PARTICLE DEPOSITION RATES ON A WATER SURFACE AS A FUNCTION OF PARTICLE DIAMETER AND AIR VELOCITY

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Deposition rates of airborne monodispersed particles onto a water surface were determined in a wind tunnel. Average air velocities over water were 2.2, 7.2, 13.8 m/sec, and particle diameters were from 0.3 to 28 μm. For particles greater than 1 μm, deposition rates increased with both particle diameter and wind speed. For particles less than 1 μm diam, phoretic forces are comparable to transport forces from eddy diffusion and Brownian diffusion. Minimum deposition velocities are approximately 1×10^{-2} cm/sec. Maximum deposition velocity was 37 cm/sec, the largest ever reported for any surface.

INTRODUCTION

Dry deposition of airborne pollutant particles onto water surfaces is one means by which pollutants are removed from the atmosphere. Since approximately two-thirds of the earth's surface is covered with water, the dry deposition rates of particles onto water should be known if the true pollutant removal capacity from air to water is ever to be established. In discussing pollutant removal rates at the air-sea interface, dry deposition rates include all mechanisms for particle removal not attributed to precipitation. These mechanisms include eddy diffusion, gravitational settling, inertial effects attributable to air eddy size and particle relaxation time, impaction, interception, electrostatic effects, wave spray collection, diffusiophoresis and thermophoresis.

The deposition velocity, K, describes transfer rates of single sized particles and includes only surface resistance to mass transfer. The deposition velocity, K, is defined as

$$K = \frac{N}{C} = \frac{\text{amount deposited/cm}^2 \text{ of surface/sec}}{\text{airborne particle concentration above the surface/cm}^3} \qquad (1)$$

The concentration, C, for the monodispersed particles is measured about 1 cm above the deposition surface.

One would expect for water surfaces a deposition velocity dependence on particle diameter and wind velocity. Some particle size dependency was observed in a wind tunnel by Möller and Schumann,[21] but no wind velocity dependence was observed. They showed that deposition velocities, K, were from 0.01 to

0.04 cm/sec for particle diameters ranging from 0.03 to 1 μm. No data were reported for larger sized particles.

Particle deposition mechanisms onto an ocean surface are complex since the water surface is usually covered with a monolayer film or multilayer film composed of fatty acids or glycoproteins. These films could alter mass transfer rates at the surface. Baier and Goupil[22] report films are usually 100 to 200 Å thick, and are up to 4000 Å in more polluted regions. Films (Szekielda)[23] may consist of about 80% inorganic material and 20% organic. Deposited particles may preferentially collect in sea foam. Film resistance can be altered by microorganisms since Twitchell[24] reports surface films are mechanically agitated with flagella (dunaliella tertioleda), which increase evaporation rates.

The purpose of this study is to determine from water wind tunnel studies the deposition velocities, K, as a function of monodispersed particle diameters from 0.3 to 28 μm and wind speeds from 2 to 14 m/sec. In the determination surface films have been ignored since distilled water was used as the deposition surface. Nevertheless, these data are the first reported for deposition of monodispersed 1 to 28-μm diam particles onto a water surface.

EXPERIMENT

Particle deposition velocities, K, for water surfaces were determined[25] using monodispersed uranine particles and distilled water on the floor of a wind tunnel. Water was contained within the wind tunnel by placing a plastic sheet (leak proof surface) across the wind tunnel floor and up the sides and over two dams placed at the inlet and outlet of the test section. The test section was 9.1 m long by 60 cm wide. The initial water depth for each run was held constant at approximately 2.2 cm. For deposition determinations, particles were generated, airborne concentrations measured and deposition fluxes measured for each experiment. Air velocity, friction velocity, wave length, wave height, and wet and dry bulb temperatures were measured in selected runs.

RESULTS AND DISCUSSION

Particle size as reported is the size of particles entering the wind tunnel. However, because uranine particles are hygroscopic, the possibility exists that particle sizes may have been enhanced by sorbed moisture just before final deposition into the water. This sorption was not believed a serious problem. Nevertheless, future research should consider using the ammonium salt of fluorescein rather than uranine (the sodium salt). The ammonium salt has a very low water solubility (Stöber).[26]

Wave Description

Water wave characteristics for the three wind speeds used were a function of wind speed. These wave lengths and heights are summarized in Table 2. For the lowest wind speed of 2.2 m/sec, neither wave length nor wave height could be characterized by the still photographic technique used. For higher wind speeds of 7.2 and 13.8 m/sec, both wave height and wave length increased with increased wind speed. The maxima observed were 2.5 and 24 cm respectively.

Table 2. Wave Description

Air Velocity m/sec	Wave Length cm	Wave Height cm
2.2	Small	Small
7.2	10 to 15	1.0 to 1.6
13.8	10 to 24	1.3 to 2.5

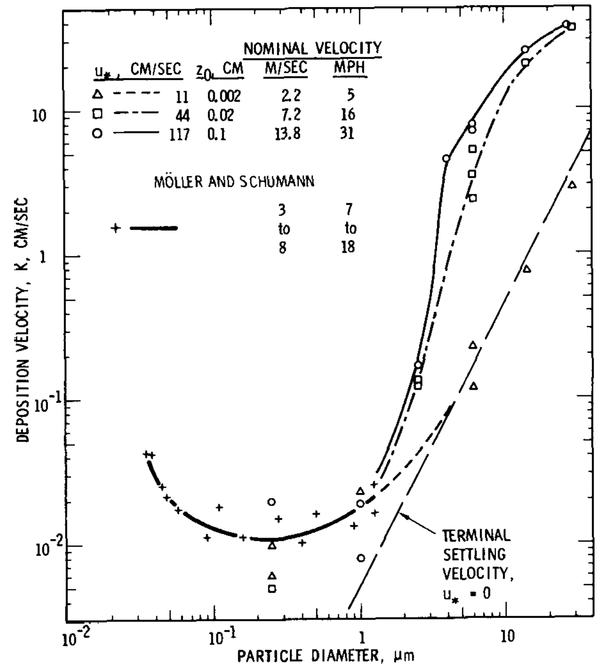

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FIGURE 3. Deposition Velocities to a Water Surface (Particle Density of 1.5 g/cm^3)

Deposition Velocities

Experimental deposition velocities are shown as a function of particle diameter in Figure 3 for wind speeds of 2.2, 7.2 and 13.8 m/sec (corresponding to friction velocities of 11, 44, 117 cm/sec, respectively). Also shown is a broken line representing particle deposition velocities corresponding to the terminal settling velocity.

Deposition velocities for particle diameters greater than 2 μm show consistency as a function of wind speed. At the lowest wind speed of 2.2 m/sec, experimental data points are considered to be indistinguishable from the terminal settling velocity broken line. At this low air speed neither increased air turbulence nor small wave motion enhanced particle deposition. At higher wind speeds, enhanced deposition was significant. Deposition velocities increased with both an increase in particle diameter and wind speed. Similar increases have been shown for dry surfaces by Sehmel.[3-6]

For the largest particles a significant difference occurs between dry surfaces and a water surface. For dry surfaces, net deposition velocities decrease with an increase in particle diameter above about 15 μm. This decreased net apparent deposition is caused by particles depositing but not sticking to a dry surface and being re-entrained into the airstream. For a water surface, re-entrainment does not occur since particles dissolve in the water.

Deposition velocity dependency upon wind speed could not be established for particle diameters below about 1 μm. Although a consistent wind speed depencency was not shown, deposition velocities are similar to those reported by Möller and Schumann,[21] who did not discuss any effect of wind speed. As indicated by temperature gradients, phoretic effects[25] are considered important in this particle diameter range. Phoretic effects were not controlled by either group of investigators. Nevertheless, data consistency suggests that the heavy solid curve reasonably represents deposition velocity data in this size range and that the minimum expected deposition velocity over a water surface is 1×10^{-2} cm/sec.

CONCLUSIONS

Particle deposition velocities now provide an experimental basis with which particle removal rates at the air-sea interface can be predicted. The rates are as expected in that: (1) a minimum deposition velocity was determined in the particle size range where eddy and Brownian diffusion are comparable and (2) deposition velocities for particles greater than 2 μm increased with both an increase in particle diameter and wind speed. Although the nonbreaking water waves developed with the small water depth in the wind tunnel were smaller than most ocean waves, deposition velocities as high as 37 cm/sec were measured for 28-μm diam particles. This is the largest experimental deposition velocity ever reported for any surface. When spray occurs the deposition velocity may be even greater. Experimental data are needed when breaking waves are simulated. This wave surface should include surface films.