Application of Nanofluid for Heat Transfer Enhancement (Spring 2013)

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Abstract—NanoFluid have amazing advantage over base cooling fluids in terms of heat transfer removal characterization. In this paper a review on potential applications of Nanofluid technology in heat transfer enhancement has been addressed. This review sheds light on the current state of the art experimental research undertaken in this field and introduces today's novel ideas to resolve the present and upcoming issues with fast developing devices and power generation technologies that the world is experiencing. The continent and nation-wide funded research projects along with problems and shortcomings are addressed and research gaps in the way of technology exploitation are introduced.

Index Terms—Nanofluid, Nanoparticles, Heat transfer, industry, emission , efficiency, conductivity, convection, Critical heat Flux

I. INTRODUCTION

Nanofluids consist of base fluid enriched with particles of size smaller than 100 nm (Nanoparticles). The first thorough fundamental studies with "nanoparticles" were underway in the USA and Japan by in ERATO project. Nanofluids as introduced earlier are characterized by an enrichment of a base fluid like Water, toluene, Ethylene glycol or oil with nanoparticles in variety of types like Metals, Oxides, Carbides, Carbon. Mostly commonly recalled Nanofluids could be typified as TiO₂ in water, CuO in water, Al₂O₃ in water, ZnO in Ethylene glycol. Today Nanofluid are sought to have wide range of applications in medical application , Biomedical industry, detergency, power generation in nuclear reactors and more specifically in any heat removal involved industrial applications.

Amazing potential of Nanofluid in heat removal improvement was first discovered in 2001 by Eastman et. al and Choi et al. They discovered that less than 1% volume fraction of copper nanoparticles or carbon nanotubes dispersed in ethylene glycol or oil can increase their thermal conductivity by 40% and 150%, respectively. The ongoing research ever since then has extended to utilization of Nanofluids in Microelectronics, Fuel cells, Pharmaceutical processes, Hybrid-powered engines, Engine cooling, Vehicle thermal management, Domestic refrigerator, Chiller, Heat exchanger, Nuclear reactor coolant, grinding, Machining, space technology, Defense and ships, and boiler flue gas temperature reduction. Today it is estimated that the potential market for Nano-fluids in heat transfer applications reach over 2 billion dollars per year, and likely to grow even further in the next few years.

Facing contradictory viewpoints in study of properties of Nanofluid is found a routine as in many other research studies about different topics. This is well justifiable by the fact that not much of fundamental studies have been devoted to this topic to date. As an instance, while it was reported by Buongiorno and Hu in 2007 that Nanofluids behave as is expected from normal flows, Kaufui V. Wong and Omar De Leon showed later in 2010 that classical models cannot be used to explain adequately the observed anomalous enhanced thermal conductivity and heat convection of Nanofluids. Analogously, researchers like Kleinstreuer et al. brought this challenge in 2008 that central question in microfluidics and off course in Nano-fluid modeling is the validity of the continuum assumption. In addition to this, Reynolds
number in convectional micro-channel flow of Nanofluids is in applications like drug delivery and heat removal from hyper compact systems is in the order of 0.002 to 0.04 which is comparably very small to normal flows and this huge difference violates the regular expectation of Laminar-to-Turbulent transition threshold associated to this particular type of flow.

In this paper it is tried to highlight the promising applications of Nanofluid technological concepts in industrial sections as well as power generation section with a critical focus on efficiency improvement and emission mitigation potential as well as consideration of hazard and peculiarity measures.

II. HEAT TRANSFER APPLICATIONS

Amazing capability of Nanofluids in heat transfer enhancement has encouraged researcher in recent decades to develop concepts and technologies advocated by manufacturers of ultra-compact, miniaturized and intrinsic electronic chips. The uplifting demand for higher speed, multiple functioning, more powerful and smaller sized boards has almost doubled number of transistors on electronic chips with production of localized heat flux over 10 MW/m2 and the total power exceeding 300 W. Promising to fulfill this critical need, technologies like “Nanofluid in Oscillating Heat Pipe” and “Nanofluid With Tunable Thermal Properties” emerged by Ma et al. 2006 and Philip et al. 2008 respectively (Fig. 1 top and bottom rows respectively). According to Ma et al. “there is no exiting low cost cooling mechanism that can effectively manage this amount of heat effectively”. According to Philip et al., the observed reversible tunable thermal property of Nanofluid with advantage of %300 increase in thermal conductivity of the based fluid may find many technological applications for this fluid in nanoelectromechanical system (NEMS) and microelectromechanical system (MEMS) based devices. For example, depending upon the cooling requirement, the current or magnetic field can be precisely programmed to obtain the desired level of TC enhancement or cooling.

Although no typical answer exists to explain the odd behavior of the Nanofluid material to date, researcher could properly explain the great privilege of the Nano particles over micro particles in formation of enriched fluid for their super-efficient heat removal capability. He et al. 2008 explains that on one hand micro/macro particle bring about little thermal enhancement to the base fluid while on the other hand abrasion, channel clogging and higher pressure drop are comparably higher than those of Nanofluids. Furthermore according to Eastman et al. 2004, to achieve such an enhancement concentrations above %10 of volume fraction must be applied which very readily face stability and rheological disorders. He et al. further highlights Nanofluids by their excellent stability, higher thermal conductivities than that predicted by currently available macroscopic models as well as their advantage of little pressure drop. Interestingly Eastman et al. has pointed out similar properties accompanying the advantages of strong temperature dependent effects and significant increase of critical heat flux (up to 3 times greater than the base fluid).

In study of Nanofluids researchers like Jeyhooni et al. 2012, Hea 2006 and 2012, Madhusree et al. 2012 concluded that up to an optimum point there exists a direct ascending trend of conductivity of Nanofluid with increase of concentration of particles and decrease of particle size.

III. PHYSICS OF NANOFLOIDS

In 2004 Eastman assessed the nanofluidic properties of the carbon Nanotubes. The driving force for this study were interesting properties like astonishingly high
conductivity, low density and high aspect ratio other factors. As their study did not produce expected results, significance of intervening factors was critically investigated. They found out that alignment of the nanotubes, volume loading, adhesion between the fibers and the matrix, and particle were responsible for deviation of results. According to Eastman 2004, particle coating plays a negative role in performance of nanoparticles towards increasing the thermal conductivity of the base fluid at only 3% weight loading of the Nanotubes.

As another example Choi et al. in 2003 observed a 300% increase of thermal conductivity of the Nanofluid compared to the based fluid. Alignment factor was proved important by Choi at al. in 2003 after an additional 10% thermal conductivity to the already increased thermal conductivity (300%) was observed with tubes aligned with the fluid movement direction. As of their conclusion Choi et al. considers the interaction between matrix and tubes as an important factor as well as interfacial resistance, aspect ratio. Surprisingly they used molecular dynamic and Atomistic simulation in their as a tools for better understanding and analysis of the governing phenomena.

IV. ADVANTAGES OF NANOFLOUIDS

Spectacular capability of Nanofluids in heat transfer/removal enhancement can properly address the energy demand and emission issues of the present world. In United State only, utilization of Nanofluids for industrial cooling could result in great energy savings and resulting emissions reductions. For U.S. industry, the replacement of cooling and heating water with Nanofluids has the potential to conserve 1 trillion Btu of energy. For the U.S. electric power industry, using Nanofluids in closed-loop cooling cycles could save about 10–30 trillion Btu per year (equivalent to the annual energy consumption of about 50,000–150,000 households). The associated emissions reductions would be approximately 5.6 million metric tons of carbon dioxide; 8,600 metric tons of nitrogen oxides; and 21,000 metric tons of sulfur dioxide.

In more localized end points, faster and more robust data servers and computers, electronic devices, sensors and actuators can appreciably boost the businesses, reduce the instances of circuit burns and electricity cut-offs and hence save a significant amount of money to end users and service providers. Consequently a potential of 2-billion dollar-per-year investment is estimated to flow into this great technology. Figure 2 shows a surprising advantage of %60 more efficiency in server cooling which is expected to bring about a significant boost of efficiency for the service provider.

V. A REVOLUTION IN NUCLEAR POWER GENERATION

As was discussed earlier utilization of Nanofluid cooling technology can effectively boost electric power generation. The novelty is to increase the critical heat flux on surfaces of tubes which are exposed to hot reactor core by subsiding heat transfer inhibitive generation of bubbles through deposition of a very thin layer of nanoparticle floating in the coolant media. Kim et al. in 2007 experimented a media containing 0.01 percent volume loading of Alumina nanoparticle and demonstrated their finding in fig. 3 of this report.

The revolutionary change in nuclear power generation technology stems from the fact that currently 437 nuclear plants are in operation worldwide and considering a potential of 20 percent power uprate without changing fuel assembly and marginal safety of the plant (Buongiorno et al. 2008) can cover the annual nuclear electricity production of the Germany and France.

On the other side, rapid cooling of Nanofluid agent in the media in case of any accident can dramatically reduce the safety risks associated with melting of the core and impressively renders the situation well controllable. (Buongiorno and Hu 2007)
VI. MORE ON APPLICATION OF NANOFLUIDS IN HEAT TRANSFER ENHANCEMENT

Geothermal power extraction

One of limitations in extraction of heat from depth of the ground is thermal limitation of drilling tools, pipes, and sensory devices. Nanofluid cooling has great application in cooling down the apparatus which are supposed to work under high temperature and friction conditions. While there is a wide gap development of concepts related to this application, impressive profit strongly invites and encourages researchers to enable the world to exploit far beyond 200ZJ energy out of 2000ZJ extractable geothermal energy and this is possible through the superconductor Nanofluid (Wong and Leon 2009).

Automotive industry

Application of Nanofluids as coolants in different cooling units like radiators and intercooler, AC etc is well attended these days. Enhanced cooling of the engine with smaller radiator in size and increased engine efficiency through hotter combustion, optimum transmission, and breaking functioning through lower working temperature has absorbed attention of big investors nowadays. The driving force for investment is higher efficiency, cheaper radiators and pumps, 6 percent less fuel consumption, less emission production and in summary higher quality while cheaper automobiles, economic profitability for manufacturer and renewability considerations.

As pioneers of Nanocoolant fluid for automobile application, NanoHex ® project started in European union in 2009 with initial funding of 8.3 million Euros. Similarly researcher from Argonne ® Company started a supported project by the United States government in 2009 to pioneer a Nanocoolant used for purpose of power electronic cooling in hybrid electronic vehicles. These engineers aspire to achieve 15 percent more cooling power through this technology and they hope that with the support from Valvoline ® their graphite based Nanofluids can remove the need to the second heat exchanger of the vehicle.

VII. PROBLEMS AND DRAWBACKS

knowledge in atomic levels

According to Eastman et al. 2004, although the potential for the use of Nanofluids in a wide range of applications is promising, a seriously hindering fact in development of the fields and applications is that a detailed atomic-level understanding of the mechanism(s) responsible for the observed property changes remains elusive. In the absence of this treasury of knowledge people rely on few simplistic models and in some cases large discrepancies between prediction and measurement remains a secret. As an instance, different scenarios have been proposed by Estman et al 2004 to explain the true reason for remarkably lower measured conductivity of Nanotubes in water.

Toxicity and disposal problems

Nanoparticles like silicon are extremely health threatening and presence of these particles in aquatic environment will severely endanger life of humans and animals through digestion and inhalation of these contaminants. Therefor some issues regarding the use of Nanofluids in a power plant system include the unpredictability of the amount of nanoparticles that are carried away by the boiling vapor. One other concern is what extra safety measures that have to be taken in the disposal of the Nanofluid. Hence extra caution must be taken in regards to the concentration and disposal of the material which calls for development of standards and procedural instructive and training sessions.

Erosion and abrasion

In the light of advantages of Nanoparticles over micros particles, still abrasion and erosion problems issues exist with these extremely fine particles. In particular, consideration of possible chemical reactions and oxidation with materials of the media (walls and the fluid base) must be carefully accounted for. As a practical measure, Wong and Leon 2009 refer to the fact that application of Nanofluid coolant to boiling water reactors (BWR) is predicted to be minimal because nanoparticle carryover to the turbine and condenser would raise erosion and fouling concerns.
Cost inhibition

Use of diamond, gold, silver, and has been studied in study of researchers like Patel and coworkers 2003, Eastman 2004, Ma et al. 2006. Associate cost of integration of gold in water as a Nanofluid with volume fraction loading of 0.011%vol for a system containing 200 milliliter of the fluid will be $4035\textsuperscript{1}. As another instance, the price of 200 milliliter of a 1% volumetrically loaded water-carbon nanotube fluid will be $6500\textsuperscript{2}. In the view of the author of this paper, insurability about cost effectiveness besides technical aspects explained above will confine the development of systems to laboratory scale experiments and prototypes still for a considerable time.

VIII. RESEARCH GAPS

Critical knowledge needs to be collected about phenomena happening in atomistic scales and This invaluable treasury of knowledge along with results of extensive experimental study will enable the experts and professionals towards predicting the behavior of different material under different working conditions and categorizing them for specific applications based on suitability, compatibility and optimum functionality. Knowledge about controlling the deposition film characteristics such as the structure and thickness in nuclear power plants, effect of size, shape and type of nanoparticles and type and temperature of the media including the base fluid, surfactant and heat exchanging surfaces for wide range of materials form part of the gaps in the young Nanofluid cooling technology to be filled attentively.

Moreover, the author has not found a through theoretical and mathematical study on analysis of this specific type of multiphase flow. Erosion, abrasion, deposition, agglomeration and clustering and clogging are phenomena which are expected to be theoretically and numerically studied in near future. Besides, production and synthesis of nanoparticles to optimum size and shape and for strong stability Nanofluids is another broad research area which will prospectively devout to itself enormous number of publications in near future.

\textsuperscript{1} The daily price of Gold (47.51 USD/gr) was used according to http://goldprice.org/ and density of Gold (13 g/cm\textsuperscript{3}) from http://en.wikipedia.org/wiki/Gold
\textsuperscript{2} The price of CNT (255 USD/gr) was used according to http://www.cheaptubesinc.com/carbon-nanotubes-prices.htm and density of Gold (13 g/cm\textsuperscript{3}) from http://en.wikipedia.org/wiki/Gold

IX. CONCLUSION

Nanofluid cooling has variety of application in power generation, industrial, information technology, and business sections. Promising advantages of Nanofluids through enhancement of heat transfer have been summarized as efficiency and safety boos in power generation, product size, cost and waste reduction, product quality and aesthetic improvement, energy consumption and emission reduction, faster communication and computation and ultimately in one word prosperity of the society. Besides research and communication not only will invaluably advance the science but will also bring the researcher form different parts of the word closer together for an enjoyable participation and collaboration.

Finally dangerous and many unknown sides of the Nanofluids utilization must be addressed to ensure about impressive role of this advanced technology in driving the life on planet earth towards more prosperity. This end will be met thorough years of extensive research and development of models, experiments and patents.

REFERENCES


