ABSTRACT

Interfacial phenomena are ubiquitous in nature and technology. It refers to the complex physio-chemical behavior at the interface of binary and ternary systems. The majority of phenomena occurring in our surroundings encompass a stage that transpires through an interface. Some of the naturally occurring interfacial phenomena include capillary action in plants and trees, blood flow in micro-capillaries, and water cycle- from evaporation of water to formation of rain drops. Insects and animals like water striders and lizards leverage interfacial forces to perform their routine tasks, thereby equipping them with crucial tools for survival. The interfacial forces such as capillary, electrostatic, and Van der Waals become prominent at small scales, especially at the micro/nano domain, due to increased surface area to volume ratio. Inspired by nature and taking advantage of the interfacial forces at a small scale, various technologies are developed in engineering and biomedical domains, like cooling technologies, water purification, biosensors, drug delivery, and biomedical imaging, to name a few. In the present study, we take the opportunity to exploit the interfacial science for tuning its characteristics to augment momentum, energy, and species transport phenomena toward practical applications in energy conversion, thermal management, and biomolecule analysis.

The dissertation commences by investigating electrokinetic energy conversion within a nanochannel, wherein the electrical energy is harvested from the salinity gradient induced by the Gibbs free energy of mixing. The surface charge leading to the formation of an electric double layer (EDL) at the solid-electrolyte interface influences conversion efficiency. To enhance this efficiency, we fine-tune the physio-chemical characteristics at the interface by altering concentration and introducing temperature gradients by harnessing solar energy. We subsequently explore how interfacial properties can be modulated to optimize the heat transfer. We designed an effective and sustainable thermal management system that ensures maximum heat dissipation with minimum pumping losses for microelectronics.

The final part of the dissertation deals with biomolecule analysis. The research importance, in this particular field, hikes especially in the post-COVID-19 world. Nanopore-based macromolecule sequencing technology, based on electrokinetic and interfacial phenomena, thanks to the inherent charge and nano size of these macromolecules, has gained popularity due to fast and portable technology. However, this new nanopore sequencing technology still faces some challenges, such as capturing the macromolecule in the nanopore and slowing down the speed of the macromolecule within the nanopore. Here, again, by tuning the physio-chemical characteristics at the solid-electrolyte interface, we addressed the aforementioned two challenges.

Keywords: Interfacial phenomena; Electrokinetics; Heat transfer; DNA translocation; Nanopore sequencing; Micro-electronics cooling.