Spontaneous Dispersion of Particles on Fluid-liquid Interfaces

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ABSTRACT

When powders come in contact with a liquid surface they disperse so quickly to form a monolayer that it appears explosive, especially on mobile liquids like water. Our PIV measurements show that the adsorption of a particle causes a flow which moves away nearby particles on the surface.

INTRODUCTION

It is well known that particles trapped in liquid surfaces interact with each other via lateral capillary forces, which arise because of their weight, to form clusters or monolayer arrangements. A common example of capillarity-driven self-assembly is the clustering of breakfast-cereal flakes floating on the surface of milk. The deformation of the interface by the flakes gives rise to lateral capillary forces that cause them to cluster. This, as discussed below, is also the mechanism by which pollen grains cluster together to form pollen rafts. In recent years, many studies have been conducted to understand this behavior of trapped particles because of their importance in a range of physical applications and biological processes[1-4], e.g., formation of insect egg rafts, stabilization of emulsions, and the self-assembly of particles at fluid-fluid interfaces to form novel nano-structured materials that can be used in anti-reflection coatings for high-efficiency solar cells, photonic crystals and biosensor arrays.

For example, in *Ruppia maritime*, a hydrophilous plant, pollen can be released either below or above the water surface depending on the position of its anthers relative to the water surface. Before they are released from an anther, the pollen grains are clumped together in a kidney-shaped mass; when the pollen mass comes in contact with the water surface, its pollen partially disperses. These partially dispersed clumps cluster together to form a pollen raft which may contain pollen from several different anthers. The formation of pollen rafts is important because this enhances the probability of pollination as larger sized rafts are attracted more strongly towards an anther. For this reason the pollen rafts are also referred to as search vehicles.

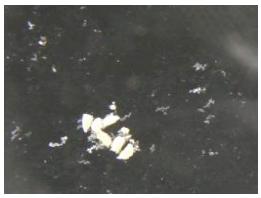

Figure 1. A pollen raft formed from the clustering of pollen masses from several anthers. The pollen masses were released above the water surface and partially dispersed immediately after reaching the water surface, and subsequently several dispersed masses clustered to form a pollen raft.

Similarly, when a clump of particles comes in contact with a liquid surface the particles located at its outer periphery are pulled into the interface by the capillary force overcoming the cohesive forces which keep them attached with the clump[5-7] (see Fig. 2). The clump continues to lose particles from its outer periphery progressing towards the center. The detached particles move radially outward from the clump because of the lateral interfacial flow that is induced by the newly adsorbed particles and those that are subsequently broken apart from the clump. This process of particles breaking away from the clump continues until all the particles have broken away to form a monolayer of particles on the liquid surface.

The newly-adsorbed particles move away from the clump, and each other, because when particles are adsorbed on a liquid surface they cause a flow on the interface away from themselves. Consequently, the initial distance between particles of the monolayer formed due to the breakup of a clump is several times the particle diameter. After the flow on the interface due to the adsorption of particles subsides, they cluster under the action of lateral capillary forces to form monloayers in which particles touch each other.

A millimeter-sized clump of some materials can break up and spread on a liquid surface in a few seconds and thus it appears that they spread on a liquid surface spontaneously, just like some drops can spread on a solid surface. It is worth noting that the mechanism by which a clump spreads on a liquid surface is similar to that by which a pinch of powder sprinkled onto the liquid surface disperses except that for the latter the cohesive forces are negligible and so the powder disperses immediately.

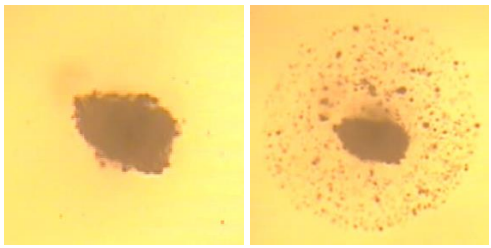

Figure 2. Photographs showing the breakup a clump of 10-170 μm glass particles on the corn oil-water interface. The initial size of the clump was around 1.86 mm. The clump settled through corn oil to reach the corn oil-water interface and dispersed violently at the interface.

EXPERIMENTAL SETUP

The setup consisted of a square Petri dish which was partially filled with Millipore water (see Fig. 3). The cross-section of Petri dish was 10x10 cm, and the depth was 1.5 cm. PIV measurements were performed in a vertical plane (normal to the camera axis) illuminated by a laser sheet. The vertical position of the camera was in line with the water surface, providing an undistorted view of the volume directly below the water surface. The test particles were dropped on the interface in an area near the intersection of the laser sheet and the camera axis.

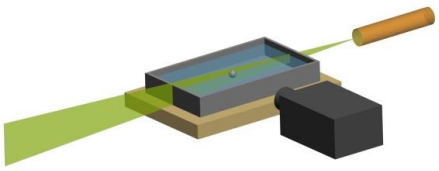

Figure 3. Schematic diagram of the experimental setup.

A high-speed camera was used to record the motion of seeding particles visible in the laser sheet. A Nikon 1 series V1 camera

equipped with a 30 mm Kenko automatic extension tube and a Tamron SP AF 60 mm 1:1 macro lens was used to provide the required magnification. The laser sheet was generated using a ZM18 series 40 mw solid state diode laser of wavelength 532 nm (green color). Movies were recorded at a resolution of 1280 x 720 pixels. For the particle size range considered (~500 μm to 2 mm), the optimal recording speed for performing the PIV analyses was found to be 60 frames per second. This was determined by a trial and error procedure.

The water was seeded with silver-coated hollow glass spheres of density around 1 gm/cc and average size of around 8-12 μm. The density of the seeding particles closely matched the water density, but there was a small particle-to-particle variation. Consequently, some particles sedimented and some rose slowly giving us ample time to record their motion when a flow was induced due to the adsorption of one or more test particles. The seeding particles were silver coated which ensured that the intensity of the scattered light was sufficient to track their motion.

An open-source code, PIVlab, was used for performing the time-resolved PIV analysis. PIVlab is a MatLab-based software which analyses a time sequence of frames to give the velocity distribution for each of the frames. A MatLab code was developed for post-processing and plotting results[8].

RESULTS AND DISCUSSION

We next discuss our measurements of the transient flow on a water surface that was induced due to the adsorption of a single test particle. Glass particles of several different diameters were used to obtain the qualitative nature of the flow, and determine how the strength and time duration of the induced flow vary with the particle size.

In agreement with the analytic results obtained[6,8], test particles in all cases oscillated vertically before reaching their equilibrium positions in the interface.

The adsorption of a test particle caused a flow on the air-water interface, which caused tracer particles trapped on the surface to move away from the adsorbed test particle. Consequently, the water surface near the test particle had few tracer particles which made fluid velocity measurement at and near the water surface difficult. Also, the air-water interface near the test particles was deformed since their density was larger than the water density. In fact, the center of particles was a fraction of radius below the level of the undeformed interface. The deformation of the interface made viewing of the interface by a camera mounted on a side difficult. Therefore, in our PIV measurements, the velocity was measured only in the region below a horizontal line passing through the point of contact of the interface with the particle which was a fraction of the particle radius below the undeformed interface.

Although the water near the test particle started to move as soon as the particle came in contact with the surface, the adsorption-induced streaming flow intensity developed over a period of time (see Fig. 4). The intensity reached a maximal strength after a fraction of a second and then it decreased. In the time interval after which the streaming flow reached its maximal strength, the vertical oscillations of the test particle were already negligible. The PIV measurements show that the streaming flow was approximately axisymmetric about the vertical line passing through the center of the test particle (see Fig. 4). Tracer-particles in the region below the test particle moved upwards, and those near and in the water surface moved away from the test particle. The trajectories of fluid particles were qualitatively similar to that for a stagnation point flow, with the center of the test particle being the stagnation point.

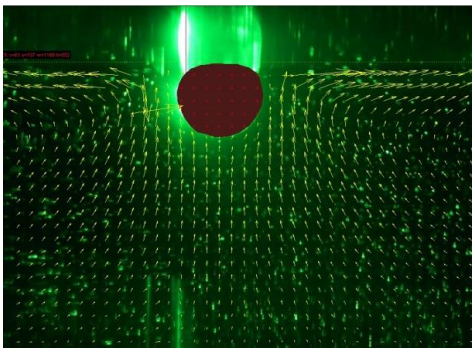

Figure 4. Velocity vectors for the streaming flow induced by a 2 mm test particle 0.67s after it came in contact with an air-water interface. The particle was dropped in a vertical plane illuminated by a thin sheet of laser light. The velocity vectors of tracer particles have been superimposed on the PIV image.

CONCLUSION

When a particle comes in contact with a fluid-liquid interface the vertical capillary force pulls it into the interface which gives rise to a transient streaming flow. The PIV measurements show that the liquid below a newly-adsorbed particle rises upwards and the liquid near the surface moves away from the particle. The induced flow for a spherical particle was axisymmetirc about the vertical line passing through the particle center. Also, the maximum flow strength is not established immediately after the particle comes in contact with the interface, but builds up over a short time interval. For a 650 μm glass sphere the maximum flow strength occurred about 0.4 s after the particle come in contact, and for a 2 mm sphere after about 1.5 s.

When two or more particles were simultaneously adsorbed, the streaming flow was a combination of the flows induced by the particles individually and so the flow strength increased with increasing number of particles. Consequently, the distance travelled by the particles near the outer periphery of a cluster sprinkled on a liquid surface can be several orders of magnitude larger than any dimension of the area over which the particles were sprinkled.

As discussed in Introduction, dispersion of particles is important in several physical processes occurring on a water surface, such as the pollination of hydrophilous plants, and the transportation and rate of spread of microbes and viruses on a water surface. Furthermore, the streaming flow can break apart agglomerates of particles when they are adsorbed at a fluid-liquid interface which is important in various processes in the pharmaceutical and food industries such as wet granulation and food processing.

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