NANO-DEVICES FOR THERMAL MANAGEMENT, SESNING AND THERMAL STORAGE

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ABSTRACT

Recent scientific and technological advances in the area of thermal and fluid sciences (more particularly in multi-phase flows) have demonstrated the significant impact of the small scale effects on augmenting the transport processes. The applications of these fundamental aspects in multi-phase flows are quite diverse – ranging from solar thermal energy storage to cooling applications to life sciences. Hence, the activities in the research group of the author are geared towards addressing these technological advances, ranging from fundamental focus to commercial applications. These endeavors are primarily at the interface of:
(a) multi-phase flows (e.g., nanofluids, micro/nano-scale flows, and boiling), and
(b) emerging technologies (e.g., MEMS, micro-capillary driven flows, bio-microfluidics, and bio/nano-technology).
The research results from these topics are summarized in this paper.

INTRODUCTION

The research activities in the research group of the author explores the various micro/nano-scale effects in multi-phase flows. These research topics address both nanofabrication/ nano-synthesis techniques as well as the development of nanotechnology enabled sensing platforms to investigate the mico/nano-scale transport phenomena in multi-phase flows.. The primary application of these research topics is in the Thermal Energy Storage (TES) and improving thermodynamic efficiencies of thermal systems (such as HVAC equipment). The several topical areas that are under investigation in the research group of the author (“Multiphase Flows and Heat Transfer Lab.) are itemized below.

AREA 1: NANOFLUIDS FOR COOLING AND THERMAL STO-RAGE (SOLAR THERMAL ENERGY PROGRAM AND THERMAL ENERGY STORAGE)

The research group of the author has demonstrated cooling enhancements by ~8-30% using nanofluids in compact heat ex-changers (in collaboration with AFRL as an ASEE/AFOSR Summer Faculty Fellow in 2006 and 2007) [1]. The nanofluids were found to precipitate nano-fins on the heater surface and thereby augment the heat flux. The nanofluids were synthesized using Poly Alpha Olefins (PAO) – a synthetic oil that is used for avionics/ electronics cooling. The nanofluids were synthesized by doping PAO with nanoparticles at 0.3% and 0.6% concentration by weight. The nanoparticles used in this study were ex-foliated graphite and multi-walled carbon nanotubes (MWCNT). Surprisingly, it was observed that the nanofluid specific heat capacity was enhanced by 50%. Hence, it was concluded that nanofluids have better efficacy in thermal energy storage applications compared to cooling applications.

This observation led to another project funded by the DOE Concentrated Solar Power (CSP) program for harnessing solar thermal energy conversion. Thermal Energy Storage (TES) techniques are currently under development at DOE to enhance the thermodynamic efficiencies of Solar Energy and Thermal Power (SETP) systems. It is expected that raising the storage temperatures to 600 °C (from the current practice of 400 °C) can reduce the cost of solar energy production by as much as 50%. However, the Phase Change Ma-terials (PCM) available to operate at these extremely high temperatures suffer from very poor thermo-physical properties (e.g., low specifc heat capacities and thermal conductivity). Typical PCM under in-vestigation in the CSP program include alkali metal salt eutectics (e.g., nitrates, chlorides and carbonates of sodium, potassium, lithium, calcium, etc.). In these research investigations anomalous enhancement of specific heat capacity value of these eutectics was observed on doping with minute concentrations of nanoparticles. Using CNT at 0.05-0.5% weight concentrations the specific heat was enhanced by more than 20%. Using silica nanoparticles at ~1-1.5% weight concentrations the specific heat of these eutectics was enhanced by more than ~20-100% [2-7].

Current research efforts are focused on performing Molecular Dynamics (MD) simulations to explore the role of nano-fins in augmenting nano-scale transport mechanisms (this research study was funded by DARPA-MF^3 Center). The role of fluid properties and nano-scale geometries as well as the material properties of the nano-fins (e.g., carbon nanotubes, silicon nanofins, etc.) in augmenting the transport processes are being explored in this study. These fundamental studies will help to illuminate and resolve the conflicting data reported in the literature for heat flux enhancement by nanofluids and by nano-structured surfaces. MD simulations are being used to design nanofluids for solar thermal storage applications [8-13].

With research funding from Qatar National Re-search Foundation (QNRF) in 2009 a three year study commenced in the research group of the author on measuring the fundamental transport proper-ties of nanofluids as well as to study their thermo-fluidic interactions during flow in heated microchan-nels and nanochannels. Experiments are in progress using a confocal microscope and by seeding flows inside microchannels and nanochannels using nano-particles [7].

AREA 2: POOL & FLOW BOILING ON NANO-STRUCTURED SURFACES:

The research group of the author are also investigating micron-to-nano scale heat transfer phenomena in pool and flow boiling. Micron-scale features in boiling cause the formation of “cold spots”. These cold-spots are able to transmit almost 60-90% of the total heat transfer in boiling. Using Carbon Nano-Tube (CNT) coated surfaces cooling was enhanced by 60-300% in pool boiling of refrigerants (compared to uncoated surfaces), probably due to enhancement of these cold spots [14-20] (this research study funded by Texas Engineering Experiment Station). It was also found that these nano-structures behave as “nano-fins” (enhanced heat transfer surfaces due to augmentation of effective surface area). To further investigate these phenomena, using silicon nano-fins as heater surfaces the pool boiling of refrigerants was enhanced by 120% [21-23] (this research study was funded by NSF).

An experimental apparatus for flow boiling studies was developed subsequently. Using CNT coated hea-ters, flow boiling experiments were conducted using this apparatus [24]. Using CNT coatings flow boiling was enhanced by ~80-180% [24-26] (research study funded by ONR

Thermal Management Program). The applications are in materials processing and thermal management (electronics cooling). Further investiga-tions are in progress with support from ONR Thermal Management Program.

AREA 3: TEMPERATURE NANO-SENSORS FOR STUDY OF BOILING CHAOS AND FRACTAL STRUCTURES:

The research personnel in the research group of the authored designed, fabricated and tested several architectures/ configurations of temperature nano-sensors ("Thin Film Thermocouples" or "TFT") using thin film deposition techniques [27-29]. The TFT are ~ 10 micron in width and ~200-400 nm in thickness. These TFT have response times of ~ 10 nano-seconds (frequency response of ~ 10 MHz) and can be fabri-cated in a high density array (~ 20-50 microns square pitch). It may be noted that if required these TFT ar-rays can be fabricated to much higher spatial densities with each sensor having a width and depth of ~ 200nm. Such small sensors would have the ability to measure temperature transients of the order of MHz or higher.

These sensors were used to measure surface tem-perature fluctuations ("cold spots") in pool boiling. Using the transient temperature data we were able to estimate the non-linear dynamical nature of the trans-port processes (boiling chaos) on bare and nano-structured surfaces. It was observed that the order of the boiling chaos was much higher than predicted in the contemporary boiling chaos literature. These sen-sors were also used to investigate the temperature transients during flow boiling [30-34].

In collaboration with Prof. Jungho Kim (University of Maryland) the research group of the author also explored the fractal structures for wall void fractions (bubbles) in pool boiling. From the fractal models it was observed that the fractal structures associated with bubble perimeter is related to the wall heat flux. It was also observed that the fractal structures associated with bubble area (contact area of the bubble on the heater surface) is related to the wall superheat. Physically, this relates to the for-mation of cold spots in pool boiling. Since the perime-ter of the bubbles controls the size of the cold spots (which is responsible for 60-90% of heat flux in pool boiling) – it is expected that the fractal structures con-trolling the bubble perimeter controls the wall heat flux. Similarly the fractal structures associated with the bubble contact area on the heater surface controls the wall temperature (and therefore the wall superheat) [35].

AREA 4: NANO-FABRICATION & NANO-SYNTHESIS:

DPN™ (Dip Pen Nanolithography) is a versatile technology that leverages microfluidic ink delivery systems with Scanning Probe Microscopy (SPM) tech-niques, such as Atomic Force Microscopy (AFM). The author and his research group members are currently developing the next generation micro-fluidic devices for DPN [36-41] (e.g., Fountain Pen Nanolithography or "FPN") using capillary driven multi-phase flows (research study funded by Texas Space Grants Consortium). The applications are in nano-catalysis, combinatorial nano-synthesis, bio-nanotechnology (e.g., cancer nanotechnology), mask-less-lithography and nano-sensors for homeland secu-rity, bio-security and explosives detection (e.g., “nano-nose” and “nano-tongue”).

The authior invented a process for synthesizing Carbon Nanotubes with tunable chirality (either metallic or semi-conducting) using DPN [42-44] (research study funded by SPAWAR/ DARPA-MTO). In this research program he also developed processes for synthesizing CNT of a single chirality under “room temperature” conditions using MEMS enabled platform consisting of a series of micro-heaters inte-grated with micro-cantilever array [45]. This technique is a “dry” process obviating the need for process gasses.

The author also developed an innovative MEMS platform called PIMTEM (manufactured under sub-contract by MEMS Exchange Inc). PIMTEM platform will be used in future studies for in-situ microscopy of the synthesized CNT and for characterizing their chirality (material properties) [47, 48].

The pre-cursor to these inventions was a study in the synthesis of CNT using a combination of nano-patterning of catalyst seeds using DPN (such as Ni, Fe, Pt, Pd, etc.) followed by Chemical Vapor Deposition (CVD) process using acetylene as the organic source [49, 50]. Recently this technique for synthesis of CNT was also verified using Plasma Enhanced CVD (PECVD) process for synthesis of individual CNT and carbon nano fibers (CNF) [51].

AREA 5: MICRO/NANO-TECHNOLOGIES FOR SENSING (MEMS AND CAPILLARY DRIVEN FLOWS IN MICRO/NANO-FLUIDICS):

The author also reported several studies where he also explored the applications of micro/nano-scale flows in biological flows and biomedi-cal devices. For example a Lab-On-Chip device for synthesis of gold nano-particles was developed using a peptide-protein/antibody assay (funded by AFRL). The applications for this micro/nano-fluidic device are in water quality monitoring applications and can aid in the development of auto-nomous, cheap, disposable devices which operate like a “litmus-paper” where a piece of paper changes color if the sample contains hazardous levels of industrial or toxic pollutants (e.g., containing mercury or arsenic). This paper substrate is designed for such operation using capillary driven multi-phase flows [52-54].

Utilizing fundamental aspects of two phase flows the author and his graduate student demonstrated that bulk properties of liquids (e.g., viscosity) can vary drastically in confined spaces (funding from DAPRA-MF3 Center). This study provides fundamental insights into behavior of fluids which are planned for further exploration and has implications in wide ranging disciplines from tribology to biology/ life-sciences [55-57].

The author also developed a MEMS platform, which in combination with DPN techniques, can be utilized for explosives sensing applications (e.g., “nano-nose” and “nano-tongue”). This MEMS device was successfully demonstrated for testing several explosives vapors and chemical warfare agents, e.g., alcohol, acetone, gasoline, ammonium nitrate, mustard gas, etc. [58] (initially funded by Mary Kay O’Connor Process Safety Center and Texas Engineering Experimentation Station, sub-sequently by DARPA-MF3 Center).

The author also developed a miniturized system that can be used to make artificial cell walls (“lipid bi-layers”). This is an automated apparatus that does not require human intervention or control for the artificial synthe-sis of lipid bi-layers [60]. These cell walls can be used as bio/nano-sensors to test next generation pharma-ceuticals and drugs, and also to test the effect of these drugs in micro-gravity (deep space). This work was sponsored by NASA in collaboration with the Texas A&M Health Science Center.

In addition, the author’s research group also developing novel ways of performing DNA analyses on a CD microfluidics platform by design optimization of capillary driven multi-phase flows [61] (in collaboration with Dr. Marc Madou at University of California at Irvine and funding from DARPA-MF3: “Micro/Nano-Fluidics Fundamentals Focus Center).

The author’s research group is also exploring exotic applications of multi-phase flows on the micro/nano-scale. For example, in collaboration with Nano-MEMS Research LLC we completed an AFOSR STTR Phase I study for design-ing a microfluidic device to realize Photonic Band-gap Crystals (PBC) [62]. These PBCs act as meta-materials (which have negative refractive index) and can be used as reconfigurable devices for tele-communications applications.

CONCLUSIONS

In summary, various fundamental mechanisms and their applications were explored for micro/nano-scale effects in multi-phase flows. The results seem to suggest that for cooling applications nano-coatings (especially those derived from silicon) have better efficacy than nano-particle doped coolants (i.e., nanofluids). Nanofluids have high viscosity with associated non-Newtonian behavior which renders them ineffective for cooling applications. On the other hand, nanofluids are more suitable for thermal energy storage applications – owing to their enhanced specific heat capacity values (i.e., for most coolants other than water). In addition, several exotic and emerging applications for multi-phase flows are also under investigation [63, 64].

NOMENCLATURE, ACRONYMS, ABBREVIATIONS

AFOSR = Air Force Office of Scientific Research
AFRL = Air Force Research Lab.
ATB = Advanced Technology Branch (San Diego, CA)
CNT = Carbon Nanotubes
DPN = Dip Pen Nanotechnology
ONR = Office of Naval Research
PRPS = Propulsion Division, Power Systems Branch
SPAWAR = Space and Naval Warfare Center
SSC = SPAWAR Systems Command
WPAFB = Wright Patterson Air Force Base (Dayton, Ohio)

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REFERENCES

1. Nelson, I.C., Banerjee, D., and Rengasamy, P., "Flow Loop Experiments Using Polyalphaolefin Nanofluids", *AIAA Journal of Thermophysics and Heat Transfer*, Vol. 23, No. 4, pp.752-761, doi: 10.2514/1.31033, October – December, 2009.
2. Shin, D., and **Banerjee, D.**, "Enhanced specific heat of molten salt based SiO_2 nanofluid for solar thermal energy storage application", *ASME Journal of Heat Transfer* (accepted for publication, July, 2010).
3. Jung, S., Jo, B., Shin, D., and Banerjee, D., "Experimental Validation of a Simple Analytical Model for Specific Heat Capacity of Aqueous Nanofluids", *Paper No. SAE-10PSC-0134, SAE Power Systems Conference*, November 2-4, Fort Worth, Texas, 2010.
4. Jeon, S., Kang, S., and Banerjee, D., "Investigation of Thermal Characteristics of Nanofluids during Flow in a Micro-channel using an Array of Surface Temperature-nano-sensors", *Paper No. SAE-10PSC-0135, SAE Power Systems Conference*, November 2-4, Fort Worth, Texas, 2010.
5. Shin, D., and Banerjee, D., "Enhanced specific heat capacity of molten salt-metal oxide nanofluid as heat transfer fluid for solar thermal applications", *Paper No. SAE-10PSC-0136, SAE Power Systems Conference*, November 2-4, Fort Worth, Texas, 2010.
6. Shin, D., Jo, B., Kwak, H., and Banerjee, D., "Investigation of High Temperature Nanofluids for Solar Thermal Power Conversion and Storage Applications", *Paper No. IHTC14-23296, 14th International Heat Transfer Conference,* August 8-13, Washington, D.C., 2010.
7. Shin, D., and Banerjee, D., "Investigation of Nanofluids for Solar Thermal Storage Applications", *Paper No. ES2009-90465, ASME Energy Sustainability Conference,* July 20-25, San Francisco, CA, 2009.
8. Unnikrishnan, V.U., Reddy, J.N. and Banerjee, D., "Atomistic-Mesoscale Thermal Analysis of Carbon Nanotube Systems", *International Journal of Thermal Sciences*, Volume 47, Issue 12, Pages 1602-1609, December, 2008.
9. Unnikrishnan V. U., Reddy J. N., Banerjee D., and Rostam-Abadi F., "Thermal Characteristics of Defective Carbon Nanotube-Polymer Nanocomposites," *Interaction and Multiscale Mechanics, An International Journal,* Vol. 1, No. 4, pp. 397-410, 2008.
10. Singh, N., and Banerjee, D., "Thermal Analysis of Carbon Nanotubes suspended in PAO Mixtures", *Paper No. SAE-10PSC-0137, SAE Power Systems Conference*, November 2-4, Fort Worth, Texas, 2010.
11. Singh, N., and Banerjee, D., "Investigation of Thermal Interfacial Resistance on Nano-Structures Using Molecular Dynamics", *Paper No. IHTC14-22930, 14th International Heat Transfer Conference,* August 8-13, Washington, D.C., 2010.
12. Singh, N. and Banerjee, D., "Effect of polymer chains on heat transfer on nanofins", *ASME Paper No. HT2008-66390, Proceedings of ASME- Summer Heat Transfer Conference '08, 2008 ASME Summer Heat Transfer, Fluids, Energy & Energy Nano Conferences*, August 10-14, 2008, Jacksonville, Florida, USA.

13. Singh, N., Unnikrishnan, V., Banerjee, D., and Reddy, J.N., "Multiscale analyses of transient thermal interface resistance between CNT Nanofins and various fluids", *International Conference on Multiscale Modeling and Simulation*, Indian Institute of Science, Bangalore, January 2-4, 2008.
14. Ahn, H.S, Sinha N., Zhang, M., Feng, S., Banerjee, D., Baughman, R., "Pool boiling experiments on Multi Walled Carbon Nanotube (MWCNT) Forests", *ASME Journal of Heat Transfer*, Vol. 128, No. 12, pp.1335-1342, December, 2006.
15. Ahn, H-S., Sinha, N., Banerjee, D., "Pool Boiling Experiments on a Nano-Structured Surface", *IEEE Transactions Journal of Components and Packaging Technology*, Vol. 32, No. 1, pp. 252-260, doi 10.1109/TCAPT.2009.2013980, March, 2009.
16. Sathyamurthi, V., Ahn, H.S., Banerjee, D., Lau, S.C., "Subcooled Pool Boiling Experiments on Horizontal Heaters Coated With Carbon Nanotubes", *ASME Journal of Heat Transfer*, doi:10.1115/1.3000595, Vol. 131, No. 7, pp. 071501-1 – 071501-10, July, 2009.
17. Sathyamurthi, V., and Banerjee, D., "Pool boiling studies on nano-textured surfaces: impact of high subcooling", *Paper No. IMECE2007-42508, Proceedings of ASME-IMECE*, 2007, Nov. 11-15, Seattle, WA.
18. Sathyamurthi, V., and Banerjee, D., "Subcooled pool boiling experiments on nano-textured surfaces", *Paper No. IPACK 2007-33207, Proceedings of the InterPACK 2007, ASME JSME Joint Summer Heat Transfer Conference*, July 8-12, Vancouver, BC, Canada.
19. Ahn, H-S.*, Sinha N., Banerjee, D., and Lau, S.C., "Pool Boiling Experiments Using Surface Micromachined Thermocouples", SAE Paper No. 06PSC-44, SAE Power Systems Conference, New Orleans, Nov. 7-9, 2006.
20. Ahn, H-S., Sinha, N., Banerjee, D., and Lau, S.C., "Boiling on experiments on Carbon Nanotube Forests and using Micromachined Thin Film Thermocouples", *AIAA-ASME Joint Thermophysics Conference*, San Francisco, CA, June 5-8, 2006.
21. Sriraman, S.R., and Banerjee, D., "Pool boiling studies on nano-structured surfaces", *Paper No. IMECE2007-42581, Proceedings of ASME-IMECE*, 2007, Nov. 11-15, Seattle, WA.
22. Sriraman, S., and Banerjee, D., "Subcooled and Saturated Pool Boiling on Nano-Finned Surfaces", *ASME Paper No. HT2008-56393, ASME Paper No. HT2008-66390, Proceedings of ASME- Summer Heat Transfer Conference*, 2008 ASME Summer Heat Transfer, Fluids, Energy & Energy Nano Conferences, August 10-14, 2008, Jacksonville, Florida, USA.
23. Sriraman, S.R., M.S. Thesis Title: "Pool Boiling on Nano-Finned Surfaces" (Thesis Committee Chair: D. Banerjee), Texas A&M University, December, 2007.
24. Sunder, M and Banerjee, D., "Experimental investigation of micro-scale temperature transients in sub-cooled flow boiling on a horizontal heater", *International Journal of Heat and Fluid Flow*, Vol. 30, No. 1, pp. 140-149, doi:10.1016/j.ijheatfluidflow.2008.08.003, February, 2009.
25. Singh, N., Sathyamurthi, V., Patterson, W., Arendt, J.L., and Banerjee, D., "Flow Boiling Enhancement on a Horizontal Heater Using Carbon Nanotube Coatings", *International Journal of Heat and Fluid Flow*, Vol. 31, pp. 201-207, doi:10.1016/j.ijheatfluidflow.2009.11.002, 2010.

26. Jeon, S., Roy, P., Anand, N.K., and Banerjee, D., “Investigation of Flow Boiling on Nanostructured Surfaces”, *Paper No. IHTC14-22926, 14th International Heat Transfer Conference*, August 8-13, Washington, D.C., 2010.
27. Ahn, H-S., Sinha, N., Williams, R., Banerjee, D., “Packaging of Surface Micromachined Thin Film Thermocouples (TFT): Comparison of the Resistance Arc Micro-Welding Technique with Wire Bonding”, *IEEE Transactions Journal of Components and Packaging Technology*, Vol. 32, No. 2, pp. 252-260, doi 10.1109/TCAPT.2009.2013982, June, 2009.
28. Sinha, N., M.S. Thesis Title: “Design, Fabrication, and Testing of Thin Film Thermocouples for Boiling Studies” (Thesis Committee Chair: D. Banerjee), Texas A&M University, 2010.
29. Ahn, H-S., Sinha, N., and Banerjee, D., “Micro-Machined Temperature Sensor Arrays for Studying Micro-Scale Features in Film Boiling”, *Proceedings of ASME-International Mechanical Engineering Congress and Exposition 2005*, November 5-11, Orlando, FL.
30. Sathyamurthi, V. and Banerjee, D., “Non-Linear Dynamical Analyses of Transient Surface Temperature Fluctuations During Subcooled Pool Boiling”, *International Journal of Heat and Mass Transfer*, Volume 52, No. 23-24, pp. 5608-5623, doi:10.1016/j.ijheatmasstransfer.2009.06.023, November, 2009.
31. Sathyamurthi V. and Banerjee, D., “Investigation of pool boiling on a flat horizontal heater using surface nano-thermocouples: Is Boiling Chaotic or Stochastic?”, *BOILING 2009 :: 7th International Conference on Boiling Heat Transfer*, May 03 - 07, 2009 - Florianópolis - SC – Brazil, 2009.
32. Sathyamurthi, V., and Banerjee, D., “Determination of dimensionality of pool boiling on a thin horizontal disk under subcooled conditions using thin film thermocouples”, *ASME Paper No. HT2008-56378, Proceedings of ASME- Summer Heat Transfer Conference 2008, 2008 ASME Summer Heat Transfer, Fluids, Energy & Energy Nano Conferences*, August 10-14, 2008, Jacksonville, Florida, USA.
33. Sathyamurthi, V., PhD Dissertation: “Dynamics of Pool Boiling: Impact of Surface Texturing and Subcooling” (Dissertation Committee Chair: D. Banerjee), Texas A&M University, December, 2009.
34. Sathyamurthi, V., M.S. Thesis Title: “Pool Boiling Studies on Nanotextured Surfaces under Highly Subcooled Conditions” (Thesis Committee Chair: D. Banerjee), Texas A&M University, December, 2006.
35. Sathyamurthi, V., Banerjee, D., Sakamoto, H., and Kim, J., “Measurement of the fractal order of wall void fraction during nucleate boiling”, *International Journal of Heat and Fluid Flow*, doi10.1016/2007.03.009, September, 2007.
36. Banerjee, D., Amro, N.A., and Fragala, J., “Optimization of microfluidic ink-delivery apparatus for Dip Pen Nanolithography™”, *SPIE Journal of Microlithography, Microfabrication and Microsystems (“JM^3”),* vol. 4, pp. 023014-023021, April, 2005.
37. Rosner, B., Duenas, T., Banerjee, D., Shile, R., Amro, N., Rendlen, J., “Functional extensions of Dip Pen Nanolithography™: active probes and microfluidic ink delivery”, *IEEE Journal of Smart Materials and Structures*, Vol. 15, page S124-S130, 2005.

38. Rivas-Cordona, J.A. and Banerjee, D., “Microfluidic device for delivery of multiple inks for Dip Pen Nanolithography”, *SPIE Journal of Micro/Nanolithography, MEMS and MOEMS*, (“JM^3”), Vol. 06, No. 03, pp. 033004-12, 2007.
39. D. Banerjee, et al., “Methods and apparatus for ink delivery to nanolithographic probe systems”, *US Patent No. 7,034,854* (Issued: April 25, 2006).
40. Banerjee, D., “Dip pen technologies for bio-molecular devices” (Book Chapter) in *Book: Vol. I: Biological and Biomedical Nanotechnology,* Editor: A. Lee, Pub.: Kluwer, N.Y., 2006.
41. Rivas-Cordona, J.A., M.S. Thesis Title: “Development of a Microfluidic Device for Patterning Multiple Species by Scanning Probe Lithography”, (Thesis Committee Chair: D. Banerjee), Texas A&M University, August, 2006.
42. Gargate, R., and Banerjee, D., “In-Situ synthesis of carbon nanotubes on heated scanning probes using dip pen techniques”, *Scanning: The Journal of Scanning Probe Microscopies*, (invited paper for the special issue on Dip Pen Nanolithography), Vol. 30, No. 2, pp. 151-158, March/April 2008.
43. Gargate, R., M.S. Thesis Title: “Synthesis of carbon nanotubes using Dip Pen Nanolithography”, (Thesis Committee Chair: D. Banerjee), Texas A&M University, December 2008.
44. Gargate, R., and Banerjee, D., “Synthesis of Carbon Nanotubes at ‘Room Temperature’ Using Capillary Microfluidics and Dip Pen Techniques”, *Paper No. μTAS 2008-1075, Proceedings of the 12th International Conference on .Miniaturized Systems for Chemistry and Life Sciences*, San Diego, October 12-16, 2008.
45. Gargate, R., and Banerjee, D., “Room temperature synthesis of Carbon Nanotube using Dip Pen Nanolithography”, *SPIE Paper No.6959-19, SPIE Defense and Security Symposium*, March 17-20, Orlando, FL, 2008.
46. Sravani, S., and Banerjee, D., “Carbon Nanotube synthesis using Thermal Scanning Microscopy Probe”, *ASME Paper No.ENIC2008-53048, Proceedings of ASME- 3rd Energy Nanotechnology International Conference 2008, 2008 ASME Summer Heat Transfer, Fluids, Energy & Energy Nano Conferences*, August 10-14, 2008, Jacksonville, Florida, USA.
47. Gargate, R., and Banerjee, D., “Nanolithographic patterning of catalysts for synthesis of carbon nanotubes”, *NSTI Nanotechnology 2008, Paper No. 1543*, (invited paper in special session on Dip Pen Nanolithography), Boston, MA, June 1-5, 2008.
48. Huitink, D., M.S. Thesis Title: “Nano-Lithographic Control of Carbon Nanotube Synthesis”, (Thesis Committee Chair: D. Banerjee), Texas A&M University, December 2007.
49. Huitink, D.R., Banerjee, D. and Sinha, S.K., “Precise control of carbon nanotube synthesis of a single chirality”, *Paper No. IMECE2007-42588, Proceedings of ASME-IMECE*, 2007, Nov. 11-15, Seattle, WA.
50. Huitink, D., Banerjee, D., and Sinha, S.K., “Nanolithography of metal catalysts by Dip Pen Nanolithography”, *SPIE Paper No. 6556-22, Proceedings of the SPIE Defense and Security Conference (SPIE-DSS 2007)*, 2007, April 9-13, Orlando, FL.

51. Kang, S.W., Banerjee, D., Kaul, A.B., Megerian, K.G., “Nano-Patterning of Catalysts by Dip Pen Nanolithography (DPN) for synthesis of Carbon Nanotubes (CNT)”, *Scanning: The Journal of Scanning Probe Microscopies* (Invited paper in Special Issue on “Advancing Dip Pen Nanolithography), Volume 32, Issue 1, Pages 42 – 48, April, 2010.
52. Dutta, S., M.S. Thesis Title: “Synthesis of gold nano-particles in a microfluidic platform for water quality monitoring applications”, (Thesis Committee Chair: D. Banerjee), Texas A&M University, December 2008.
53. Datta, S., and Banerjee, D., “Characterization of micro-valves for Lab-On-Chip device”, *Paper No. IMECE2007-42587, Proceedings of ASME-IMECE,* Seattle, WA., 2007.
54. Datta, S., and Banerjee, D., “Paper microfluidics platform for gold nano-particle synthesis”, *ASME Paper No. FEDSM2008-55214, Proceedings of ASME- Fluids Engineering Division Summer Conference 2008, 2008 ASME Summer Heat Transfer, Fluids, Energy & Energy Nano Conferences,* August 10-14, 2008, Jacksonville, Florida, USA.
55. Gauntt , S., and Banerjee, D., “Contact angle dependence of viscosity for micro-scale flows”, *American Physical Society, Division for Fluid Dynamics (DFD) Meeting,* Nov. 25, San Antonio, TX.
56. 14. Gauntt, S., and Banerjee, D., “Micro-chamber filling experiments with applications in capillary driven microfluidics”, *ASME Paper No. FEDSM2008-55216, Proceedings of ASME- Fluids Engineering Division Summer Conference 2008, 2008 ASME Summer Heat Transfer*, Fluids, Energy & Energy Nano Conferences, August 10-14, 2008, Jacksonville, Florida, USA.
57. Gauntt, S.B., M.S. Thesis Title: “Micro-Chamber Filling Experiments for Validation of Macro Models with Applications in Capillary Driven Microfluidics”, (Thesis Committee Chair: D. Banerjee), Texas A&M University, December 2007.
58. Nelson, I.C., Banerjee, D., Rogers, W.J., Mannan, S., “Detection of Explosives using Heated Micro-Cantilever Sensors”, *SPIE Paper no. 6223-24, SPIE Defense and Security Symposium*, 2006, Orlando, FL, Paper no. 6223-24.
59. Ranil Banneyake, M.S. Thesis Title: “Microfluidics device for synthesis and testing of Lipid Bi-Layers” (Thesis Committee Chair: D. Banerjee), Texas A&M University, December 2007.
60. Banneyake, B.M.R.U., and Banerjee, D., “Microfluidic device for synthesis of lipid bi-layers”, *ASME Paper No. FEDSM2008-55219, Proceedings of ASME- Fluids Engineering Division Summer Conference 2008, 2008 ASME Summer Heat Transfer, Fluids, Energy & Energy Nano Conferences*, August 10-14, 2008, Jacksonville, Florida, USA.
61. Siegrist, J., Amasia, M., Singh, N., Banerjee, D., and Madou, M., "Numerical Modeling and Experimental Validation of Uniform Microchamber Filling in Centrifugal Microfluidics", *Journal of Lab on a Chip,* doi: 10.1039/b917880e, Vol. 10, pp. 876-886, 2010.
62. Kang, S.*, De Los Santos, H.J., and Banerjee, D., “Lumped Parameter Modeling for Microfluidic Networks for Realizing Reconfigurable Nano-Optics Architectures”, Paper No. FEDSM-ICNMM2010-31256; Proceedings of the ASME 2010 Fluids Engineering Summer Meeting (FEDSM2010); European Mechanical Engineering Societies, the International

Conference on Nanochannels, Microchannels, and Minichannels (ICNMM); and the International Symposium on Fluid-Structure Interactions, Flow-Sound Interactions, and Flow-Induced Vibration & Noise (FSI2 & FIV+N), August 1-5, Montreal, Canada, 2010.

63. Lloyd, S., Banerjee, D., Bejan, A., Beretta, G.P., Chu, S., Geskin, E., Ghoniem, A., Gutowski, T.G., Gyftopoulos, A.P., Keck, J.C., Lior, N., Miller, S., Nieuwenhuizen, T.H., Peterson, R., Salamon, P., Williamsonk, L., *"The Second Law and Energy" (Book Chapter) in: MEETING THE ENTROPY CHALLENGE: An International Thermodynamics Symposium in Honor and Memory of Professor Joseph H. Keenan; 2008, Editor: Beretta, G.P., Publisher: AIP (American Institute of Physics), M.D.* doi:10.1063/1.2979062
64. Singh, S., Shin, S., and Banerjee, D., "Nano-Scale Effects in Multi-Phase Flows and Heat Transfer", (Book Chapter), *MEMS and Nanotechnologies: From Science-to-Electronic Systems*, Ed. Dr. A. Kaul (JPL), 2010.

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