Micro-scale Transport Laboratory

Laboratory Coordinator: Dr. P. K. Panigrahi

List of Major Equipment:

- Digital holographic interferometry (DHI)
- Digital holographic microscopy (DHM)
- Micro Particle image velocimetry (μPIV)
- Infrared Thermography (IRT)

Brief description of the laboratory:

In this laboratory, works related to the understanding of processes at microscale are carried out. Evaporation from reservoirs/wells has several applications such as microfluidic cell culture, protein/DNA microarray, micro reactors for chemical synthesis, point of care diagnostics and biological lab on chip devices, protein crystallization etc. Internal hydrodynamics as well as vapor phase transport of an evaporating body are studied using various optical techniques. Micro particle image velocimetry technique is utilized for velocity measurement inside the droplet, microchannel etc. Techniques such as Digital holography which is capable of providing instantaneous three-components of fluid flow velocity (3D-3C) using a single camera is utilized for the velocity measurement. Digital holographic interferometry is used for the non-intrusive measurement of temperature. The work on development of high heat flux electronic cooling system using electrohydrodynamic based atomization (Electrospray) and propulsion (Ionic wind) is another focus of our laboratory.

Laboratory research keywords:

Holography, Micro PIV; Micro fluidics, Protein crystallization, Interferometry, High Heat flux cooling, Corona wind, Electrospray, Magneto-hydrodynamics, Electro-hydrodynamics

Major Research and Development Contribution of the Laboratory

Year	**Major research and development activity**
2020-2021	*A hybrid cooling system using combined electrospray and corona wind has been designed, fabricated and tested in our lab. The cooling system is light weight, cheap and requires less coolant flow compared to the other existing technologies. The system can be used in several applications i.e. high heat flux electronics, data center and other manufacturing industries.* **Patent**: 1, **Journals**: 4 1) Digvijay Shukla, M. K. Sharma and P. K. Panigrahi, " Hybrid electrospray and ionic wind-based thin-film evaporative cooling system for thermal management applications ", **Indian Patent Filed**

	2) Digvijay Shukla. Bal Krishan Mishra and P K Panigrahi "Digital holographic study of corona wind assisted evaporation of hydrocarbon from a microliter well", **Applied Physics B,** 128, 123 (2022) 3) Digvijay Shukla and P K Panigrahi, "Interaction of vapor cloud and its effect on evaporation from microliter coaxial well", **Colloids and Surfaces A: Physicochemical and Engineering Aspects,** Vol. 629, 20, 127391(2021) 4) Sunil K. Saroj, Pradipta Kumar Panigrahi, "Magnetophoretic control of diamagnetic particles inside an evaporating droplet", **Langmuir,** 37, 51, 14950–14967 (2021) 5) Tapan K. Pradhan, and Pradipta Kumar Panigrahi, "Vapor mediated interaction of two condensing droplets", **Colloids and Surfaces A: Physicochemical and Engineering Aspects,** Vol 608, 125555, (2021)
2019-2020	*The data analysis tool for estimation of vapor cloud concentration over an evaporating liquid pool using holographic measurements has been developed. The detailed microscale characterization carried out in our laboratory has proposed several designs for fabrication of superior quality protein crystal.* **Journals**: 3 1) Digvijay Shukla, Pradipta Kumar Panigrahi, "Digital Holographic Interferometry Investigation of Liquid Hydrocarbons Vapor Cloud Above a Circular Well", **Applied Optics,** Vol 59, No. 19, 5851 (2020) 2) Tapan K. Pradhan, and Pradipta Kumar Panigrahi, "Suppressing internal convection of a droplet using confinement during protein crystallization", **Journal of Applied Physics,** Vol 128, 084701, (2020) 3) Sunil K. Saroj, Pradipta Kumar Panigrahi, "Magnetic suppression of the coffee ring effect", **Journal of Magnetism and Magnetic Materials,** Vol 513, 167199 (2020)
2018-2019	*The laboratory has proposed and demonstrated several design using magnetic field for controlled deposition pattern of particle on surfaces. The magnetophoretic based deposition pattern control proposed in the manuscript can find application in several interdisciplinary subjects i.e. micropatterning, inkjet printing, fabrication of micro or nanostructures, DNA/RNA micro-arrays deposition, forming templates on solid surfaces, biochemical assays etc.* **Journals**: 2 1) Sunil K. Saroj, Pradipta Kumar Panigrahi, "Drying pattern and evaporation dynamics of sessile ferrofluid droplet on a PDMS substrate", **Colloids and Surfaces A,** Vol. 580, pp. 1-13 (2019)

	2) Sunil K. Saroj, Pradipta Kumar Panigrahi, "Effect of salt concentration (NaCl) on drying pattern of ferrofluid droplets", **Journal of Flow Visualization and Image Processing,** Vol. 25, pp. 245-258 (2018)
2017-2018	**Journals**: 3 1) Tapan Kumar Pradhan and Pradipta Kumar Panigrahi "Convection inside a condensing and evaporating droplet of aqueous solution", **Soft Matter,** Vol. 14, pp. 4335-4343 (2018) 2) Tapan Kumar Pradhan and Pradipta Kumar Panigrahi "Hydrodynamics of two interacting liquid droplets of aqueous solution inside a micro-channel", **Langmuir,** Vol. 34, pp. 4626-4633 (2018) 3) Tapan Kumar Pradhan and Pradipta Kumar Panigrahi "Evaporation induced natural convection inside a droplet of aqueous solution placed on a superhydrophobic surface", **Colloids and Surfaces A: Physicochemical and Engineering Aspects,** Vol. 530, pp. 1-12 (2017)
2016-2017	**Journals**: 3 1) Tapan Kumar Pradhan, Pradipta Kumar Panigrahi "Evaporation-induced natural convection of a liquid slug of binary mixture inside a microchannel: effect of confinement", **Microfluidics and Nanofluidics,** Vol. 20, pp. 115 (2016) 2) Sunil Kumar Saroj, Mohammed Asfer, Aman Sunderka, Pradipta Kumar Panigrahi "Two-fluid mixing inside a sessile micro droplet using magnetic beads actuation" **Sensors and Actuators A: Physical,** Vol. 244, pp. 112-120 (2016) 3) Tapan Kumar Pradhan, Pradipta Kumar Panigrahi "Influence of an adjacent droplet on fluid convection inside an evaporating droplet of binary mixture" **Colloids and Surfaces A: Physicochemical and Engineering Aspects,** Vol. 500, pp. 154-165 (2016).
2015-2016	**Journals**: 3 1) Tapan K Pradhan and P K Panigrahi "Thermo-capillary convection inside a stationary sessile water droplet on a horizontal surface with an imposed temperature gradient", **Experiments in Fluids,** Vol. 56, 178 (2015). 2) Tapan K Pradhan and P K Panigrahi "Deposition pattern of interacting droplets", **Colloids and Surfaces A: Physicochemical and Engineering Aspects,** Vol. 482, pp. 562-567 (2015). 3) Singh Dhananjay Kumar and Panigrahi P. K." Three Dimensional Investigation of Liquid Slug Taylor Flow Inside a Micro Capillary Using Holographic Velocimetry", **Experiments in Fluids,** Vol. 56:6, pp. 1-15 (2015).

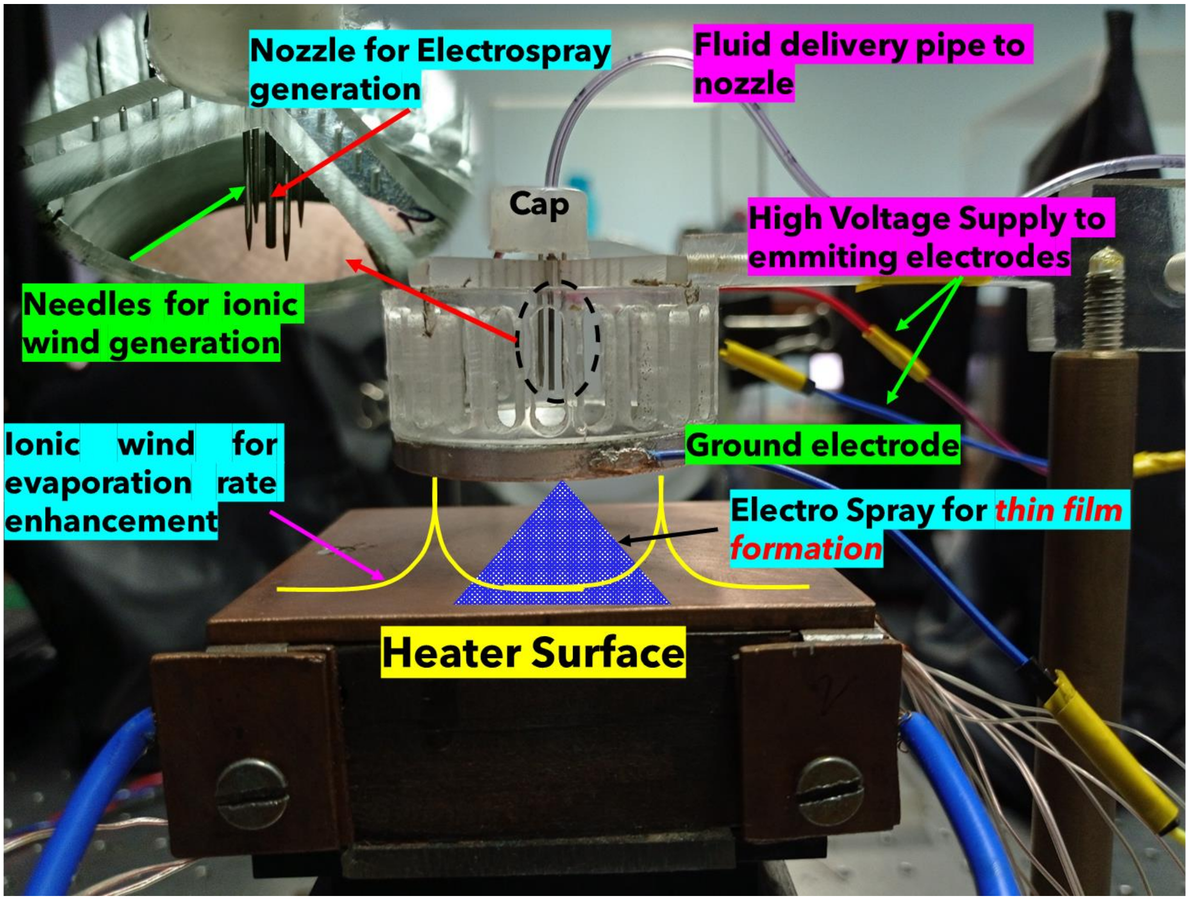

Figure #1: Snapshot of the hybrid electrospray (ES) and ionic wind (IW) based thin film evaporative cooling system for the thermal management of electronic components. Results indicates the effectiveness of hybrid mode where superior heat transfer performance is observed compared to existing techniques. This can be attributed to the utilization of **thin film based evaporation mechanism**, where thin film of liquid is created using **Electrosparying** and **Ionic wind** jet enhances the evaporation from thin film due to two phase heat transfer technique.

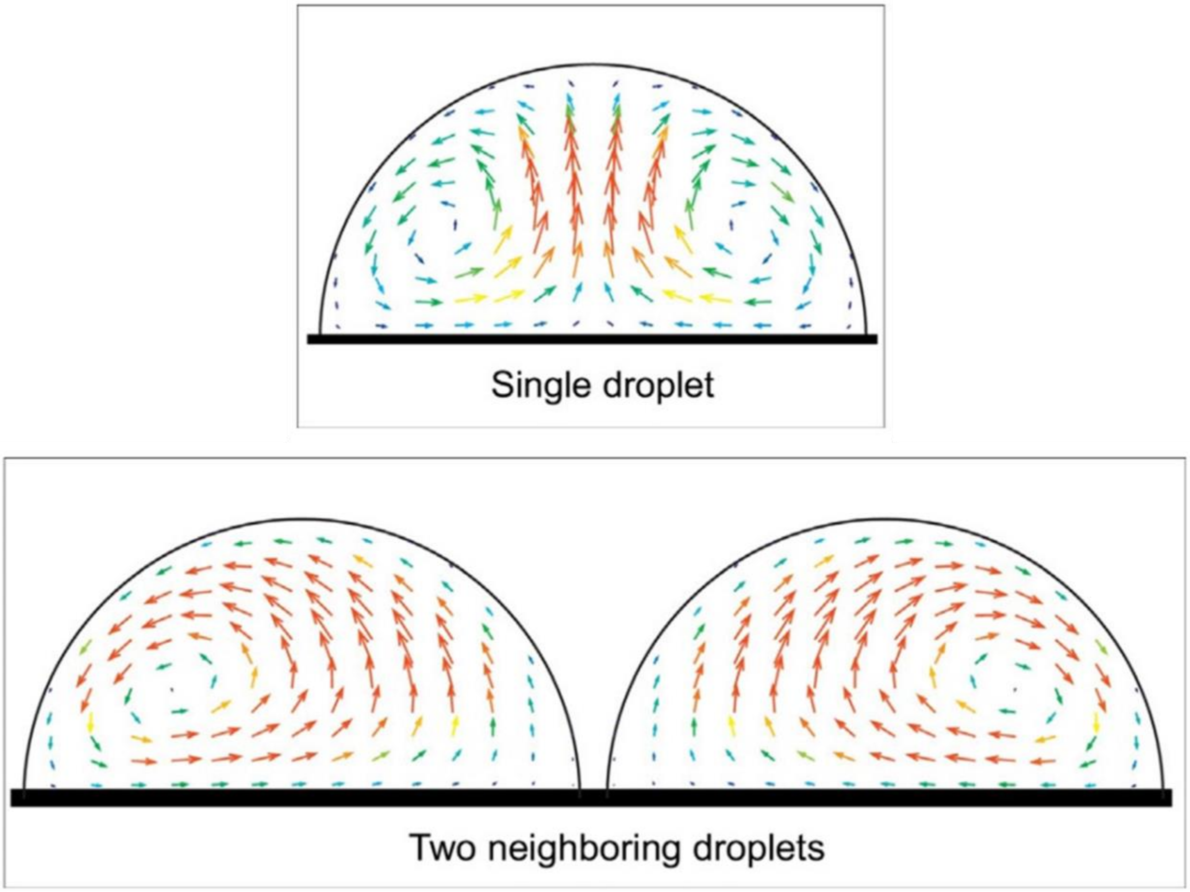

Figure #2: Interaction between droplets plays crucial role in several applications i.e. droplet coalescence, digital microfluidics, dropwise condensation, protein crystal growth by vapor diffusion method and surface coating etc. where droplets are surrounded by other droplets. Velocity filed inside the evaporating droplets is captured using **Micro PIV technique**. Single droplet shows a symmetrical flow pattern with two recirculating bubbles. This behavior is attributed to the symmetric evaporative flux distribution on the droplet surface. Presence of another droplet changes the evaporative flux distribution and results in asymmetric concentration field inside the droplet.

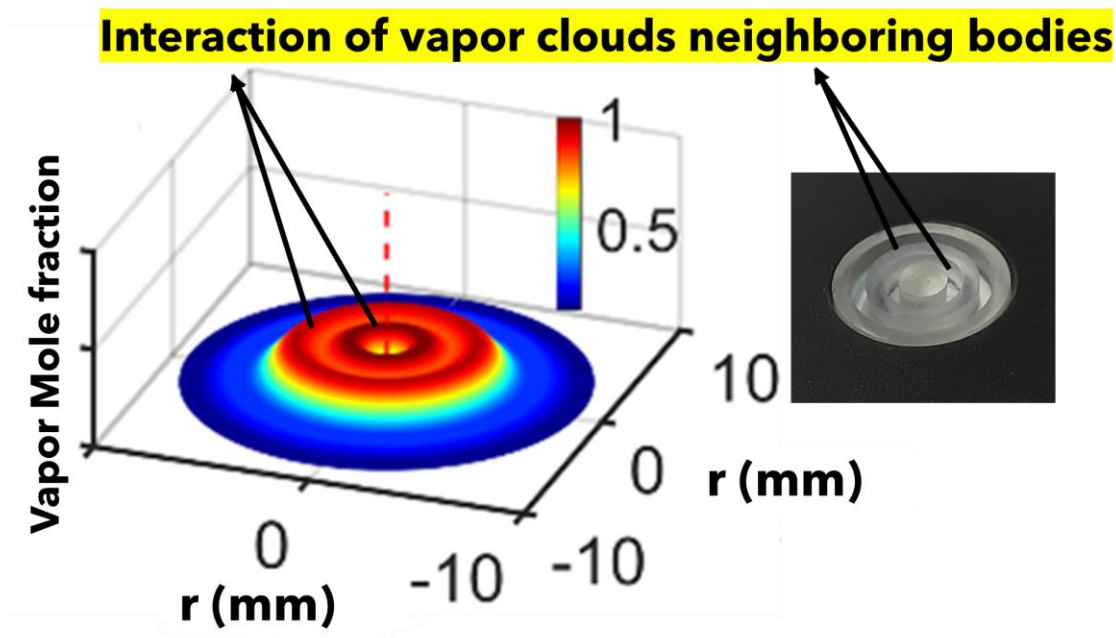

Figure #3: Presence of an adjacent evaporating body (i.e., droplet/ well cavity) leads to asymmetric evaporative flux distribution on the droplet surface **due to the influence of the neighboring droplet on the free stream mass fraction**. The vapor phase transport from evaporating co-axial microliter wells is presented. **Digital holographic Interferometry** is used to decipher the vapor mole fraction field above the coaxial well. Normalized Vapor cloud mole fraction distribution at liquid vapor interface of hexane evaporating from coaxial cavity at the initial time period (t = 0 + (s)) is shown in the figure. Vapor cloud interactions of microliter volume coaxial cavities can influence the evaporation rate of individual coaxial cavity and the convection inside the liquid phase. The present study demonstrates the capability to precisely control the evaporation process by appropriate design of coaxial well.

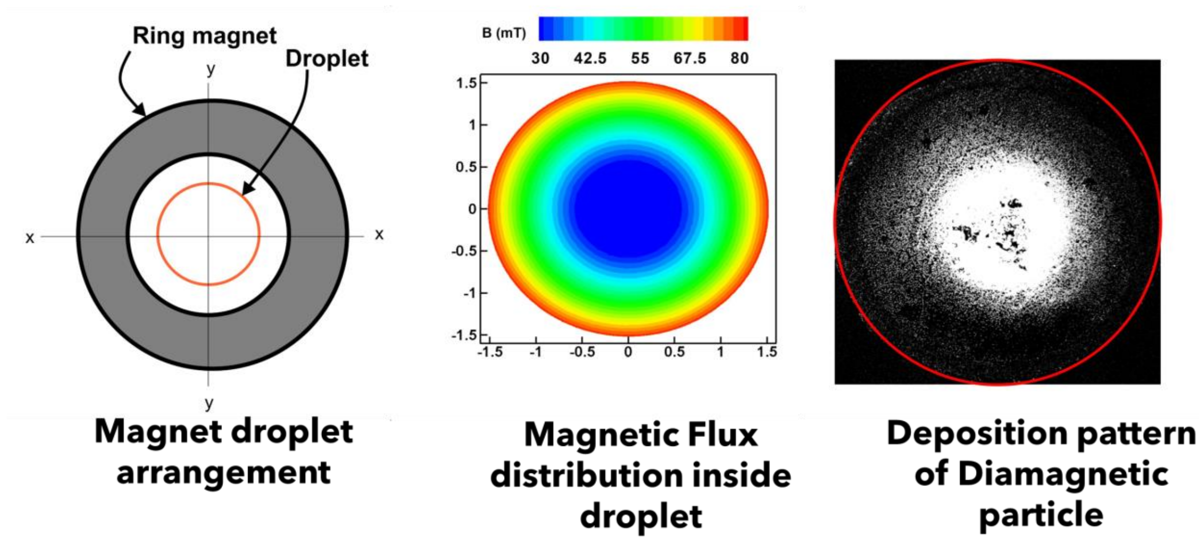

Figure #4: Negative magnetophoretic effect on nonmagnetic particles in the ferrofluid droplet during evaporation is presented. The selective deposition of the diamagnetic particles at the contact line and center of the droplet is obtained by controlling the particle motion inside the droplet. In the absence of the magnetic field, there is a coffee-ring formation and the diamagnetic particles. Magnetic particles travel toward the higher magnetic field zone and diamagnetic particles move toward the smaller magnetic field zone when a magnetic field is applied by a solid magnet placed over the droplet. The deposition behavior can be reversed or suppressed using a ring magnet. In this case, the negative magnetic force is stronger at the contact line region of the droplet and decreases as it approaches the center region of the droplet. Therefore, deposition pattern can be controlled with the help of the magnetic field, which can be useful in many applications i.e. manufacturing and biotechnology.