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Concentration Polarization and Nonequilibrium Electro-osmotic Instability at an Ion-Selective Surface Admitting Normal Flow

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We revisit and build upon on the prototypical problem of ion transport across a flat ideal ion-selective surface. Specifically, we examine the influence of imposed fluid flows on concentration polarization (CP) and electrokinetic instability at over-limiting currents. We consider an ion-selective surface, or membrane, that admits a uniform flow across itself. The membrane contacts an electrolyte, whose concentration is uniform in a well-mixed region at a prescribed distance from the membrane. A voltage across the system drives an ionic current, leading to CP in the "unstirred layer" between the membrane and well-mixed bulk. The CP reflects a balance between advection of ions with the "normal flow" and diffusion. A Peclet number, Pe, parameterizes their relative importance; note, Pe is signed, as the flow can be toward or away from the membrane. An asymptotic analysis for thin Debye layers reveals a nonlinear CP profile, in contrast to the familiar linear profile at Pe=0. Next, we consider over-limiting currents, wherein a non-equilibrium space-charge layer emerges near the membrane surface. Finally, we examine the instability of the quiescent concentration polarization due to second-kind electro-osmosis in the space-charge layer. A stability analysis shows that the imposed normal flow can enhance or retard the instability, depending on its direction.