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VISCOPLASTIC FLOWS IN SUPERHYDROPHOBIC CHANNELS: THEORETICAL MODELING AND COMPUTATION

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ABSTRACT

Poiseuille flows of a viscoplastic fluid in a channel with a grooved superhydrophobic (SH) wall is modeled theoretically and computationally. It is assumed that the SH wall grooves are completely filled with gas, forming a flat interface with the overlying viscoplastic liquid. The pressure gradient can be oriented at any arbitrary angle θ relative to the grooves, allowing for longitudinal ($\theta = 0$), transverse ($\theta = 90°$), and oblique ($0 < \theta < 90°$) flow configurations. The slippery motion along the liquid/air interface is modeled using a slip number alongside the Navier slip law to relate shear stress and slip velocity at the interface. The viscoplastic behavior of the fluid is described using the Bingham constitutive model. A combination of semi-analytical, explicit-form, and numerical models is developed to characterize the velocity distribution, effective slip length tensor, and secondary flow field. In the creeping flow regime, five dimensionless parameters define the system: the Bingham number (B), slip number (b), groove periodicity length (ℓ), slip area fraction (φ), and groove orientation angle (θ). It is observed that the highest and lowest slip velocities occur in longitudinal and transverse flow cases, respectively. Moreover, the effective viscosity varies with θ, making each flow case unique and preventing the oblique flow solution from being directly derived from the longitudinal and transverse cases, unlike Newtonian fluids. In oblique flows, a secondary flow component emerges perpendicular to the pressure gradient direction. The critical angles θ_{max} corresponding to the peak secondary flow rate and the maximum effective slip shear component are determined and analyzed as functions of the Bingham number. An increase in Bingham number leads to a continuous decrease in θ_{max}. Lastly, the onset of a no-shear condition at the liquid/air interface is quantified, identifying when an unyielded plug region forms at the interface.