KELVIN-HELMHOLTZ AND RAYLEIGH-TAYLOR INSTABILITIES DURING ACCUMULATION AND DISPERSION OF FERROFLUID AGGREGATES

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Ferrohydrodynamics is dedicated to the study of fluids that are strongly magnetized in the presence of magnetic fields. Experimentally resolving the internal flow structure of ferrofluids has proved elusive due to their opacity. However, their dynamics remain important in the application of ferrofluids to mixing, heat transfer, medical devices, and others. To date, experimental techniques have been limited to free surface measurements, ultrasonically measured velocity profiles, and pressure distributions [1,2].Moreover, through 40 years of research in ferrohydrodynamics, a very limited body of work has experimentally tackled the interaction of a ferrofluid aggregate with a carrying bulk fluid [3,4]. The present work addresses this limitation and provides the first spatiotemporal analysis of the aggregation and dispersion ferrohyrdodynamics under steady and pulsatile flow conditions. Herein, the ferrofluid dynamics were studied in terms of accumulating and dispersing conditions, effect of magnetic field gradients, and inertial and unsteady effects.

Shadowgraph experiments were performed first to study the interfacial phenomena associated with a ferrofluid aggregate retained by a permanent magnet in both accumulating and dispersing conditions. Steady and pulsatile flow conditions were investigated for a range of Reynolds numbers of 100-1000 and for magnetic field strengths of 0.075 to 0.375 Tesla. Sequential images were recorded for up to 6 minutes at 30 Hz sampling, capturing the complete accumulation and dispersion process. For all of the conditions the shadowgraphs are quantitatively processed using in-house developed image processing tools and analyzed using basic statistical tools, spectra and Proper Orthogonal Decomposition.

During accumulation, the aggregate dynamics were studied for both top and bottom injection through a capillary tube. The injection velocity was adjusted to match the mean flow velocity. Figure 1 shows a representative case of top injection accumulation. As the streakline approaches the magnet, it is both bent and accelerated by magnetic forces. This phenomenon results in the Rayleigh-Taylor instability, which manifests as a series of expanding vortex rings that collapse as they approach the shear layer between the aggregate and the bulk flow.

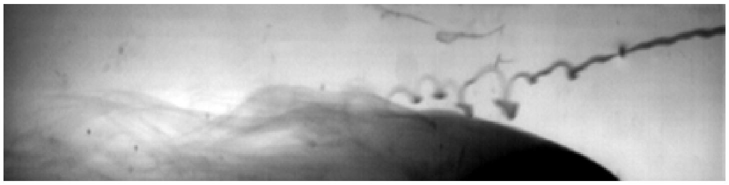

Figure 1. Shadowgraph of ferrofluid aggregate under accumulating conditions, with ferrofluid streakline injected from top of test section.

The dispersion is governed by a classical Kelvin-Helmholtz (K-H) shear layer instability shedding downstream for the cases where the Reynolds number exceeds the magnetic field forces. Such an example is shown in Figure 2 at a Reynolds number of 300 in pulsatile flow.

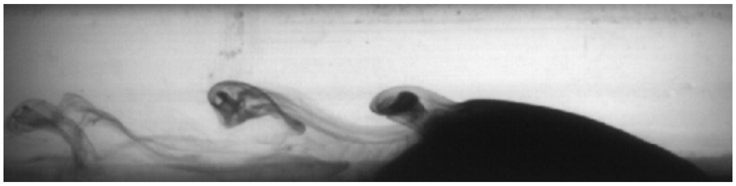

Figure 2. Shadowgraph of ferrofluid aggregate under pulsatile at peak flow rate, with K-H vortices.

Time Resolved Digital Particle

Image Velocimetry (TRDPIV) [5,6], was employed to measure the flow field characteristics of a ferrofluid mixed with flow tracers. Similar steady and pulsatile flow conditions and magnetic field gradients as the ones used in the shadowgraph experiments were considered. The flow velocity was measured spatiotemporally with a sampling rate of 100 Hz and spatial resolution of 240 microns within a laser sheet aligned mid-plane and streamwise to the flow direction.

A representative case of intra-aggregate and bulk flow interaction is shown in Figure 3. Three instantaneous vorticity fields overlaid with streamlines for a mean Reynolds number of 350 are shown. The aggregate interaction with the pulsatile flow involves suction (Figure 3A), roll up (Figure 3B), and ejection (Figure 3C) of ferrofluid. These behaviors correspond to near zero flow in 3A, accelerating flow in 3B, and peak flow in 3C. At the lowest flow rate, a large scale vortex encompasses the entire aggregate region. As flow increases, the single vortex breaks into three smaller vortices. Finally, as flow peaks, the aggregate is sheared downstream, and the flow streamlines are distorted only to a limited degree due to the presence of the ferrofluid.

In conclusion, this effort investigates the stable and unstable regimes of ferrofluid aggregates and their intra-aggregate flow structure. The emergence of spatiotemporal instabilities is documented and their significance with respect to the dynamics of the aggregate is analyzed.

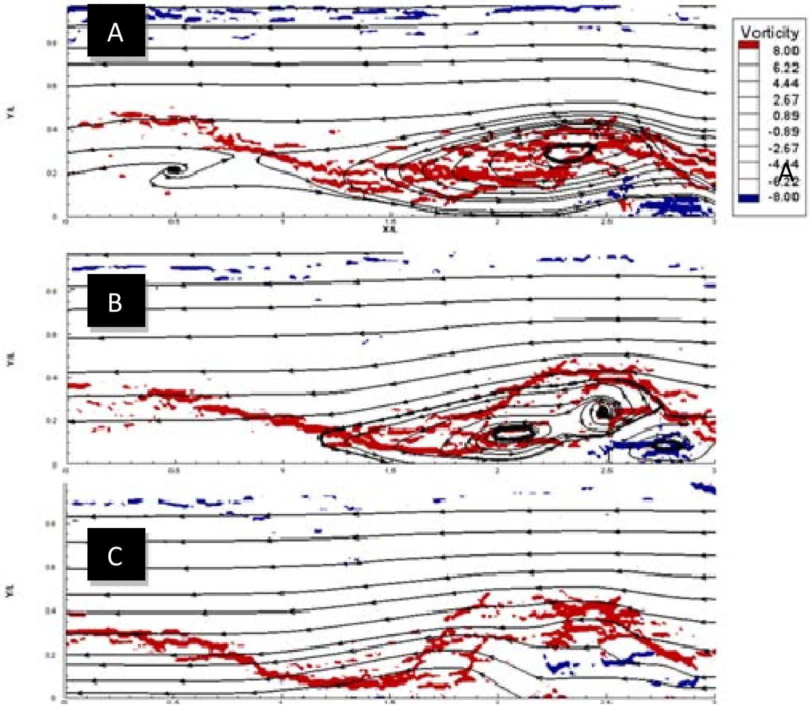

Figure 3. Time resolved post-processed frames showing contours of vorticity overlaid with streamlines

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