Abstract

This thesis provides a detailed investigation of electrohydrodynamic transport phenomena in microchannels, thoroughly examining the interaction between electroosmotic (EOF) and streaming-potential-driven (SPF) flows in response to the simultaneous effects of electric, magnetic, and thermal field variations. The study advances theoretical, computational, and practical frameworks to address momentum, energy, and heat transport governed by nonlinear equations, incorporating Newtonian, and non-Newtonian rheology (Oldroyd-B, Couple stress Casson, Maxwell models), magnetic nanofluids (Fe_3O_4-H_2O), slip/jump boundary conditions, and multi-physical interactions such as Lorentz forces, Hall currents, ion slip, Joule heating, viscous dissipation, and thermal radiation.

Building on this framework, the thesis develops a semi mathematical model is developed to examine microscale transport of Oldroyd-B fluids in electroosmotic pressure driven flows under time periodic oscillations and wall slip conditions. A finite difference method (MATLAB bvp4c) is employed to solve the strongly non-linear electrical potential and concentration equations. A time-periodic oscillation effect on the velocity profile, concentration distribution, and mass transport is analyzed under low or high zeta potentials at the wall. The results show that fluid elasticity significantly enhances flow oscillations and mass transport, with a peak velocity increase of 142.75% at $\bar{\xi}$=4 compared to $\bar{\xi}$=1, and a 21.01% rise in velocity amplitude as the elasticity parameter increases from $\bar{\lambda}_1$=0.1 to $\bar{\lambda}_1$=0.2. A resonant mass transfer behavior driven by the coupled effects of angular Reynolds number and fluid elasticity is also identified, highlighting the potential of oscillatory viscoelastic flows for enhanced microfluidic transport applications.

Building upon this, the study examines electrokinetically driven flow, thermal transport, and energy conversion in microchannels containing hybrid viscoplastic fluids under slip-sensitive boundaries. A model for pressure-driven viscoelastic Casson fluids with couple-stress effects incorporates slip-modulated surface potential and external electric and magnetic fields, and is optimized using the non-dominated sorting genetic algorithm-II (NSGA-II) algorithm to enhance energy harvesting and reduce thermodynamic inefficiencies. The findings show that microstructural couple-stress and Casson viscoplasticity strongly influence streaming potential, energy harvesting, thermal gradients, and heat transfer, while frictional losses, ohmic heating, and radiation significantly affect convective thermal performance. According to the results, the electrokinetic energy conversion (EKEC) efficiency increases with slip-modulated surface charge potentials in couple-stress Casson fluid, couple-stress fluid, Casson fluid, and Newtonian fluid by 45.92%, 47.10%, 42.81%, and 37.68%, respectively, compared to scenarios with fixed surface charge potentials. At the center of the microchannel, under thermal jump boundary conditions, the temperature rises by 2.95% relative to systems governed by no-jump boundary constraints.

The unsteady pressure driven streaming potential flow of viscoelastic Fe_3O_4-H_2O nanofluids through porous media is analysed under transient forces, Hall current, Lorentz force, and ion slip effects. The Maxwell fluid model is solved using separation of variables and the finite difference method, with emphasis on electroviscous heat transfer rate and entropy generation. A multi objective optimization framework based on the Non-Dominated Sorting Grey Wolf Optimizer Algorithm (NSGWOA) and NSGA-II is employed to enhance electroviscous heat transfer while reducing entropy production through Pareto optimal solutions. Five decision variables namely relaxation time, Hall current, ion slip parameter, nanofluid volume fraction, and Hartmann number are considered. The results reveal a 1.92% reduction in streaming current with 2% nanoparticle loading and an 809.91% increase in electrokinetic energy conversion efficiency for slip dependent zeta potential compared to the slip free case. Further optimization using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) yields a 128% enhancement in heat transfer rate and an 82.5% reduction in entropy production.

The analysis is extended to electromagnetohydrodynamic time periodic wavy streaming potential flows of Oldroyd-B fluids relevant to drug delivery and biomolecular separation. Finite difference methods are employed to evaluate velocity field, volume flow rate, concentration distribution, mass transfer rate, temperature, Nusselt number, and entropy generation in a largely unexplored regime. A multi parameter multi objective optimization strategy using the NSGWOA and NSGA-II is developed to simultaneously improve heat transfer and minimize entropy generation. Four key parameters namely Hartmann number, electrokinetic width, zeta potential, and Dukhin number are optimized, and Pareto optimal solutions are identified using the TOPSIS. The optimized results demonstrate a 6.286% improvement in the Nusselt number and a 6.872% reduction in thermal irreversibility, along with a comparative assessment of NSGWOA and NSGA-II.

Extending toward practical implementation, this thesis introduces rectangular and hyperbolic nanochannel architectures for gravity-assisted desalination using ion concentration polarization (ICP) in nanochannel array systems. A computational framework is used to assess flow characteristics, desalination effectiveness, energy demand, and economic viability, with particular attention to scalability in freshwater generation. At an applied potential of 30 V_0 (thermal voltage is V_0), the rectangular nanochannel achieves an approximately 48% greater reduction in outlet Cl^- concentration than the hyperbolic configuration, indicating that geometric sharpness suppresses anion transport and enhances desalination efficiency. The parallelization of nanochannels under gravitational effects demonstrates high-throughput desalination while mitigating fouling issues inherent in conventional membranes.

Data-driven frameworks, including neural networks and adaptive neuro-fuzzy systems, are used to predict optimal Pareto solutions for electroviscous heat transfer and entropy generation from NSGWOA, with the neuro-fuzzy system achieving the lowest mean absolute percentage error. Combining hybrid finite difference methods, optimization algorithms, and machine learning, this work unifies electroosmotic and streaming potential phenomena to guide the design of advanced microdevices for biomolecule separation, energy harvesting, and sustainable water purification, setting a benchmark for predictive optimization in microscale thermos-fluidics.