NEXT FRONTIER IN NANOFLUIDS RESEARCH AND DEVELOPMENT

Liqiu Wang

Department of Mechanical Engineering, the University of Hong Kong, Pokfulam Road, Hong Kong

Introduction

Nanofluids**,** fluid suspensions of nanometer-sized particles, are research challenges of rare potential but daunting difficulty. The potential comes from both scientific and practical opportunities in many fields. The difficulty reflects the issues related to multiscales. Nanofluids involve at least four relevant scales: the molecular scale, the microscale, the macroscale and the megascale. The molecular scale is characterized by the mean free path between molecular collisions, the microscale by the smallest scale at which the law of continuum mechanics apply, the macroscale by the smallest scale at which a set of averaged properties of concern can be defined and the megascale by the length scale corresponding to the domain of interest [1, 2]. By their very nature, research and engineering practice in nanofluids are to enhance fluid macroscale and megascale properties through manipulating microscale physics (structures, properties and activities). Therefore, interest should focus on addressing questions like: (i) how to effectively manipulate at microscale, (ii) what are the interplays among physics at different scales, and (iii) how to optimize microscale physics for the optimal megascale properties. In this talk we summarize methodologies available to effectively address these central problems and identify the future research needs by taking heat-conduction nanofluids as examples.

Microscale Manipulation: Microfluidic Nanofluids

The ability to manipulate at microscale depends very much on nanofluids synthesis techniques. The functional outcomes of existing nanofluids have not been satisfactory because of the inadequacies of conventional synthesis approaches in engineering microstructures and properties of nanofluids. We have developed a one-step chemical solution method (CSM) for synthesizing nanofluids that takes advantage of the ability of manipulating atoms and molecules through chemical reactions in the liquid phase, and applied the CSM to synthesize several novel nanofluids (Fig. 1) [3-5]. In an attempt to resolve the issue of controlling the microscale while operating at the macroscale in the CSM, we propose to replace batch-based macroreactors in the CSM by continuous-flow microfluidic microreactors (for example, those in Fig. 2), thereby proposing a novel microfluidic one-step CSM for effective synthesis of high-quality nanofluids with controllable microstructures. Our aim is to define the potential of this promising synthesis technique against an important target of controlling reactions accurately with a rapid and precise mixing. The success of this technology may change the way nanofluids are synthesized and applied and will positively impact nanofluid technology.

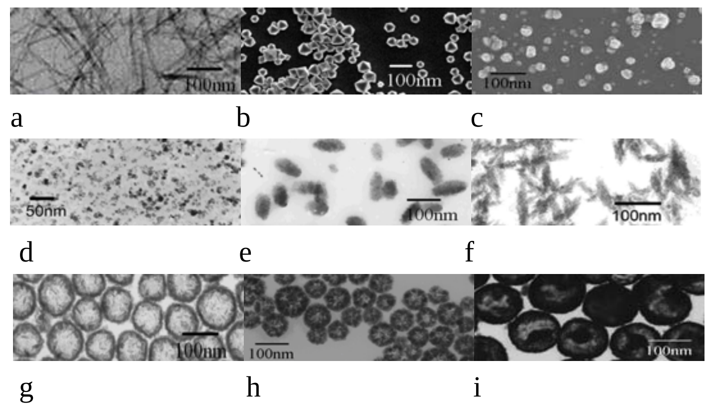

Figure 1: TEM/SEM images of some nanoparticles from “drying” samples of nanofluids synthesized by the chemical solution method [3-5] (**a**: $CePO_4$ nanofibers; **b**: octahedral Cu_2O nanoparticles; **c**: N-vinylcaprolactam polymer-nanoparticles; **d**: spherical Fe_3O_4 nanoparticles; **e**: elliptic Cu nanorods; **f**: needle-like CuO nanoparticles; **g:** hollow CuS nanoparticles; **h**: hollow *and* wrinkled Cu_2O nanoparticles; **i**: Cu_2O (core)/CuS (shell) nanoparticles).

Macroscale Heat Conduction: Thermal Waves

In an attempt to determine how the presence of nanoparticles affects the heat conduction at the macroscale and isolate the mechanism responsible for the reported significant enhancement of thermal conductivity, a macroscale heat-conduction model in nanofluids is rigorously developed [3]. The model is obtained by scaling-up the microscale model for the heat conduction in the nanoparticles and in the base fluids. The approach for scaling-up is the volume averaging with help of multiscale theorems. The result shows that the presence of nanoparticles leads to a dual-phase-lagging heat conduction in nanofluids at the macroscale. Therefore, the molecular physics and the microscale physics manifest themselves as heat diffusion and thermal waves at the macroscale, respectively. Depending on factors like material properties of nanoparticles and base fluids, nanoparticles' geometrical structure and their distribution in the base fluids, and interfacial properties and dynamic processes on particle-fluid interfaces, the heat diffusion and thermal waves may either enhance or counteract each other. Consequently, the heat conduction may be enhanced or weakened by the presence of nanoparticles. Focused efforts are required to find the correlation between the microscale physics and macroscale properties based on the three closures and to detail properties of thermal waves and how they interact with the heat diffusion.

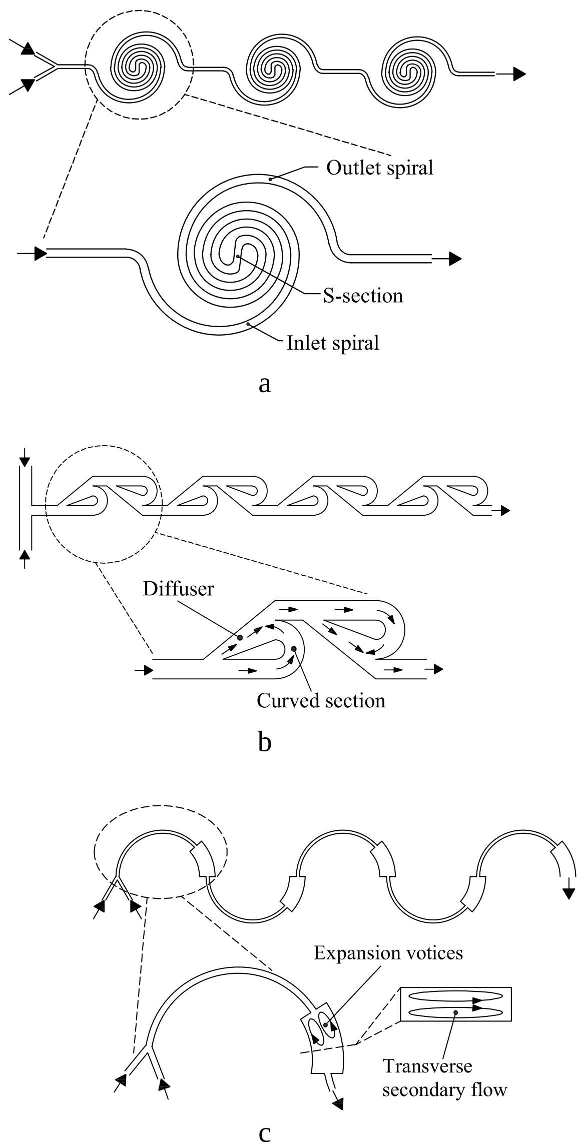

Figure 3: Three kinds of microfluidic reactors (a: three spiral-microchanel units; b: four modified-Tesla-structure units; c: five semicircular-arc units).

Megascale Optimization: Constructal Nanofluids

Practical applications of nanofluids are always with an ultimate megascale goal to which nanofluid research must pay attention [6]. The constructal design employs a hierarchical strategy to construct nanofluids for the optimal megascale performance and thus serves this very well [7, 8]. Such a study shows, for example, that the march towards uniformly-dispersed particles in base fluids not necessarily leads to an optimal megascale performance depending on systems that use nanofluids [6]. Our focus of future research and development should thus be not only on nanofluids themselves but also on their systems and ultimate goals. The march toward micro and nano scales must also be with the sobering reminder that useful devices are always be macroscopic, and that larger and larger numbers of small-scale components must be assembled and connected by flows that keep them alive. Clearly, an intensive effort is in great demand to *construct* nanofluids with respect to available freedoms for various systems of practical applications.

Acknowledgement: The financial support from the Research Grants Council of Hong Kong (GRF717508) is gratefully acknowledged.

References

1. Wang, L. Q., Xu, M. T. & Wei, X. H. 2008 Multiscale theorems. *Advances in Chemical Engineering* **34**, 175-468.
2. Wang, L. Q. 2000 Flows through porous media: a theoretical development at macroscale. *Transport in Porous Media* **39**, 1-24.
3. Wang, L. Q. & Wei, X. H. 2009 Nanofluids: synthesis, heat conduction, and extension. *J. Heat Transfer* **131**, 033102/1-033102/7.
4. Wei, X. H., Zhu, H. T. & Wang, L. Q. 2009 $CePO_4$ nanofluids: synthesis and thermal conductivity. *J. Thermophysics Heat Transfer* **23**, 219-222.
5. Wei, X. H., Zhu, H. T., Kong, T. T. & Wang, L. Q. 2009 Synthesis and thermal conductivity of Cu_2O nanofluids. *Int. J. Heat Mass Transfer* (in press).
6. Bai, C. & Wang, L. Q. 2009 Constructal design of particle volume fraction in nanofluids. *J. Heat Transfer* (in press).
7. Bejan, A. & Lorente, S. 2008 *Design with Constructal Theory*. Wiley.
8. Bejan, A. & Lorente, S. 2006 Constructal theory of configuration generation in nature and engineering. *J. App. Phys.* **100**, 041301/1-041301/27.