# DISPERSION OF PARTICLES ON FLUID-LIQUID INTERFACES

Pushpendra Singh[a)], Ian Fischer, Bhavin Dalal, Sathish Gurupatham, Md.Shahadat Hossain & Naga Musunuri
*Department of Mechanical & Industrial Engineering, New Jersey Institute of Technology, Newark, NJ 07102, USA*

*Summary* When small particles, e.g., glass, flour, pollen, etc., come in contact with a fluid-liquid interface they disperse so quickly to form a monolayer on the surface that it appears explosive, especially on the surface of mobile liquids like water. This is a result of the fact that when a particle comes in contact with an interface the capillary force pulls it into the interface causing it to accelerate to a relatively large velocity in the direction normal to the interface. The maximum velocity attained increases with decreasing particle size; for nano particles, e.g., viruses and proteins, on an air-water interface it can be as large as ~47 m/s. Particle Image Velocimetry (PIV) measurements show that the adsorption of a spherical particle causes a transient axisymmetric flow which on the interface is away from the particle and directly below is towards the particle. Therefore, when two or more particles are simultaneously adsorbed, each of them causes a flow on the interface away from itself which moves the other particles away. The rate of dispersion depends on several parameters such as the size of particles, the interfacial tension, the viscosities of the fluids involved, and the contact angle.

## INTRODUCTION

An experiment showing dispersion can be performed easily in a household kitchen by filling a dish partially with water and then sprinkling a small amount of a finely-ground powder such as wheat or corn flour onto the water surface. The moment the flour comes in contact with the surface it quickly disperses into an approximately-circular shaped region, forming a monolayer of dispersed flour particles on the surface (see Fig. 1). The interfacial forces that cause this sudden dispersion of flour particles are, in fact, so strong that a few milligrams of flour sprinkled onto the surface almost instantaneously covers the entire water surface in the dish. The focus of this work is on understanding the physics of particle adsorption and the spontaneous dispersion of particles when they come in contact with an interface [1,2].

This phenomenon has importance in a wide range of applications, such as pollination in hydrophilous plants, transportation and spreading of microbes, viruses and nanoparticles, and the self-assembly of particles leading to the formation of novel nano-structured materials, etc. [1]. The forces causing dispersion can even break apart agglomerates of micron-sized particles that remain intact within a liquid. This breakup and spreading of agglomerates is important in various processes in the pharmaceutical and food industries such as wet granulation and food processing [2].

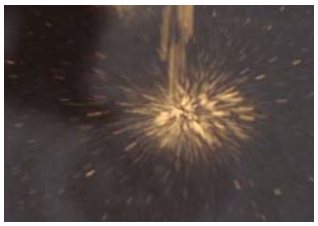

Fig. 1. Sudden dispersion of flour sprinkled onto the water surface in a dish. Streaklines formed due to the fast radially-outward motion of the particles emanating from the location where they were sprinkled. The size of particles was ~2-100 μm.

## METHOD AND RESULTS

The experimental apparatus consisted of a chamber containing a single liquid with a free-surface, or two immiscible liquids, one liquid above and the other liquid below and the interface between them. Particles were sprinkled at the free-surface or placed in the upper liquid through which they sediment to the interface. A microscope-camera mounted on the top of the chamber recorded movies of the particles which were then analyzed frame-by-frame using a calibrated digital ruler to determine the displacements of the particles. A high-speed camera mounted on the side was used to record the vertical motion and oscillations of particles when they come in contact with the interface. The fluid velocity was measured by tracking small tracer particles as well as by using the PIV technique.

When a particle comes in contact with a fluid-liquid interface the vertical capillary force pulls it into the interface causing it to accelerate to a relatively-large velocity in the direction normal to the interface (see Fig. 2). The maximum velocity increases with decreasing particle size; for nanometer-sized particles the velocity on an air-water interface can be as large as ~47 m/s [1]. The inertia of the particle plays an important role in its motion in the direction normal to the interface, and so as in an under-damped dynamic system, an adsorbed particle has characteristic linear and rotational frequencies that can be excited by an external forcing [3]. Although the importance of inertia diminishes with decreasing particle size, on an air-water interface the inertia continues to be important even when the size is as small as a few nanometers. Consequently, the particle oscillates vertically several times about its equilibrium height before the viscous drag causes it to stop. As expected, a single particle does not move laterally during adsorption.

The vertical motion of a single spherical test particle while it is being adsorbed causes a flow on the interface which moves away small tracer particles placed on the interface for flow visualization [1,2]. The interfacial fluid velocity increased with decreasing distance from the test particle and decayed to zero a short time after the test particle came in contact with the interface (in ~0.8 s on the air-water interface for 850 μm particles). The PIV technique has been used to

a) Corresponding author. Email: singhp@njit.edu

measure the complete three-dimensional structure of the time-dependent flow that arises because of the adsorption of a spherical particle [4]. The induced flow is axisymmetirc about the vertical line passing through the particle's center (see Figure 3). The liquid below the particle rises up, and near the surface moves away from the particle.

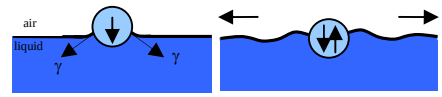


Fig. 2. Adsorption of a particle at an interface. (Left picture) When the particle comes in contact with the interface it is pulled inwards by the interfacial force (γ). (Right picture) The particle oscillates about the equilibrium height inducing a flow on the interface away from itself. This flow was visualized using tracer particles which moved away from the test particle.

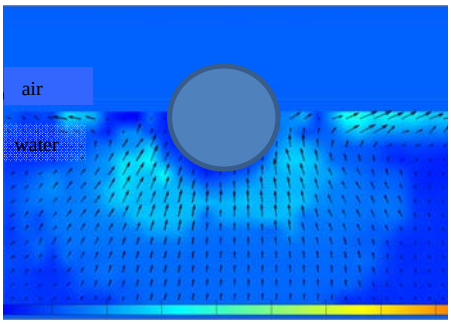


Fig. 3. The velocity distribution obtained using the PIV technique 0.45 s after an 800 μm glass particle is adsorbed on an air-water interface. The velocity vectors are shown on a vertical plane passing approximately though the center of the particle. The flow is axisymmetric about the vertical line passing through the particle center. The velocity magnitude is shown by the colored isovalues and also by the lengths of the arrows.

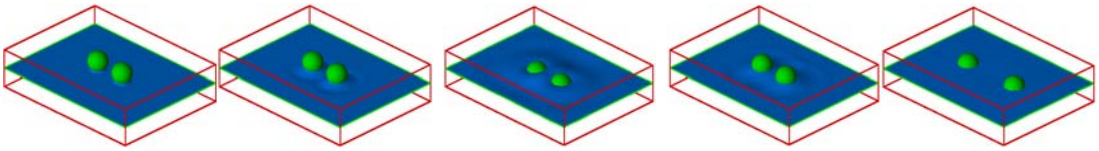


Fig. 4. Direct numerical simulation of the motion of two particles released above their equilibrium height in the interface. The particle radius was 0.1 cm and the contact angle was 85°. The initial height of the two particles was 0.95*R* above the undeformed fluid interface, where *R* is the radius. The initial lateral distance between the particles was 3.2*R*. The densities of the particle, the upper fluid and the lower fluid were 0.5, 0.1 and 1.0 g/cm$^3$, respectively, and the interfacial tension was 10.0 dyn/cm. The viscosities of the upper and lower fluids were 0.1 and 1.0 cP. The interface near the particles deformed to meet the contact angle condition. The resulting vertical capillary force pulled the particles downwards. The particles motion also caused the interface to deform and waves to develop. The resulting flow caused the two particles to move apart. For the final figure, the distance between the particles was 6.19R. The dimensionless parameters are: Re=14.6, G=368.2, Ca=7.3x10$^{-4}$. Taken from Ref. [1].

Therefore, when two or more particles are simultaneously adsorbed at an interface, each of these particles causes a secondary lateral flow on the interface away from itself causing the other particles to move away (see Fig. 4). When two particles are adsorbed the maximum distance by which they move apart is about a few diameters. However, as the number of particles being adsorbed increases, the distance travelled by a particle, especially if it is near the outer periphery of the cluster, can be very large—several orders of magnitude larger than any dimension of the area over which particles are sprinkled. For example, as noted above, a few milligrams of flour sprinkled over a very small area on the water surface almost spontaneously disperses to cover the entire water surface in the dish.

## CONCLUSION

When a particle comes in contact with an interface the capillary force pulls it into the interface causing it to accelerate to a relatively large velocity in the direction normal to the interface. This gives rise to a transient three-dimensional flow which on the interface is directed away from the particle and below is directed towards the particle. Therefore, when two or more particles are simultaneously adsorbed, each of these particles causes a lateral flow on the interface away from itself causing the other particles to move away.

### Acknowledgements

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