博士論文（要約）

Numerical study on interaction of two bubbles rising in Newtonian and non-Newtonian fluid
(ニュートン流体及び非ニュートン流体中を上昇する二気泡の相互作用に関する数値解析)

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The three-dimensional direct numerical simulations based on VOF method are utilized to understand the mutual interaction of two rising bubbles for both the Newtonian and non-Newtonian bulk fluid. The study considers the interaction between two bubbles for Reynolds number ranging from 10 to 100, for various initial configuration of bubbles and for various non-Newtonian fluids described by the power index ranging from 0.8 (Shear-thinning fluid) to 1.2 (Shear-thickening fluid). The initial configuration takes into consideration of not only the bubble separation S ($3 \leq S \leq 10$) S being the distance between the bubble centers normalized by the bubble radius), but also the angle of inclination that ranges from $0°$ (side by side) to $90°$ (in-line bubbles). The interaction between two side by side bubbles can be repulsive due to interaction between the vorticity fields of two individual bubbles and can be attractive due to potential flow mechanism. The local change in viscosity due to non-Newtonian characteristics significantly change the interaction between two rising bubbles.

The present numerical method utilizes multidimensional THINC scheme for interface reconstruction. The power law model is used to model the non-Newtonian characteristics of the surrounding fluid. The present numerical method is validated for both Newtonian and non-Newtonian fluid with experimental and numerical studies available in literature. The interaction force experienced by each bubble is calculated using Kirchhoff’s generalized equation of motion. Force analysis for bubbles rising in side by side configuration in Newtonian fluid shows that the interaction force changes sign at critical Reynolds number for a particular bubble separation and at critical bubble separation for a constant Reynolds number. Force analysis for similar configuration in non-Newtonian fluid shows that the repulsive interaction between bubbles is stronger for shear-thickening fluid. In contrast, bubbles rising in shear thinning fluid experience stronger attractive interaction. In addition to critical Reynolds number and critical bubble separation, there exist a critical power index where interaction force changes sign for given Reynolds number and bubble separation.

Interaction between inline bubbles showed that at low Reynolds number, inline configuration is stable and bubbles collide. At high Reynolds number, bubble tends to deviate from the rectilinear path and tend to shift towards side by side configuration. The deviation from inline configuration takes place at certain Reynolds number for Newtonian fluid. Analysis for non-Newtonian fluid suggest that the Reynolds number at which path deviation takes place is dependent upon the power index of the surrounding fluid and is higher for Shear-thickening fluid. In the case of Newtonian fluid, the distance at which onset of path deviation (equilibrium distance) takes place is independent of the initial separation between two bubbles and is a function of only Reynolds number. However in the case of non-Newtonian fluid, the equilibrium distance is a function of both the bubble Reynolds number and the initial separation between two bubbles.

The study for bubbles initially placed in inclined configuration has been conducted to study the effect of angle of inclination on the interaction between two bubbles. The interaction between two bubbles is the resultant effect of vorticity interaction, potential flow effects and significant wake effect observed on the trailing bubble. Force analysis for two bubbles rising in Newtonian fluid shows that the interaction force changes sign at critical angle which depends upon the bubble Reynolds number for a constant bubble separation. The study extended for non-Newtonian fluid shows that the critical angle is dependent upon the power index (n) of the surrounding fluid. In case of the viscous dominated flows the critical angle is found to be higher for Shear-thickening fluid. In contrast, the critical angle for potential flow effects dominated regime is found to be higher for Shear-thinning fluid.