid was studied in submerged single jet impingement cooling while Cu-ethylene glycol/water nanofluid was introduced into free surface jet array impingement cooling, respectively. In submerged single jet impingement, nanofluids with volume fraction ranged from 1.5% to 3.0% were studied for different jet-to-target spans. Experiments have revealed that the suspended nanoparticles increase the heat transfer performance of the base liquid in the jet impingement cooling system. It had been found that an enhancement of 18.5% compared with the base fluid at the Reynolds number of 8000 when nanofluids are used. In addition, the experiments have shown that the suspended nanoparticles almost result in no extra addition of pressure drop in both submerged single jet and free surface jet array impingement.

Chapter 8 – The purpose of this chapter is to demonstrate the effects of nanoparticles on boiling heat transfer coefficient and heat flux. Effects of nanoparticles on force balance at the triple line, behavior of triple line, wettability, roughness, active nucleation site density, initiation of nucleation, dynamics of bubble growth, bubble departure, advancing and receding contact angles, wetting and rewetting, boiling heat transfer coefficient and critical heat flux will be discussed in this chapter.

Nanoparticles have two main roles on boiling heat transfer phenomenon, a) suspended nanoparticles modify the physical properties of nanofluids; b) deposited nanoparticles modify the characteristics of heated substrate. Behavior of the triple line might be changed by deposited nanoparticles as well as the suspended nanoparticles inside nanofluids. This chapter attempts to explore and discuss the effects of both mechanisms on boiling heat transfer phenomenon in details.

Droplet and bubble formation methods are developed to investigate the effect of nanoparticles on force balance and behavior of triple. In case of droplet method, gravity is in favor of the expansion of triple line and reduction of contact angle which will reduce the accuracy of evaluation of effects of nanoparticles on behavior of triple line. Droplet contact angle changes with volume, so droplet method can not be a unique method to study the effects of nanoparticles on behavior of triple line including surface wettability, thus asymptotic contact angle will be discussed to investigate the behavior of triple line, regardless of gravity.

In case of bubble growth method, gravity affects as buoyancy force and lifts the bubble upward, so triple line can move more freely and effect of nanoparticles on triple line could be noted easier. Formation of bubbles inside nanofluids has a great capacity to express effects of nanoparticles on behavior of triple line, bubble growth, waiting time, bubble formation time, bubble frequency, departure process, receding and advancing dynamic contact angles, wetting and rewetting. Indeed, effects of nanoparticles depend on concentration, and characteristics of nanoparticles such as shape, size, coating and material.

Chapter 9 – An Oscillating Heat Pipe (OHP) is a heat transfer device that can be utilized to transfer a large amount of heat from heating to cooling sections. A typical OHP is fabricated from a long capillary tube bent into many turns with an evaporator and a condenser located at two opposite sides, and an adiabatic region between the evaporator and condenser. In order to form a train of vapor bubbles in an OHP, the liquid and vapor must not be able to stratify in the channel. When nanoparticles are added in the base fluid in an OHP, the OHP effectively utilizes 1) the oscillating motion in the OHP to suspend nanoparticles; 2) the higher heat capacity of nanofluid; 3) the higher thermal conductivity; 4) the nanoparticle effect on the fluid field; and 5) the nanoparticle effect on the surface wetting conditions. The unique feature of the oscillating motion fully utilizes the nanofluid features to significantly enhance the heat transport capability in an OHP.

In the fabrication process of OHPs, preparation, charging the OHP with nanofluids and sealing it are inevitable and requiring careful attention for successful testing. Nanofluid was first used as the working fluid in a 12-turn OHP by the Center for Thermal Management at the University of Missouri in 2006. The results of using nanofluids showed a significant improvement over results which used the traditional base fluid of water as the working fluid. The improvement was especially significant at low power; however, even at high power the improvement was measurable. The parameters affecting heat transfer performance were systematically investigated by researchers around the world. It was reported that the thermal resistance for the Al_2O_3-water nanofluid was lower than that of pure water, while the thermal performance of SiO_2-water nanofluid was worse than pure water. There is an optimal nanofluid concentration for the OHP. It is also worth noting that the effect of nanoparticle deposition on thin-film evaporation has not been investigated and might play a significant role in the thermal performance of the nanofluid OHP.

CONTENTS

In: Nanofluids
Editor: Yuwen Zhang
ISBN: 978-1-62618-165-6

Chapter 1

CRITICAL ISSUES IN NANOFLUIDS RESEARCH AND APPLICATION POTENTIALS

Milivoje M. Kostic*
Department of Mechanical Engineering, Northern Illinois University
DeKalb, IL, US

ABSTRACT

The objective of this chapter is to present critical research issues and application potentials of selected nanofluids, as related to the research accomplished and a number of hypotheses posed by different investigators – the goal is to shed some light on the subject as opposed to merely "generating heat." There are significant discrepancies among the experimental data available, as well as between the experimental findings and the theoretical model predictions, related to nanofluids thermo-physical characteristics. Oddly, there are more hypothetical theories proposed than reliable experimental results to verify those theoretical models. The nanofluids were hyped-up in the past, but it would be a mistake to hype-down nanofluids now and make premature judgments based on inconsistent and incomplete research to-date.

Regardless of ever-increasing number of research studies in this area, the basic research of convenience (repetition of similar experimentation with unstable nanofluids) remains in the initial stage; the promising nanofluids are still to be developed and results are still to be experimentally re-confirmed and established.

Development of many industrial and new technologies is limited by existing thermal management, and need for enhanced heat transfer and high-performance cooling. Nanofluids, stable colloidal mixtures of nanoparticles (including nanorods, nanofibers, nanotubes, nanosheets, and functional nanocomposites, even nano-droplets and nano-bubbles) in common fluids, have a potential to meet these and many other challenges. Colloidal nano-mixtures with functionally-stable and active-like nanostructures that may self-adjust to the process conditions, require systematic surface-chemistry study and enhancements (coatings with functional layers, surfactants, etc.), in addition to investigation of thermo-physical characteristics and phenomena.

* Email: kostic@niu.edu.

A comprehensive, systematic and interdisciplinary experimental research program is necessary to study, understand and resolve critical issues in nanofluids research to date. The research must focus on both, synthesis of nanofluids and a careful exploration and optimization of thermo-physical characteristics. Development of new-hybrid, drag-reducing nanofluids may lead to enhanced flow and heat transfer characteristics. The nanoparticles in these fluids yield increased heat-transfer while the long-chain polymers are expected to enhance flow properties, including active and functional interactions with nanoparticles, thus providing potential for many applications yet to be developed and optimized.

1. Introduction and Critical Issues

Regardless of ever expending nanofluid research effort, comprising many inconsistent experimental results and unproven hypothetical theories, followed by growing number of related publications, including a number of review articles, the state of the nanofluid research is still inconsistent and often conflicting, thus incomplete and inconclusive. Many challenges are to be resolved and unforeseen opportunities are to be pursuit in the future. The nanofluids were hyped-up in the past, but it will be a mistake to hype-down nanofluids now and make premature judgments based on limited research and inconclusive results.

It is not objective here to review the nanofluids' related literature, since it has been done in a number of publications. Many reviews on nanofluid research are provided [1-6], and more recently [7-9]. Therefore, the objective here is to present this author's views on selected nanofluids' critical research issues and application potentials, as related to the research accomplished and a number of hypothesis posed by different investigators – the goal is to shed some light on the subject as opposed to merely 'generating heat'.

Development of nanofluids, nano-technology based heat-transfer and other fluids, i.e., suspensions of different nano-materials in common and novel, base fluids (with rather complex structures and interactions), is a new challenge but also unforceen opportunity. It may open the road for development of many, complex nanofluids (including organic nanofluids) with diverse additives (including known surfactants, interfacial surface enhancers and other polymers), with many and unprecedented applications in existing critical areas as well as emerging and novel applications. The trend in further development of nanomaterials is to make them multifunctional and controllable by external means or by local environment, thus essentially turning them into useful nano-devices.

Nanofluids are stable colloidal suspensions of nano-materials (nanoparticles, nanorods, nanotubes, nanowires, nanofibers, nanosheets, other nanocomposites, or even nano-droplets and nano-bubbles) in common, base fluids, such as water, oil, ethylene-glycol mixtures (antifreeze), refrigerants, heat transfer fluids, polymer solutions, bio-fluids, and others. Nanoparticles are very small, nanometer-sized particles with their smallest dimension usually less than 100 nm (nanometers). The smallest nanoparticles, only a few nanometers in diameter, may contain a few thousand atoms. These nanoparticles can possess properties that are substantially different from their parent materials, and they may interact quite differently within their dynamic molecular structure with the base fluids, than the corresponding microparticles, and respond differently within different force-flux processes accompanied with mass-energy transfers. Similarly, nanofluids may have properties that are substantially different from their base fluids, like much higher thermal conductivity, and other flow and heat transfer characteristics.

Since Choi coined the term "nanofluids" [10] for carbon and metal-based nanoparticles in common heat-transfer fluids, research has intensified, due to the substantially increased thermal conductivity of those nanofluids, and the tremendous potential for many applications. Biologists Turner et al. [11] and physicists Pozar and Gubbins [12] have used the term nanofluids to describe bio-nanoparticles, like DNA and other protein molecules in aqueous solutions, or for fluids confined in slit nano-pores or other nano-meter sized enclosures.

Argonne National Laboratory is recognized for pioneering scientific activities in nanofluids research, including innovative production methods, thermal characterization, and theoretical studies that correlate enhanced thermal conductivity with static and dynamic mechanisms between nanoparticles and base-fluid molecular interlayers. At many other institutions around the world, including some industrial companies and collaborative associations, is underway [6, 13]. Number of publication rate increased considerably in recent years, from several per year rate in 1990's to over hundred per year recently, with several hundreds of archived publications so far [in *Science Citation Index* journals].

Regardless of accumulated research outcomes, many results are incomplete, some conflicting and without conclusive results. The state of the art in nanofluid research is still in initial phases, in part due to rather complex nature of nanoparticle materials and even more complex nanoparticle-base fluid interactions, often involving diverse surfactants and stabilization additives to prevent inherited tendency of nanoparticle conglomeration and clustering in the unstable colloidal mixture. The inherited complexity and inconsistency make it almost impossible to establish well-defined and reliable experimental results to verify existing hypotheses and to improve and develop new ones. There are many other issues to be addressed and resolved. It is hypothesized by this author that nanofluid thermal conductivity may be a function of temperature gradient (thus heat flux), in addition to temperature level dependence, the way non-Newtonian fluid viscosity is dependent on shearing rate, i.e., velocity gradient (thus flow rate).

Even a so-called "benchmark study" [14] is based on very limited and unfortunate choice of types of nanofluids, thus with rather limiting results; therefore, it may produce a disservice to the future research in this important area with unprecedented potentials. It may mislead (since "benchmark study" title) that the classical mixture theory predicts thermal conductivity of (most) nanofluids. It would be surprising that simple static mixture-theory (that includes only volume fraction ratio) will predict complex dynamic interactions of diverse constitutions, size and shapes of nanoparticles in base fluids. Mostly alumina nanoparticles (conveniently obtained) were tested and not those known to demonstrate anomalous TC enhancements, like metallic and CNT nanoparticles with relevant concentrations. Why such nanofluids were not reproduced by the participating institutions in the benchmark study?

Regardless of many publications of similar research, in essence, the nanofluids research is still in initial phase, when the present limited research (repetition of convenience) should substantially expend in type and scope, not to mention many other and yet to be discovered/engineered functional nanoparticles and innovative additives to enhance and optimize nanofluids properties and flow characteristics. The issue, in this author's opinion, is to discover or reproduce the nanofluids which show enhanced properties. Researching different nanoparticles with different additives in different base fluids using difference synthesis methods is a challenge, but (exactly because of it) also opportunity with many application potentials! That what the future research should be focusing on.

There are many important variables and issues related to making and using nanofluids, which is confirmed by significant discrepancy in the reported experimental data. Type of nanoparticles, their size, shape and distribution are important but not easily measured and usually not well-defined nor properly reported in the publications. Type of base fluids used, method of nanofluid production, use of surfactants and stabilization additives, including pH adjusters, etc. Conglomeration and clustering of nanoparticles in the nanofluid mixture is taking place before and after the nanofluid is made and during its use, and depends on many factors, especially on additives used. Two nanofluid samples with all of the parameters being the same but different type and amount of surfactants and/or pH adjusters used may result in quite different thermo-physical properties and flow and heat-transfer characteristics of apparently the same nanofluids. These and other unknown factors may explain anomalous and controversial results obtained by different researches. Furthermore, ultrasonic vibration is commonly utilized to enhance dispersion and breaking the clusters of nanoparticles. It is obvious that the duration and the intensity of the ultrasonication will affect the dispersion characteristics, however, the clusters will form again and their size will increase in time after ultrasonication [15]. Therefore, by using apparently the same samples, different results could be obtained just by varying the time between the ultrasonication and measurement of nanofluid characteristics.

In the advanced electronics and new emerging industries there is a great need for efficient thermal management and cooling. In many other industries such as energy production and utilization, manufacturing, transportation and commercial and residential buildings, thermal management is critical and nanofluids could yield significant benefits.

2. Production of Nanofluids and Challenges for Commercialization: Improved One-Step Method

There is a number of methods used to manufacture nano-materials, referred often as nanoparticles, and for production of nanofluids. Nanoparticles of various materials and forms have been produced by physical or chemical synthesis techniques. Typical physical methods include the mechanical grinding method and the inert-gas condensation technique [16]. Chemical methods for producing nanoparticles include chemical precipitation, chemical vapor deposition, micro-emulsions, spray pyrolysis, and thermal spraying. The specific processes for making metal nanoparticles include mechanical milling, inert-gas-condensation technique, chemical precipitation, spray pyrolysis, and thermal spraying. The production methods are reviewed by several researchers, including [6] and more recently by [9, 17].

Strong temperature dependence of thermal conductivity of nanofluids is very important and has potential to expend the possible application areas of nanofluids. Additional important issues during application of nanofluids are flow erosion and settling. Before commercialization of nanofluids, possible problems associated with these issues should be investigated and resolved. It should also be noted that, customary increase in viscosity of nanofluids over the base fluids is an important drawback due to the associated increase in pumping power. Therefore, further experimental research is required in that area in order to improve flow properties and to determine the feasibility of nanofluids.

Nanofluids of various qualities have been produced mainly in small volumes and for research purposes, but large-scale production at low cost of well-dispersed, stable nanofluids is required for commercial applications. The lack of large-scale production is a major barrier to testing and use of nanofluids in the transportation, industry and other applications.

Most of the nanofluids used in research so far are produced by a two-step process. First, nanoparticles are produced as a dry powder, typically by inert gas condensation [16]. The second step involves dispersion of dry nanoparticle powder into a base fluid, like water, oil or ethylene-glycol. An advantage of the two-step process is that the inert-gas condensation technique has been scaled up to commercial nano-powder production [18]. A deficiency of this method is the tendency of nano-powders to agglomerate during storage and dispersion in the base fluids, particularly with heavier metallic nanoparticles. Surfactants and other surface-stabilization additives can be used to achieve more homogeneous and more stable suspensions, however they may influence the nanofluids properties. In addition to mechanical mixing, ultra-sonic mixers are used to break up agglomerates and give more uniform dispersions. In general, although the process works well for some oxides, it has not been able to yield metallic nanofluids with substantially enhanced thermal conductivity.

By contrast, the one-step physical and chemical methods have potential to produce better quality nanofluids. For example, a physical one-step method consists of a direct-evaporation process, involving nanoparticle source evaporation and direct condensation and dispersion onto the base fluid in a single step. This method has been developed by Yatsuya et al. [19] and improved by Wagner et al. [20]. The one-step method has been employed by Choi and Eastman [21] in Argonne National Laboratory (ANL) and successfully used to produce nanofluids with very small copper nanoparticles (about 10 nm) and exceptionally high thermal conductivity [22]. However, the one-step process is intrinsically more difficult to reproduce, since particles cannot be characterized and pre-sorted before addition to the fluid. Consequently, the ANL method, although an excellent idea, needed to be substantially improved in order to yield improved control of nanoparticle sizes and sustained nanofluid production. The improvement of the Argonne one-step method for nanofluid production has been realized and a U.S. patent has been issued recently (Kostic et al. [23]). Details of the improvement will be presented below.

2.1. Improvement of Physical One-Step Production Method

For nanofluids with high-conductivity metals such as copper, a single-step technique is preferable to the two-step process to enhance dispersion and prevent oxidation of the particles. Argonne National Laboratory developed a one-step physical method for creating nanofluids, by nanoparticles being formed and dispersed in a fluid in a single process. This patented single step method involves direct evaporation and has been used to produce non-agglomerating copper nanoparticles that remain uniformly dispersed and stably suspended in ethylene glycol [21]. The technique consists of condensing nanoparticles from the vapor phase directly into a flowing low-vapor-pressure ethylene glycol or oil in a vacuum chamber. The well-dispersed nanofluids of Cu in ethylene glycol enhance the thermal conductivity of the base fluid by up to 40% at the particle volume concentration of 0.3 %, significantly larger than the prediction of effective medium theory [22]. Although the one-step physical method has produced nanofluids in small quantities for research purposes, it has a number of deficiencies, and needed to be improved, since lack of consistent nanofluid production limits the progress of the future research in this and related areas.

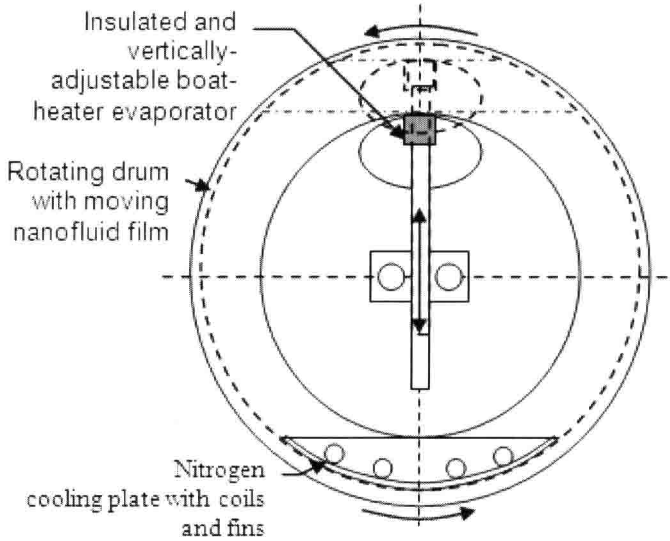


Figure 1. Improved new-design for the one-step, direct-evaporation nanofluid production apparatus (U.S. Patent No. 7,718,033) [23].

An improved "One-step method for the production of nanofluids" has been developed and a U.S. patent has been issued recently [23], see also Figure 1. The improved method and system is provided for producing nanofluids by a so called one-step direct metal evaporation and its deposition on a moving liquid film and further dispersion and mixing of nanoparticles within the fluid.

The improved method and system is achieved by the following: better positioning (longitudinal instead of crosswise) and variable-adjustable distance between the metal evaporation source and liquid film, which achieves smaller particle deposition path and smaller fluid-film exposure over the heated source and thus smaller nanoparticle size, but at the same time it provides larger liquid film area and thus larger deposition rate. Furthermore, better heater evaporation source insulation reduces the heating power which is possible to be balanced by an improved new heat-exchanger design of nitrogen cooler and increased drum rotation, thus providing lower liquid temperature and pressure which contributes to smaller nanoparticle size, and provides for continuous, steady-state production of nanofluids with desired nanoparticle size distribution. Additional improvement features include a liquid feed-in, inert gas flashing, visual observation, and better process heating control all of which further contribute to continuous, steady-state operation and control of temperature and pressure for production and optimization of desired nanofluid qualities and quantities.

The improved one-step process and system for production of nanofluids includes placing a base fluid, such as ethylene glycol or oil, in a rotating cylindrical drum situated in a vacuum chamber. The rotating axis of the drum is preferably horizontal, and the drum with solid back-