Monday Morning, October 18, 2010

Frontiers in Inkjet Technology Topical Conference
Room: Tesuque - Session IJ+BI+MN-MoM

Frontiers in Inkjet Technology
Moderator: T. Boland, University of Texas at El Paso

8:20am **IJ+BI+MN-MoM1 Drop Impact on Liquid, Solid and Porous Surfaces**, ***A.L. Yarin***, University of Illinois at Chicago **INVITED**

The talk covers drop impacts on thin liquid layers, dry impermeable surfaces, and porous surfaces with nano-scale texture. Splashing and corona formation and propagation on liquid layers are discussed first. Then, some additional kindred, albeit non-splashing, phenomena like drop spreading and deposition, receding (recoil), jetting, fingering and rebound on liquid and dry impermeable solid surfaces are covered. A number of practical applications of drop impacts are mentioned and relevant experimental, theoretical and computational aspects are considered.

After that, a novel method of enhancement of drop and spray cooling for microelectronic, optical and radiological elements and server rooms, which require extremely high heat fluxes, is discussed. The key idea of the method is to cover the heat transfer surfaces with electrospun nonwoven polymer nanofiber mats. The experiments reveal that drop impacts on nanotextured surfaces of nanofiber mats produce spreading similar to that on the impermeable dry surfaces. However, at the end of the spreading stage the contact line is pinned and drop receding is prevented. All the mats appear to be dynamically permeable for water drops. The enhanced efficiency of drop cooling in the presence of nanofiber mats observed experimentally results from a complete elimination of drop receding and bouncing characteristic of the current spray cooling technology. Therefore, the drops evaporate completely, and the large cooling potential associated with the latent heat of water evaporation is more fully exploited. This is paradoxical: the best cooling can be provided by a "furry overcoat"! The results on drop impact on porous surfaces are also relevant for drop impacts on paper and nonwovens in the context of ink-jet-printed microelectronics.

9:00am **IJ+BI+MN-MoM3 Upper and Lower Bounds for the Stability of Inkjet Printed Lines**, ***B. Derby***, *J. Stringer*, University of Manchester, UK

Many applications for inkjet printing require the ability to print continuous linear features. Inkjet printing achieves this through the overlap and coalescence of a series of liquid drops on a planar substrate, which then transform to a solid through phase change or solvent loss. In order to produce regular parallel sided printed lines, the intermediate fluid thread must retain morphhological stability prior to solidification. Drying fluid drops often show considerable hysteresis between the advancing and receding contact angles. This behaviour is shown to impose upper and lower bounds for the width of a line formed by the overlap of printed drops. The lower bound for line width is determined by the minimum separation distance for spreading drops to spread, overlap and coalesce. However, for liquids with zero receding contact angles (as is the case for many evaporating solvents) there is a further limit for parallel sided lines [1]. The upper bound for line width is determined by a dynamic fluid instability that occurs through competing fluid flows between the spreading and coalescence processes [2]. This dynamic instability is a function of both drop spacing and the rate of droplet deposition. By considering both the upper and lower bound limits we can construct a map in a parameter space defined by drop size, drop spacing, drop/substrate contact angle and linear printing velocity that shows the conditions under which stable linear features can be printed.

9:20am **IJ+BI+MN-MoM4 Particle Deposition and Assembly of Inkjet-Printed Colloidal Drops in Line and Pattern Printing**, *A. Joshi*, *V. Chhasatia*, ***Y. Sun***, Drexel University

Precise control of process parameters during inkjet printing is essential to enable uniform, accurate and repeatable deposition of functional materials. In this work, we present a combined in-situ observation and computational study to examine particle deposition and assembly during evaporation of inkjet-printed colloidal drops. Unlike previous computational models that use tracer particles and known velocity fields inside the drop, our computational model uses a multi-phase lattice Boltzmann method (LBM) that directly simulates the flow of the liquid drop, surrounding vapor phase and the motion of the liquid-vapor interface. The motion of suspended particles within the liquid phase is directly coupled to the fluid flow and also influences the velocity field in the liquid. Evaporation is accomplished by reducing the vapor pressure above the drop and different evaporation modes including evaporation with contact line pinning and self-similar evaporation with a constant contact angle are examined. A novel visualization technique is developed wherein aqueous suspensions of fluorescent particles are jetted onto transparent surfaces and the evaporation dynamics are observed in real-time using a fluorescence microscope. The effects of drop spacing, jetting frequency, substrate wettability, particle size and volume fraction, and environmental conditions (temperature and humidity) on the final deposition morphology are presented for line and pattern printing of functional materials on substrates.

9:40am **IJ+BI+MN-MoM5 Inkjet Printing of Flexible Hybrid Solar Cells based on P3HT and ZnO**, ***G. Carryon***, *J.B. Baxter*, *Y. Sun*, Drexel University

Inkjet printing of organic solar cells offers an inexpensive alternative to conventional solar cell fabrication methods. Despite the attractiveness of organic solar cells, they have demonstrated some degradation problems and have yet to achieve the efficiencies necessary to make them economically viable. In contrast to their organic counterparts, inorganic semiconductors have demonstrated advantages in their high dielectric constant which facilitates carrier generation processes, high carrier mobility, and thermal morphological stability. In recent years, improvements in device performance have been seen in the development of organic-inorganic hybrid materials (e.g., ZnO nanoparticle-polymer composites or CdSe quantum dot-polymer composites) as the photoactive layer. To date, most studies on hybrid solar cell fabrication have focused on using lab-scale spin-coating methods to deposit ZnO nanoparticle-polymer materials. In this paper, we present our results in using an industrial piezoelectric-driven printing device for inkjet printing of ZnO nanoparticles/nanorods-polymer [e.g., poly(3-hexylthiophene (P3HT)] ink materials for large-scale processing of hybrid solar cells. The deposition morphology and properties of printed photoactive layer are examined as a function of the solvent properties (e.g., wettability and vapor pressure), particle size, volume fraction, and polydispersity, as well as the aspect ratio of nanorod. The effects of jetting parameters (e.g., wave form and jetting frequency) and printing patterns on film thickness and uniformity are also discussed in detail. Finally, the feasibility of printing P3HT onto aligned ZnO nanorod arrays for novel heterogonous nanostructures for reduced exciton diffusion lengths is explored.

10:00am **IJ+BI+MN-MoM6 Anomalies in Applications of Inkjet Printing in Microfluidic Device Fabrication**, ***W.E. Dieterle***, *C.P. McNary*, California University of Pennsylvania

Utilization of inkjet-generated masks for UV photosensitive materials as a cost-effective method for the generation of microfluidic devices requires resolution of certain anomalies related to combinations of various color components. These anomalies are demonstrated for UV exposures with a high-pressure mercury vapor source and possible solutions are discussed, including implications for inkjet manufacture designs targeted to similar applications.

10:40am **IJ+BI+MN-MoM8 Fabrication of Miniature Drug Screening Platform Utilizing Low Cost Bioprinting Technology**, ***J. Rodriguez***, *T. Xu*, University of Texas at el Paso

In the pharmaceutical industry, new chemicals and substances are being tested to find appropriate compounds for treating a specific disease. The demand for screening large compound collections against and increasing number of therapeutic targets has stimulated technology development in the areas of assay automation and miniaturization. Current methods for evaluating the reactions of cells use a relatively large volume in the range from microliters to milliliters; since reliability has to be met, it exists the need to have several assays to confirm the biochemical reactions, which ultimately cause the usage of large amounts of volume for each substance. Unfortunately, some of these new compounds are rather hard to obtain, which causes an expensive researched and limited material availability; therefore, increasing the time development for future cures. We have developed a new and low-cost deposition method to fabricate miniature drug screening platform that can realistically and inexpensively evaluate biochemical reactions up to 4 substances per trial in a picoliter-scale volume.

This study focues on the development of the controls for a deposition method (inkjet printing technology) which will simultaneously place therapeutic drugs and cells onto target sites to fabricate cell/drug chips for drug screening application. Using a modified HP 5360 CD printer, droplets of GFP expressing Escherichia coli have been deposited in an agar coated coverslip chip as small reliable volume of 180 picoliters per each colony dot, along with this bacteria it has been patterned different antibiotics in such a way that we evaluated the growth of the bacteria under antibiotics presence. The viability and function of the printed cells were evaluated by the live/dead and plasmid gene transfection experiments resulting in 98% viability and maintaining DNA function. Moreover, it has been recorded as high throughput process printing 250,000 droplets/second. Due to the reduction of volume, this method will increase the effectiveness of the resources utilized for emerging drug screening processes. The results show promising usage of resources for future drug screening through new biochemicals.

11:00am **IJ+BI+MN-MoM9 Inkjet Printing of Oxygen Releasing Materials for Improved Cell Survival and Growth**, ***A. Arteaga***, *T. Xu*, University of Texas at el Paso

Introduction: A major barrier in tissue engineering is the impossibility of providing adequate oxygen to all cells within the engineered tissue before a full vascularization is achieved. To overcome this limitation, a variety of oxygen-producing particles have been developed for improving tissue survival. However, most of these particles are used in random mixtures with scaffolding materials, which usually leads to an uneven distribution of oxygen in bioengineered tissues. An ideal oxygen supply requires a precise spatial-temporal control of the oxygen-producing particles in scaffolds. Unfortunately, current oxygen delivering scaffold techniques are unable to perform as described and to precisely incorporate oxygen particles into the scaffolds. Cell inkjet printing is a novel tissue fabrication approach, in which a special inkjet printer can be programmed to deposit cells and/or biomaterials of various types and sizes in a very precise pattern. In this study we have applied the inkjet printing technology to allocate oxygen releasing materials to their designed positions for optimal cell viability and growth.

Methods: The controlled oxygen-releasing platform is fabricated by printing different patterns (“Black”, “White”, “Grey”, and “Dots” to represent different densities of the oxygen particles on the substrates) of encapsulated calcium peroxide (CPO) particles that were analyzed against C2C12 mouse myoblast cell line for cell viability. CPO has been found to release its oxygen over an extended timeframe. The effects of controlled oxygen-releasing particles on cell viability were analyzed using the cell morphology study, live/dead assay, and the MTS assay.

Results: These analyses showed the concentration of the oxygen-releasing particles in “Black” was toxic to the cells based on the decreasing trend in cell viability. The “White” did not have oxygen-releasing particles, which correlates to the decrease in cell viability over time due to oxygen deprivation. Both “Grey” and “Dots” showed a similar trend in absorbency, in which the absorbency was low at 24 hours, there was an increase in absorbency at 48 hours, and then an abrupt decrease at 72 hours. Both these results suggest that the amount of oxygen released was beneficial to the cells within the first 48 hours, yet may not have been sufficient to sustain cell viability after that time span. The cells treated in the printed “Dots” showed to have the most compatible treatment for an overall increase in cell viability.

Conclusion: The amount of oxygen released can be controlled to optimize the cell by bioprinting different densities of the oxygen releasing materials onto a substrate.

11:20am **IJ+BI+MN-MoM10 Understanding Volume Ejection of Complex Fluids through Pressure Measurements**, ***G.E. Mårtensson***, *W. Holm*, Micronic Mydata AB, Sweden

In conventional ink jetting applications, a pressure difference is used to ensure the continuous and prompt filling of the jetting chamber between jetting actuations. The delivery of precise fluid volumes utilizing inkjet-like drop-on-demand jetting technology is primarily controlled by the piezo voltage that actuates the jetting chamber (Gerhauser et al. 1983, SID 83 Digest). The jetting of large volumes, in excess of 1 nL, of complex viscous fluids is complicated by the difficulty of filling the ejection chamber quickly after the previous droplet ejection.

A novel jetting mechanism for highly viscous complex fluids, that utilizes a viscous micropump to control the amount of fluid that is ejected by a piezo actuated mechanism, has been developed and implemented by the authors. In this paper , we report results of volume, exit velocity, and pressure measurements. The piezo voltage, V_p, and the angular speed, N, of the viscous pump has been varied. A chosen V_p translates directly to displaced volume and N to flow rate.

The ejected volume has been measured by weighing a large number of droplets and via 3D profilometry methods. It has been shown in the experimental jetting setup that the volume of a jetted deposit is only affected to a minor degree, of the order of 5% of the target volume, by the chosen piezo voltage, V_p. Thus the ejected volume is almost independent of the displaced volume within the experimental range and determined by the flow rate, which in turn is controlled by N.

The exit velocity of the jet has been measured using high speed double exposure imaging. It has been shown that the speed of the ejected droplet has a nearly linear response to V_p (at least for all but the smallest N). For a given V_p, the exit velocity increase with increasing N. Thus, it seems that a larger displaced volume results in a higher exit velocity, but the ejected amount is unaffected.

In order to probe these seemingly counterintuitive results, the pressure in the ejection chamber, as well as in the viscous micropump, was measured over a large number of ejection cycles. The volume of the resulting depositions were correlated with the chamber and pump pressures. Additional measurements were performed to correlate the speed of the resulting shot with the chamber and pump pressures. Simple models are proposed to correlate the above mentioned quantities.

11:40am **IJ+BI+MN-MoM11 Determination of Effective Jet Radius from Measurements of the Perturbation Growth Rate in Thermally Stimulated Continuous Microjets**, ***J.M. Grace***, *G. Farruggia, E.P. Furlani, Z.J. Gao, K.C. Ng*, Eastman Kodak Company

Drop formation in continuous inkjet devices is based upon the Rayleigh-Plateau instability – a phenomenon in which surface tension drives the break-up of a column of fluid into droplets. In thermally stimulated continuous inkjet devices, heat pulses applied to the jet at the nozzle couple to the instability to stimulate drop formation. The level of stimulation depends upon the size of the effective perturbation and its growth rate along the jet. While the growth rate depends upon characteristics of the jet itself (fluid properties and jet diameter), the effective perturbation depends upon coupling between the source of stimulation and the jet, as well as the fluid properties. The coupling efficiency can be inferred from measurements of the perturbation growth rate and the jet diameter. For liquid microjets with diameters of 10 micrometers or less, direct determination of the jet diameter by optical microscopy is extremely challenging. Although the lateral dimensions of the microjets may be difficult to measure precisely, the break-up length can be determined with relatively good precision. Measurements of break-up length as a function of input power provide a means to determine the perturbation growth rate. From the experimentally determined growth rate as a function of stimulation frequency, the diameter of the microjet can be determined by fitting to a model for jet break-up. The experimentally determined growth rate and jet diameter provide a basis for comparing the effective coupling for different designs of jetting modules. Measurements of jet break-up and methods for determining the effective jet diameter will be presented and discussed.

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