Abstract

Microfluidics is a multidisciplinary field, encompassing engineering, physics, chemistry, and microtechnology, that focuses on the behavior, precise control, and manipulation of fluids confined to small volumes, typically at the micrometer to nanometer scale. The remarkable advancement of microfabrication technology has led to significant research in the domain of microfluidics. The objective of this thesis is to explore possibilities of harnessing the combined effects of interfacial electrokinetics and rheology to enhance energy transfer efficiencies in narrow fluidic confinements. In particular, we consider the interfacial electro-chemical interactions in viscoelastic fluids over small scales, to establish substantial improvements in electrokinetic energy conversion (EKEC) efficiency. The exploitation and utilization of renewable clean energy is crucial for the sustainable development of society. Electrokinetic energy conversion utilizing micro/nanochannels is anticipated to offer significant potential for ocean energy harvesting, self-sustaining micro/nanodevices, and compact portable power sources by transforming environmental energy into electrical energy. Thus, it is essential to develop a micro/nanofluidic EKEC system that maximizes output electric power and conversion efficiency. We derived closed-form analytical and semi-analytical solutions for the electrostatic potential, velocity, and volumetric flow rate. Here, we utilize the analytical solution of the full Poisson-Boltzmann equation to determine the potential distribution within the flow domain, without restricting the classical considerations of low surface potential (without taking into account the widely used Debye–Hückel linear approximation). We employ two different types of constitutive relations to model polymeric liquids: the simplified Phan–Thien–Tanner (sPTT) model and the generalized Phan–Thien–Tanner (gPTT), both of which are non-linear viscoelastic models capable of capturing shear thinning behavior. These two models have been chosen for their efficacy in quantifying the physical characteristics of diverse polymeric fluids, including food gums, polyethylene melts, and aqueous polyethylene oxide (PEO) solutions, under circumstances featuring high strain rates. The generalized Mittag-Leffler function, which includes the standard exponential form of the original Phan-Thien and Tanner model as a limiting case, represents the newly introduced function for the trace of the stress tensor (instead of the classical linear and exponential functions) for gPTT fluid. This function offers stronger fitting flexibility by including one or two additional fitting constants. We also established that polymer solutions with wall depletion can significantly augment the conversion efficiency when compared to simple electrolytes under the same operating conditions. This study elucidates the impact of fluid rheology characterized by the solvent viscosity ratio, wall zeta potential–altered by interfacial electrochemistry and dielectric constant ratio on velocity distribution, volumetric flow rate, streaming potential and energy conversion efficiency in the context of electrokinetic transport. Our results indicate the important consequences of incorporating the generalized Phan–Thien–Tanner model into the flow field, in contrast to the traditional Phan-Thien-Tanner models. The findings of our research have implications for the development of miniaturization technologies that are more energy efficient, in particular for the design of self-energized electrokinetic micro/nanodevices.

Keywords**:** Zeta potential; Energy conversion efficiency; Viscoelastic fluid; Power-law fluid; Streaming potential; Electrohydrodynamics; Viscoelasticity; Polymer depletion layer.