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Spreading rate and dispersion behavior of evaporation-suppressant monolayer on open water surfaces: Part 2 – under wind stress

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Abstract

Wind causes migration and eventual removal (dispersal or beaching) of evaporation-suppressing monolayer on open-water storages. Hence, an autonomous system capable of adaptive re-application of monolayer according to the prevailing wind conditions is highly desirable. Key to the design and functioning of such a system is a fundamental understanding of the spatial movement/distribution characteristics of the monolayer material. To ‘bridge’ between centimeter-scale, clean room laboratory experimentation (e.g. Petri dish–scale in a wind tunnel) and field conditions (i.e. hectare-scale open-water storages), the drift velocity and spreading behavior of C18OH monolayer (in water-emulsion), applied continuously during constant wind stress, were investigated on a 6 m-diameter indoor water tank for wind speeds in the range 4–8 m/s. Monolayer was found to spread in a teardrop shape initially, which evolved into a wedge shape whose close-to-straight edges were detectable visually due to the wave-damping effect of the monolayer. The internal angle of the wedge decreased with increasing wind speed, consistent with the force equilibrium between the lateral force of the monolayer spreading outwards and the increasing shear imposed with increasing wind speed. The relationship between internal angle of the wedge and wind velocity was a power law. The widely-accepted spreading kinetics formula was used to derive an empirical relationship for the drift velocity that is a power law with respect to the wind speed. This model was compared with the experimental data, with a modest degree of agreement.

Highlights:
• Monolayer spreading angle and drift velocity measured in 6 m diameter tank
• Models for spreading angle and drift velocity obtained versus windspeed
• Theoretical model for drift velocity derived and tested

Keywords: Monolayer, Evaporation reduction, Wind stress, Spreading angle, Drift velocity
1 Introduction

The potential utility of an artificial monomolecular film (monolayer) for evaporation mitigation has long been recognized (e.g. as reviewed by Barnes [2008]) but to date has not been convincingly demonstrated outside the laboratory. Monolayer technology for water conservation was largely abandoned in the 1970s, mainly due to their highly-variable in-field performance characteristics (e.g. as reviewed by McJannet et. al. [2008]). A major factor in this variability has been identified as the action of wind (e.g. Crow [1963]): significant wind, exceeding 3.2 km/hr, causes major surface drift downwind [Vines, 1962; McArthur, 1962; Crow and Mitchell, 1975]. This results in increased film volatilization, in the generation of waves which can break-up or submerge the film [Fitzgerald and Vines, 1963; Frenkiel, 1965; Reiser, 1969a,b] and eventually beaching of remaining material on the lee shore.

To cope with the effect of wind, an effective monolayer application system should therefore be capable of both non-continuous application during periods of calm and also continuous application during periods of wind [Brink et al., 2011]. Furthermore, application rate in the presence of significant wind must be appropriate to the instantaneous rate of monolayer drift, and this may be achieved with an adaptive multi-applicator system informed by prevailing wind speed and direction information [Brink et al., 2011]. To determine the appropriate rate of monolayer application (as well as the placement of applicators for a given open water storage) the spreading rate and dispersion behavior of the particular monolayer product under wind stress must be known.

This paper reports the measurement and modelling of the evolution of monolayer cover under the dual influence of natural dispersion (driven by radial spreading from an application point) and wind drag (driven by surface movement downwind). The present work complements that undertaken by the present group to quantify spreading behavior under conditions of zero wind stress [Brink et al., 2017] during which only radial spreading was observed.

Both the work of Brink et al. [2017] and the present work were undertaken at a scale intermediate between centimeter-scale, clean room laboratory experimentation (e.g. Petri dish and Langmuir trough) and the desired field conditions, i.e. at hectare-scale on extensive open water storages, where experimentation is particularly challenging, principally due to lack of environmental control. The present work was undertaken using a 5.8 m diameter open tank in the same sheltered environment, i.e. at a scale such that validity of extrapolation of the results to field (hectare) scale may be argued. The objectives of the experimentation were to characterize: (i) the drift rate of monolayer being continuously applied in the presence of wind stress; and (ii) the ‘spreading angle’ of the wedge-shaped distribution of monolayer observed under these conditions.

2 Background and Literature

As a monolayer film is only a few nanometers thick, and has chemical properties such that it is coupled to the topmost layer of the water surface by its hydrophilic head group [Barnes, 2008], it is subject to horizontal transport by the wind [Crow, 1963; Fitzgerald and Vines, 1963; Frenkiel, 1965; Reiser, 1969a]. The cause of this surface transport (also commonly referred to as surface drift) is a consequence of two main force components: the wind-induced shear stress and Stokes mass transport related to wave characteristics [Lange and Huhnerfuss, 1978; Dobrokloenskiy and Lesnikov, 1972]. However, with well-settled water in most laboratory water tanks, the Stokes mass transport component is usually <10% of the total surface drift rate [Wu, 1975; Dobrokloenskiy and Lesnikov, 1972].
2.1 Surface drift velocity

The ratio of total surface drift speed of clean water (i.e. no monolayer) $u_s$ to wind speed $u_w$ has been reported by many researchers. The results of laboratory studies are set out in Table 1, from which the average (and standard deviation) of the measurements for this ratio $u_s/u_w$ is 0.035 ($\pm$0.008). Field studies in lakes and open oceans have been omitted as for these $u_s$ is generally greater, most likely due to an increase in Stokes mass transport by developed deep-water waves [Lange and Huhnerfuss, 1978].

When the water surface is damped by the presence of a monolayer film, the ratio $u_s/u_w$ is reported to rise linearly from 0.03 then tend to a constant of 0.045 [Fitzgerald, 1964]. Fitzgerald is the only researcher, to the authors’ knowledge, who has quantified surface drift speed for clean water surface and monolayer covered water in the same study. He suggested that the increase in surface velocity was related to the surface concentration of the monolayer added. This may explain the difference between the results of Fitzgerald [1964] and those of Lange and Huhnerfuss [1978], and Hale and Mitchell [1997], because the latter two studies each only used one fixed concentration. They both found this ratio decreased from 0.041 then tended to a constant value of approximately 0.03. Conversely, Reiser [1969a] found the ratio $u_s/u_w$ to be constant. No general consensus is apparent between researchers for the ratio and trend of $u_s/u_w$ for a monolayer-covered surface (Table 2). However, the average (and standard deviation) of measurements for this ratio, again from these laboratory studies only, is 0.035 ($\pm$0.006), which is essentially the same as that for clean water surface, and strongly suggests that there is little if any difference in the surface drift velocity due to the presence of monolayer material.

### Table 1. Comparison of various laboratory studies investigating the relationship between clean water surface drift speed $u_s$ and wind speed $u_w$. Adapted from Lange and Huhnerfuss [1978] and Hale and Mitchell [1997].

<table>
<thead>
<tr>
<th>Source:</th>
<th>Length (m)</th>
<th>Depth (m)</th>
<th>Method of Determination (diameter)</th>
<th>Wind Speed Range (m/s)</th>
<th>Ratio $u_s/u_w$</th>
<th>Trend ($u_s/u_w$ vs Wind Speed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keulegan [1951]</td>
<td>20</td>
<td>0.14</td>
<td>Paraffin flakes</td>
<td>3.0–12.0</td>
<td>0.033</td>
<td>None</td>
</tr>
<tr>
<td>Fitzgerald [1964]</td>
<td>1.83</td>
<td>0.15</td>
<td>Talcum powder</td>
<td>3.5–7.5</td>
<td>0.03</td>
<td>None</td>
</tr>
<tr>
<td>Wu [1968]</td>
<td>14</td>
<td>1.2</td>
<td>Spheres (0.030–0.41 in.) and disks (0.1&quot;)</td>
<td>3.5–13.4</td>
<td>0.028–0.048</td>
<td>Increasing and tending to a constant</td>
</tr>
<tr>
<td>Plate et al. [1969]</td>
<td>13.7</td>
<td>0.11</td>
<td>Wax paper disks (0.6 cm)</td>
<td>3.6–12.8</td>
<td>0.032</td>
<td>None</td>
</tr>
<tr>
<td>Wright and Keller [1971]</td>
<td>4.9</td>
<td>0.28</td>
<td>Polystyrene spheres (1/8–1/4 in.) and disks (1/8–1/2 in.)</td>
<td>2.2–7.9</td>
<td>0.038–0.045</td>
<td>Linearly increasing</td>
</tr>
<tr>
<td>Dobrokloinsky and Lesnikov [1972]</td>
<td>25</td>
<td>0.8</td>
<td>Polystyrene spheres (0.4–3 mm)</td>
<td>7.0–12.0</td>
<td>0.026–0.031</td>
<td>Linearly increasing</td>
</tr>
<tr>
<td>Shemdin [1972]</td>
<td>45.7</td>
<td>0.92</td>
<td>Paper disks (0.6 cm)</td>
<td>3.1–9.1</td>
<td>0.026–0.029</td>
<td>Increasing</td>
</tr>
<tr>
<td>Mizuno and Mitsuyasu [1973]</td>
<td>13.4</td>
<td>0.35</td>
<td>Paper disks (0.6 cm)</td>
<td>2.5–10.0</td>
<td>0.030–0.034</td>
<td>Increasing</td>
</tr>
</tbody>
</table>

### Table 2. Comparison of various laboratory studies investigating the relationship between monolayer surface drift speed $u_s$ and wind speed $u_w$. Again field studies in lakes and open oceans
have been omitted from this table. Adapted from *Lange and Huhnerfuss* [1978] and *Hale and Mitchell* [1997].

<table>
<thead>
<tr>
<th>Source and Year</th>
<th>Length (m)</th>
<th>Depth (m)</th>
<th>Method of Determination</th>
<th>Wind Speed Range (m/s)</th>
<th>Ratio of (u_s/u_w)</th>
<th>Trend ((u_s/u_w) vs Wind Speed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitzgerald [1964]</td>
<td>1.83</td>
<td>0.15</td>
<td>Talcum powder</td>
<td>3.5–7.5</td>
<td>0.03–0.045</td>
<td>Increasing and tending to constant</td>
</tr>
<tr>
<td>Reiser [1969a]</td>
<td>65</td>
<td>1.2</td>
<td>Sulfur powder</td>
<td>1.5–10.7</td>
<td>0.031</td>
<td>None</td>
</tr>
<tr>
<td><em>Lange and Huhnerfuss</em> [1978]</td>
<td>18</td>
<td>0.5</td>
<td>Talcum Powder</td>
<td>2.4–8.5</td>
<td>0.03–0.043</td>
<td>Decreasing and tending to a constant</td>
</tr>
<tr>
<td><em>Hale and Mitchell</em> [1997]</td>
<td>2.5</td>
<td>0.1</td>
<td>Talcum powder</td>
<td>2.0–5.0</td>
<td>0.03–0.041</td>
<td>Decreasing and tending to a constant</td>
</tr>
</tbody>
</table>

2.2 Applicator systems and whole storage experimentation

As monolayer films are so readily transported by wind, the general approach reported in the literature has been to apply monolayer continuously at a rate equal to which it is transported downwind [*Frenkiel*, 1965; *Crow*, 1963; *Reiser*, 1969a]. However, wind is also highly dynamic and varies from location to location and in speed and direction; therefore, an effective application system should also accommodate these dynamics.

A few prototype application systems which satisfy the above requirements have been developed. All generally used a number of applicators or application points strategically arranged around the perimeter of, and/or floating within, the water body [*McArthur*, 1962; *Crow*, 1963; *Reiser*, 1969b; *Crow and Mitchell*, 1975] as summarized in Table 3. It is presumed that the number of applicators/application points used and their strategic arrangement would have been influenced by the spreading characteristics of monolayer under wind stress. However, there is no general recommendation nor consensus for appropriate spacing between applicators/application points, for their arrangement, nor specific information regarding the spreading characteristics of monolayer materials used.

*McArthur* [1962] reported that the width of a surface slick spread in the direction of the wind depends on the initial spreading rate of the source, which must overcome the lateral stress of the wind. All other factors remaining constant, higher wind velocities give narrower slicks. Only *McArthur* [1962] has provided some general measurements of slick width for winds in the range 8.0–14.4 km/h on water at 9–11°C. *Crow and Mitchell* [1975] produced film coverage maps as reproduced in Figure 1. To the authors’ knowledge this is the only published documentation depicting the spreading characteristics of monolayer under wind stress.
**Table 3.** Experimental data for published studies employing distributed (multi-point) application systems for monolayer in a liquid form. The number of carbon atoms per molecule is reported for each test (e.g. C16).

<table>
<thead>
<tr>
<th>Source</th>
<th>Film-Forming Material</th>
<th>Liquid Formulation</th>
<th>Reservoir Size</th>
<th>Method of Application</th>
<th>Maximum Working Wind Speed</th>
<th>Spacing Between Applicators</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>McArthur</em> [1962]</td>
<td>Blend of C16 and C18</td>
<td>Volatile solution</td>
<td>769 ha</td>
<td>Gravity feed dispensers and bulk additions by-hand</td>
<td>25 km/h</td>
<td>Unknown</td>
</tr>
<tr>
<td><em>Crow</em> [1963]</td>
<td>C16</td>
<td>Water-based slurry</td>
<td>0.11 ha</td>
<td>Pumped through distribution hoses with orifices</td>
<td>24 km/h</td>
<td>3.1 m</td>
</tr>
<tr>
<td><em>Reiser</em> [1969b]</td>
<td>Blend of C16-C20</td>
<td>Water-emulsion</td>
<td>113 ha</td>
<td>Pumped through distribution hoses to laterals with flat jet sprays</td>
<td>20 km/h</td>
<td>6 m</td>
</tr>
<tr>
<td><em>Crow and Mitchell</em> [1975]</td>
<td>Blend of C16 and C18</td>
<td>Water-based slurry</td>
<td>1052 ha</td>
<td>Pumped through distribution hoses to laterals with rotary sprays</td>
<td>20.8 km/h</td>
<td>45.7 m</td>
</tr>
</tbody>
</table>
Figure 1 (2 Column). Two monolayer coverage maps for a 1052 ha storage based on hourly observations made by an observer using a plane table and alidade from a vantage point atop a 27.4 m tower. The upper map shows coverage achieved under a 12.4 km/h wind speed; and the lower map shows coverage during a 17.7 km/h wind speed. Reproduced from Crow and Mitchell [1975].
Figure 1 indicates that the monolayer spreads northwards in a wedge shape out from the points of application (on each of the three ‘Distribution Laterals’) before converging. Further lateral (east-west) spreading of the material is variable and not strongly indicated, suggesting that the material may have reached monomolecular layer configuration and that the dominant dynamics was the wind drag. (However, there is no information on other potential influences on relative water surface movement across the storage, e.g. differences in water depth, which might account for differences in lateral movement.) In conclusion, Crow and Mitchell [1975] also noted three ranges of wind speed that significantly affected the film cover: (i) 100% coverage for windspeeds < 4.8 km/h, (ii) spreading of film over large areas between 4.8 and 20.8 km/h windspeed, and (iii) that at windspeeds > 20.8 km/h the necessary application rate to maintain film cover was considered to be excessive.

3 Materials and Methods

3.1 Water tank and wind apparatus

All experiments were conducted in a round water tank, 5.8 m in diameter and 0.3 m deep, located indoors on a level concrete floor and fitted with an impervious black polyethylene liner. Wind was provided by an axial-flow fan, from which air was ducted through a 0.6 m diameter flexible air duct into a horizontal expansion chamber of outlet cross-section 2.7 m by 0.2 m situated at the water level of the tank such that air exiting the expansion chamber was travelling parallel to the water surface (Figure 2). An adjustable wind vane arrangement at the inlet of the expansion chamber plus an assembly of 600 mm by 90 mm diameter PVC tubes provided reasonable equalization of outlet windspeed across the width of the chamber.

3.2 Monolayer material and application

A water-based emulsion of 1-octadecanol (C₁₈H₃₇OH) with Brij® 78 emulsifier was developed as a ‘standard’ monolayer material for this experimentation. Details of its formulation and properties are set out in Brink et al. [2017].

The monolayer water-emulsion was applied at a continuous rate during all tests with an Aqua 24 V DC peristaltic pump. Monolayer was applied continuously at a constant rate for all tests, as this was deemed necessary in the field under significant wind stress conditions (> 3.2 km/h) in order to maintain monolayer coverage [Vines, 1962; McArthur, 1962; Crow, 1963; Frenkiel, 1965; Reiser, 1969a; Crow and Mitchell, 1975]. Three application rates were used for each wind speed, specifically 16.8, 41.5 and 51.3 mL/min. The outlet tube from the peristaltic pump was fixed at the water/air interface to minimize surface disturbance and ensure minimal product loss due to submergence.
3.3 Water surface cleaning process

Before each test the water surface was thoroughly cleansed of impurities and residual monolayer by overflowing the tank. It was also found this cleansing process could be aided by repeatedly scraping the water surface to the overflowing edge of the tank with a 5 m long 90 mm diameter semi-rigid polyethylene (PE) pipe. This cleaning process was undertaken (usually for 45 minutes) until surface pressure was measured to be < 4 mN/m. This measurement was made using a range of dodecanol (C\textsubscript{12}H\textsubscript{25}OH) indicator oils calibrated in 1 mN/m steps [Brink et al., 2017] on a sectioned-off portion of the tank, such that the oil was always contained and overflowed over the edge of the tank to remove it. Once the cleaning process was completed, the water was left for 3 hours to settle and remove any drift currents set up during the cleaning process.

3.4 Windspeeds and velocity profile measurements

All windspeed measurements were made with a Comark KM 4007 thermistor probe with an accuracy of ±3%. Four different windspeeds (3.7, 4.5, 5.2 and 8.3 m/s) were used in determining the spreading angle of monolayer, but only three (3.7, 5.2 and 8.3 m/s) were used to characterize monolayer drift velocity. All reference windspeeds were measured at a standard
height of 100 mm above the water surface and on the centerline of the expansion chamber 1.0 m from the face of the outlet. Vertical profiles were measured for each windspeed and compared horizontally using a clean water surface (i.e. without monolayer). Profiles were measured at distances of 1.0 m and 3.0 m from the outlet of the expansion chamber as shown in Figure 3.

**Figure 3 (2 Column).** Vertical windspeed profiles above the water surface at distances of 1.0 m and 3.0 m on the centerline of the outlet of the duct, for reference windspeeds of (a) 3.8 m/s; (b) 4.5 m/s; (c) 5.2 m/s; and (d) 8.3 m/s.

To assess areal uniformity, windspeed measurements were made by hand approximately 20 mm above the clean water surface (without monolayer) at 88 individual locations marked out by a grid of fine twine temporarily strung across the water surface, spanning 4.5 m downwind by 2.5 m crosswind. From these measurements an area, 4.0 m downwind by 2.0 m wide, was designated the ‘workable wind’ area, in which the windspeed did not differ by more than 30%.
If the entrainment of air into the airflow is modeled as a mixing layer, the characteristic encroachment of the mixing region into the main flow [Tennekes and Lumley, 1972] is only 35 cm at the end of the tank. Therefore, within this workable wind area (close to the flow outlet), the core of the flow is largely unaffected by entrainment of the ambient air, minimizing the cross-stream component of air velocity. The uniformity of the flow achieved for the four windspeeds is illustrated in Figure 4.

**Figure 4 (Single Column).** The horizontal distribution of wind velocity for each of the four mean wind velocities 3.7 m/s, 4.5 m/s, 5.2 m/s and 8.3 m/s. Each point is the average of measurements at the nine downwind grid locations within the 2.0 m × 4.0 m ‘workable wind’ area. Error bars represent the standard deviation of all measurements at each point.

3.5 Drift velocity visualization and measurement procedure

The drift rate of monolayer was initially characterized using both lightweight paper disks (5 mm diameter) and polystyrene spheres (7 mm diameter) floating on the surface. However, the polystyrene spheres proved easier to detect, making them more reliable as a surface movement (drift) indicator, especially with wave formation at the higher wind velocities.

However, as the spheres extended both above and below the surface, they experienced forces in addition to that exerted by the movement of the surface (with or without monolayer). These were principally additional downwind force from the bulk airflow, and retardation from the subsurface water [Wright and Keller, 1971]. The spheres were observed to float with approximately 50% submergence such that the diameter was approximately level with the surface, and from which it might be argued that these two non-surface forces were approximately equal and opposite. Assuming so, and with the observation that the meniscus appeared to ‘grip’ each sphere, the horizontal movement of the spheres was taken as indicative of the surface movement. Nonetheless, the experiments of Wu [1968] suggest that the surface speed could be under-predicted by up to 40% for spheres of this size and the wind speeds tested. Studying the
results of Wright and Keller [1971] for water without monolayer application, an estimate of the under-prediction of the drift velocity can be made:

$$\varepsilon \approx -4rU.$$  

Here $\varepsilon$ is the error in the drift velocity [m/s], $r$ is the radius of the polystyrene sphere [m], $U$ is the reference windspeed [m/s] and the empirical constant 4 has units of m$^{-1}$.

To expand on this, the error in the drift velocity was estimated using the drag coefficient for a sphere. Because of the small diameter of the polystyrene spheres, the top of the sphere is located within the air boundary layer. The boundary layer thickness was estimated based on the length Reynolds number and freestream velocity at 3 m. To obtain the sphere Reynolds number, the effective air velocity was determined using a laminar boundary layer (sinusoidal profile) and turbulent boundary layer (standard 1/7 profile). The applied air drag force could then be found, which should balance the applied water drag force. At a windspeed of 3.7 m/s, the inferred drift velocity which produces this water drag force deviated from the measured values (Figure 6) by 51% for a fully-turbulent boundary layer and 21% for a fully-laminar boundary layer; at this windspeed, the boundary layer is most likely close to laminar. At a windspeed of 8 m/s, the drift velocity errors were calculated to be 28% for fully turbulent and 14% for fully laminar; the length Reynolds number could be sufficient for the boundary layer to be considered fully turbulent.

During testing, monolayer was applied continuously as the polystyrene spheres were gently placed on the water surface (spaced about a meter apart) by hand at the upwind side of the tank and allowed to drift downwind. All tests were recorded by a downward-looking digital video camera mounted 5.5 m vertically above the water tank, and drift velocities were determined by manual inspection of images and the known image geometry and frame rate of the camera (25 fps).

Drift velocity tests were first run for each windspeed without applying monolayer to determine the drift velocity of pure water. Four replicate measurements of drift velocity were then made for each wind velocity and each monolayer application rate (16.8, 41.5 and 51.3 mL/min). The drift velocity was measured as the average speed across the workable wind area (it is the length of the workable wind area divided by the measured time to span that length).

3.6 Spreading angle visualization and measurement procedure

Due to a decrease in water surface tension by application of the monolayer [Barnes, 2008], a significant wave-calming effect was observed between the covered (monolayer) and uncovered (no monolayer) water surface in the presence of wind stress. This effect was easily visible for all of the wind velocities, except the lowest at 3.7 m/s, for which there was too little contrast between the waves on the covered and uncovered surface. Hence, small amounts of talcum powder had to be applied during the 3.7 m/s tests to aid in detecting the edges between covered and uncovered surface.

For all tests the fan was turned on first and allowed to reach the predetermined test windspeed before the continuous application of monolayer was started. Once monolayer application was started it would usually take between 20 and 50 s, depending on the wind speed and application rate, for the spreading angle to reach a steady-state (i.e. the equilibrium spreading angle). The spreading angle is defined as the total internal angle of the straight lines projected on either side of monolayer material (Figure 5). Once this equilibrium spreading angle
was achieved, monolayer application was continued for at least 60 s to confirm the spreading angle. Figure 5 illustrates the evolution of a spreading angle test.

Angles were determined by fitting a straight line manually to each defined edge between calm and wavy water surface within the ‘workable wind’ area (section 3.4 above). The fit of these lines was checked for a period of 60 seconds by stepping through the video and a digital angle template was then positioned over the lines of best fit to determine the angle.

**Figure 5 (2 Column).** Frames from recorded video showing the evolution of the spreading angle of monolayer under a uniform imposed windspeed of 4.5 m/s: (a) predetermined windspeed has been reached and monolayer application has just begun; (b) monolayer is now spreading laterally and drifting downwind, showing a straight monolayer edge in the left-hand quadrants of the image; (c) the spreading angle has now reached equilibrium (showing a straight monolayer edge in all quadrants of the image) and measurement of the angle can begin; and (d) after a further 60 s the equilibrium spreading angle is maintained. The small orange square (upper left quadrant) indicates the point of monolayer application.

In Figure 5(a), there appears to be some spreading of the flow downstream of the application points (the ripples in the right quadrants were not aligned). This is not likely to be caused by entrainment of the air into the sides of the airflow since the workable wind area (the central 4 m) is outside the entrainment zone, as noted above. It is possible that there are some
surface water circulation currents due to the size and shape of the tank, which would consequently cause measurements of the monolayer spreading angle to be over-predicted. To avoid producing such circulation currents which affect measurements of spreading angle for a fetch of the order of meters would likely require a tank diameter of at least 20 m.

4 Results

4.1 Drift velocity

Drift velocity measurements were conducted at four different application rates (16.8, 25.8, 41.5 and 51.3 mL/min) and three reference wind velocities (3.7, 5.2 and 8.3 m/s) and the results as a function of application rate are set out in Figure 6.

![Figure 6](image)

**Figure 6 (Single Column).** Comparison of the drift velocities at three reference wind velocities plotted as a function of application rate. Each point represents the average of four replicates and error bars represent the standard deviation of the four replicates for each point.

Figure 6 indicates that drift velocities were affected by application rate only minimally. Hence for subsequent analyses the drift velocity results obtained at different application rates were averaged (at each reference wind speed), and for clarity are henceforth referred to as ‘float velocities’.

The measured float velocity plotted as a function of the reference wind speed is shown in Figure 7, both with and without the presence of monolayer. A linear fit is shown for both data sets, but is clearly inappropriate for the case with monolayer. Furthermore, as each of the three data points plotted is the mean of at least 12 replicate measurements (with the standard deviation of each set indicated by the error bars), a non-linear relationship is indicated.
Figure 7 (Single Column). Comparison of ‘float velocity’, with and without the continuous application of monolayer, plotted as a function of the reference wind velocity.

4.2 Spreading angle

Measurements of the spreading angle conducted at the same four different application rates (16.8, 25.8, 41.5 and 51.3 mL/min) and four reference wind velocities (3.7, 4.5, 5.2 and 8.3 m/s) were undertaken and the results as a function of application rate are set out in Figure 8. Because the edges of the monolayer region were not perfectly straight, there was some degree of judgment in measuring these angles.
Figure 8 (Single Column). Comparison of the spreading angles at four reference wind velocities plotted as a function of application rate. Each point represents the average of four replicates and error bars represent the standard deviation of the four replicates for each point.

Figure 8 indicates that like drift velocities (Figure 6), spreading angles were minimally affected by application rate. Hence for subsequent analyses the spreading angles obtained at different application rates were averaged (at each reference wind speed). These were then plotted as a function of reference windspeed and are shown in Figure 9.

As also shown in Figure 9, the spreading angle–windspeed relationship was well represented by a power law:

$$\theta = 7.73U^{-1.42}$$

where $\theta$ is the spreading angle (radians, unlike Figure 9); and $U$ is the reference windspeed (m/s). The coefficient of determination for the fitted constants in eq. (1) is $R^2 = 0.987$. 
Figure 9 (Single Column). The observed relationship between spreading angle and reference windspeed. The curve-fit is a power law.

5 Analysis and Discussion

5.1 Drift velocity and monolayer application

Although Fitzgerald [1964] related surface velocity to the surface concentration of the monolayer present, in this study no dependence of surface velocity on monolayer concentration could be detected (Figure 6). However, in contrast to the Fitzgerald [1964] experimental arrangement, in the present study monolayer was being overdosed at all times, i.e. the monolayer concentration was always in excess of the minimum amount to reach equilibrium surface pressure. This suggests the general conclusion that when monolayer is overdosed and in continuous application, the drift velocity is not dependent on dosage rate.

Furthermore, as monolayer was applied continuously, the measured float velocity would not only be a result of the force balance between the wind shear and Stokes transport, but also be enhanced due to the spreading force of the overdosed monolayer. This spreading force was unable to be quantified in the present work, other than to note again that different application rates did not affect the spreading performance (Figures 6 and 8). In addition, Brink et al. [2011] have shown that the impact of the spreading force (and therefore the spreading rate of the monolayer) will diminish over time as the material degrades on practical (non-laboratory) open water storages.

The indicated non-linear relationship between ‘float velocity’ and reference windspeed (Figure 7) is in contrast to the linearly increasing trend as suggested by Lange and Huhnerfuss [1978] and Hale and Mitchell [1997]. However, as with the prior work of Fitzgerald [1964], comparison with these results may be invalid as they did not use continuous monolayer application.

The higher surface drift velocity of monolayer-covered water for wind velocities > 5.2 m/s in this study would suggest that the dynamics of air flow near the water surface is markedly different to that for a clean water surface, for which the only apparent difference is the wave damping effect of the monolayer [Wu, 1971]. One explanation is that a more laminar flow regime may be created at, and adjacent to, the water surface when the capillary waves are
damped by monolayer, thereby increasing the wind drag coefficient. Another possible explanation may be that a wavy water surface (i.e. no monolayer present) creates zones of high and low pressure between the waves, which can act to pull the water surface backwards in the opposite direction of the air flow [Jeffreys, 1925]. This would effectively decrease the surface drift velocity of clean water.

5.2 Spreading angle modeling

When a monolayer is continuously applied in the presence of wind stress, the lateral spreading of the monolayer is limited by the linear stress exerted by the wind and water. After a period of time (depending on the wind velocity), monolayer has been shown to spread in a wedge shape (Figure 5). The apex angle of this wedge $\theta$ is a result of an equilibrium between the forces on the monolayer, which are the streamwise wind shear; tangential monolayer spreading force $S$; and the water surface current (which has unknown magnitude and direction in the current experiments, but the vector changes in both the streamwise and cross-stream directions). If the effect of the water surface current is ignored, then the monolayer spreading distance $d_m(t)$ is the arc length $AB$ and the distance travelled by any monolayer particle is the radius $d_{ext}(t)$.

Since the arc length is the radius multiplied by the angle, and using eq. (2), the distance travelled can be modeled by:

$$
\text{eq. 3} \quad \frac{d_{ext}(U,t)}{d_m(t)} = \frac{1}{3.87} U^{1.45} d_m(t).
$$

The effect of the circulation current in the current experiments on eq. (3) requires some discussion. At point B, any current would act in the upstream direction (due to the reaction force from the far side of the tank), so would cause the measurements of $d_{ext}(t)$ to be under-predicted, hence lead to an over-prediction of $\theta$. At point A, the circulation current would create additional cross-stream motion (leading to an over-prediction of $\theta$), while also retarding the streamwise motion to a lesser extent than point B (leading to an under-prediction of $\theta$). Overall, it is likely that the measurements of $\theta$ in Figure 8 are over-predicted by approximately 10% as a consequence of the water surface circulation current in this experiment.
Figure 10 (Single Column). The balance of forces present within the wedge-shaped plume OABC of surface material released from point O in the presence of wind drag \( \tau \) (in the streamwise direction), monolayer spreading force \( S \) (tangential to arc) and unknown water surface current stress \( \tau_{\text{curr}} \).

For monolayer spreading on still water, with zero wind shear, the spreading force \( S \) is related to the position of the (radially expanding) leading edge at \( d_m(t) \) by [Dussaud and Troian, 1998; Berg, 2009]:

\[
d_m(t) = K \frac{S^{1/2}}{(\mu \rho)^{1/4}} t^n
\]  

(4)

where:
This has also been demonstrated at experimental scale comparable to the present work by Brink et al. [2017]. As this study used the same C18OH water-emulsion, empirical values of $K = 1.1667$ and $n = 0.747$, with the measured value of $S = 14\pm1$ mN/m, as determined in Brink et al. [2017], are applicable.

Substituting eq. (4) into eq. (3) yields:

$$d_{\text{ext}}(U,t) = \frac{KS^{1/2}U^{1.42}}{3.87(\mu\rho)^{1/4}}t^n$$

(5)

from which the float velocity is given by differentiating:

$$u_f = \frac{d}{dt}(d_{\text{ext}}) = n \frac{KS^{1/2}U^{1.42}}{3.87(\mu\rho)^{1/4}}t^{n-1}$$

(6)

5.3 Validation of drift model

The model eq. (5) was tested by substituting the measured properties of the monolayer and comparing the predicted time to traverse the workable area to the measured time (which yielded Figure 7). The formula for this calculation was:

$$t_{\text{trav}}(U) = t_{\text{end}} - t_{\text{start}}$$

$$= t(U,d_{\text{end}}) - t(U,d_{\text{start}})$$

$$= \left[\frac{3.87(\mu\rho)^{1/4}}{KS^{1/2}U^{1.42}}\right]^{1/n} \left(d_{\text{end}}^{1/n} - d_{\text{start}}^{1/n}\right)$$

(7)
The following values were used for the constants:

\[
\begin{align*}
K &= 1.1667 \pm 0.021 \quad [-] \\
S &= (14 \pm 1) \times 10^{-3} \quad [N/m] \\
\mu &= 1.01 \times 10^{-3} \quad [Pa.s] \\
\rho &= 998 \quad [kg/m^3] \\
n &= 0.747 \pm 0.003 \quad [-]
\end{align*}
\]

with most of these values mentioned in the preceding section and the properties for water taken at the temperature of the room (due to the 4th-root, any errors in \(\mu\) and \(\rho\) contribute negligibly to the error in \(t\)). The resulting values for eq. (7) are plotted in Figure 11, and are compared to the experimental results. The bands provided by the outer lines show the results from eq. (7) with extreme values of the empirical constants (the lower band is produced by taking the maximum values of all; the upper band by taking the minimum values of all).

**Figure 11 (1.5 Column).** Validation of eq. (5) using eq. (7), the time taken to traverse the workable area. Experiment: triangles with error bars. Model determined using quoted values of empirical coefficients: solid line. Model determined using extreme values of empirical coefficients: dotted lines (upper line is coefficients taking lowest values). Circles are values for the model at same windspeeds as experiment. Horizontal dashed line near the top shows the value for no-wind spreading, calculated based on Brink et al. [2017]; vertical dashed line indicates the threshold for wind having a significant effect on monolayer motion [Vines, 1962]. (a) Using experimental data; (b) experimental data adjusted to account for 20% under-prediction of drift velocity due to polystyrene spheres.

The sensitivity of the model to the values of all the coefficients can be seen in Figure 11(a), with the greatest uncertainty in \(S_{net}\), which accounts for about half of the variability. In general the behavior of the model is modest: while the general trend satisfies what should be
expected, it under-predicts the experimental results for higher windspeeds, but greatly over-predicts the results for the lowest windspeed. If the experimental drift velocities are adjusted to account for the 20% under-prediction estimated in Sect. 3.5 [Figure 11(b)], then there is excellent agreement between the model and experiment for the higher windspeeds, but the lowest windspeed error is exacerbated. Also shown in Figure 11 is the duration for the same distance traveled under no wind load, calculated from Brink et al. [2017]. Since the effects of wind on monolayer are significant above 3.2 km/h (0.9 m/s) [Vines, 1962], it can be seen that the model significantly over-predicts this boundary. This is to be expected since there ought to be a region of negative curvature between the no-wind threshold and approximately 2–3 m/s as the influence of wind becomes significant and starts to dominate. In this transition region, the contributions to the streamwise motion would be from both the no-wind drift \( d_m \) and the wind drift \( d_w \).

Nonetheless, it seems unlikely that any acceptable model could satisfy all three experimental points in addition to the no-wind threshold: three turning points would be required, which has no physical justification.

It should be noted that the effect of the quoted error in \( n \) is small compared to the errors in the three coefficients. If values of \( K = (4/3)^{1/2} = 1.1547 \) and \( n = 0.75 \) are used [Berg, 2009], which are both within the quoted errors, the line is indistinguishable from the empirical values that are used (the change caused by \( K \) is offset by the change caused by \( n \)). This is consistent with the conclusions of Brink et al. [2017].

6 Conclusions

In this study, the drift velocity and spreading angle of monolayer continuously applied under wind stress were characterized and models developed. The nature of the drift velocity was observed to be different with the application of monolayer, with the monolayer creating a dampening effect for the intermediate windspeed, but an acceleration effect for the highest windspeed. The measurements of drift velocity are approximately 20% less than the true values owing to the usage of spheres to conduct the measurements, which have significant sub-surface drag.

Monolayer was found to commence spreading in a teardrop shape, with the sides soon starting to flatten after a period of time, depending on the wind velocity, to create a wedge-shaped spreading pattern. This wedge pattern would then be maintained for at least one minute. The edges of the wedge were easily detectable due to the wave damping provided by the monolayer. The internal angle of the wedge was then measured and was observed to decrease with increasing wind speed; the relationship was found to be a power law. It is expected that the spreading angle is over-predicted owing to the presence of surface circulation currents in the water created by the shape and limited size of the tank. Because the application rate was overdosed compared to the minimum required to produce a viable, evaporation-reducing monolayer, the application rate had no significant effect on either the drift velocity or the spreading angle.

Empirical relationships were derived for the spreading angle and the drift velocity, with the latter based on the widely-accepted spreading kinetics formula. The empirical formula for spreading angle is a function solely of windspeed, while this spreading angle formula was used in producing the drift velocity model, which is a function of windspeed and time. Using empirical values for the various constants, the model for drift velocity was compared to the experimental data. Although the experimental data was not accurately reproduced, accounting for the errors in drift velocity measurement tremendously improved the comparison. The model
under-predicts the rate of spread for no-wind conditions, although a transitional model to account for the change of regimes could ameliorate most of this error.

A key limitation of the current work is the restriction to a 6 m circular tank, which means that a significant extrapolation is required to apply the current results to real water reservoirs. For instance, it is expected that the spreading angle would diminish at large values of fetch, particularly as the effective dosage (surface density of material) approaches the minimum required to produce a viable monolayer. But, obviously, this is beyond the point at which the remaining material can produce any practical evaporation mitigation. The current results provide an advancement in the current knowledge by studying the intermediate-scale behavior in controlled laboratory conditions.

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Highlights:

- Monolayer spreading angle and drift velocity measured in 6 m diameter tank
- Models for spreading angle and drift velocity obtained versus windspeed
- Theoretical model for drift velocity derived and tested