MAGNETIC FIELD-DRIVEN MANIPULATION OF FERROFLUID DROPLETS: EFFECT OF FIELD-DEPENDENT VARIATIONS IN THE LOCAL MAGNETIZATION

ABSTRACT

Droplet dynamics, whether it is sessile on a surface or pendant in another medium, is influenced by interactions with their surroundings, governed by forces such as surface tension, adhesion, and external fields like magnetic and electric fields. Sessile droplets display behaviors such as spreading across surfaces, which are dependent on surface characteristics like as hydrophobicity or hydrophilicity. However, pendant droplets undergo deformation due to the effects of background flow and external force fields, demonstrating distinct dynamics. Gaining a comprehensive understanding of these behaviors is of utmost importance for a wide range of scientific and biomedical applications.

This thesis examines the characteristics of ferrofluid droplets and their responsiveness to magnetic fields. The study explores the proposition of ferrofluid droplet-based tunable-wettability micromachines, employing magnetic fields beyond the saturation strength. Once the magnetic field exceeds the saturation magnetization, the magnetic dipoles within the ferrofluid align themselves in the same direction as the field and migrate to regions of higher magnetic intensity. This leads to significant deformation of the droplet, altering the interfacial energy and its dynamic interaction with the magnetic field. Here, the discussion is restricted to deformation limits that avoid droplet splitting or merging, focusing on wettability modulation rather than other droplet-based operations. This study employs an energy minimization principle to describe the magnetic field-mediated alteration of the ferrofluid droplet as a function of magnetic field strength and the intrinsic magnetic properties of the ferrofluid. This analysis has significant implications for the design of physical devices and systems including the magnetic manipulation of soft matter.

In addition, this thesis examines the wetting behavior of compound droplets, which consist of a smaller droplet enclosed inside a ferrofluid shell. This is important for several applications in the fields of biomedical sciences and materials processing. Through the integration of magnetic fields, this study improves the potential of these technologies in sectors such as soft robotics and medical imaging. A finite element framework is used to conduct numerical simulations to examine the spreading characteristics of compound droplets on hydrophobic surfaces in the presence of magnetic fields. These simulations investigate the process by which compound droplets reach a stable state by gradually altering their contact angles, that is corroborated by both experimental and theoretical approaches.

Further, the present thesis explores the asymptotic theory to analyze the settling behavior of a ferrofluid drop under different magnetic field strengths relative to its saturation magnetization. Additionally, the numerical simulations using the phase-field approach expand the findings beyond the applicability of the asymptotic theory. This study highlights the distinct consequences of magnetic field-dependent susceptibility in controlling the falling dynamics of a ferrofluid droplet.

Subsequently, this thesis presents a first-principle-based theory on the morphology of ferrofluid droplets under the combined influence of external magnetic field and extensional flow. This involves an asymptotic analysis considering local magnetization dependent on magnetic field intensity, which alters the shape of the droplet. The findings highlight the significant influence of saturation magnetization and base state susceptibility on droplet dynamics. A computational model based on the phase-field method explores the limitation and regime of large droplet deformation, providing new insights into field-assisted manipulation of ferrofluid droplets for applications in process engineering and biomedical technology.

These extensive investigations on the behavior of ferrofluid droplets under different circumstances provide useful insights for improving magnetically manipulated flexible fluidic systems, which have wide-ranging uses in digital microfluidics, pharmaceutical research, soft robotics, and medical imaging.

Keywords: Ferrofluid, Magneto-Wetting, Droplet Dynamics, Droplet Deformation, Magnetic Field, Saturation Magnetization.