ABSTRACT

Microfluidics has revolutionized a wide range of applications, from biomedical diagnostics to chemical processing, due to its ability to manipulate and analyze small volumes of fluids with high precision. Among various microscale transport mechanisms, electrokinetic flow is particularly important because strong surface charge and electrostatic effects dominate at small scales. However, many real fluids exhibit non-Newtonian characteristics such as elasticity and shear thinning, which conventional Newtonian models fail to capture. This motivates a detailed study of the coupled electrokinetic, thermal, and rheological effects in confined geometries.

The methodology involves modeling thermally developing, combined electroosmotic and pressure-driven flow, as well as streaming-potential-mediated pressure-driven flow, of Phan–Thien–Tanner (PTT) viscoelastic fluids in a microchannel. The full nonlinear Poisson–Boltzmann equation is solved to represent the electrical double layer accurately, while the simplified PTT (sPTT) model describes viscoelastic behavior, accounting for both elastic and shear-thinning effects. Semi-analytical expressions are derived for the velocity field, and the energy equation is solved with viscous dissipation, Joule heating, and axial conduction to capture thermal development.

The novelty of this work lies in a unified multiphysics framework that integrates nonlinear electrokinetics, viscoelastic rheology, and thermal transport without invoking the Debye–Hückel approximation. The results show that the velocity and temperature fields are strongly influenced by surface charge density, Weissenberg number, and channel aspect ratio. The thermally developing region increases sensitivity to electrokinetic and rheological parameters, thereby altering Nusselt numbers and overall heat transfer. Entropy-generation analysis indicates that electroosmotic flows are dominated by thermal irreversibility, whereas streaming-potential-induced flows show greater frictional losses.

This methodology provides fundamental understanding and predictive capability for designing efficient lab-on-a-chip devices, bioanalytical systems, and microscale thermal-management applications where accurate control of electrokinetic and thermal transport is essential.