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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.

1. Introduction

The potential utility of an artificial monomolecular film (monolayer) for evaporation mitigation has long been recognized (e.g. as reviewed by Barnes [1]) 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. [17]). A major factor in this variability has been identified as the action of wind (e.g. Crow [5]): significant wind, exceeding 3.2 km/h, causes major surface drift downwind [24,16,6]. This results in increased film volatilization, in the generation of waves which can break-up or submerge the film [10,11,20,21] 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 [3]. 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 [3]. 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 [4] during which only radial spreading was observed.

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Both the work of Brink et al. [4] 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 [1], it is subject to horizontal transport by the wind [5,10,11,20]. 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 [15,7]. However, with well-settled water in most laboratory water tanks, the Stokes mass transport component is usually <10% of the total surface drift rate [28,7].

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 (±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 [15].

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 [9]. 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 [9] and those of Lange and Huhnerfuss [15], and Hale and Mitchell [12], 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 [20] 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 (±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.

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 [11,5,20]. 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 [16,5,21,6] 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 [16] 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 [16] 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 [6] produced film coverage maps as reproduced in Fig. 1. To the authors' knowledge this is the only published documentation depicting the spreading characteristics of monolayer under wind stress.

Fig. 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

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 [15] and Hale and Mitchell [12].

Source	Length (m)	Depth (m)	Method of determination (diameter)	Wind speed range (m/s)	Ratio u_s/u_w	Trend (u_s/u_w vs wind speed)
Keulegan [14]	20	0.14	Paraffin flakes	3.0–12.0	0.033	None
Fitzgerald [9]	1.83	0.15	Talcum powder	3.5–7.5	0.03	None
Wu [26]	14	1.2	Spheres (0.030–0.41 in.) and disks (0.1″)	3.5–13.4	0.028–0.048	Increasing and tending to a constant
Plate et al. [19]	13.7	0.11	Wax paper disks (0.6 cm)	3.6–12.8	0.032	None
Wright and Keller [25]	4.9	0.28	Polyethylene spheres (1/8–¼ in.) and disks (1/8– ½ in.)	2.2–7.9	0.038–0.045	Linearly increasing
Dobroklonskiy and Lesnikov [7]	25	0.8	Polystyrene spheres (0.4–3 mm)	7.0–12.0	0.026–0.031	Linearly increasing
Shemdin [22]	45.7	0.92	Paper disks (0.6 cm)	3.1–9.1	0.026–0.029	Increasing
Mizuno and Mitsuyasu [18]	13.4	0.35	Paper disks (0.6 cm)	2.5–10.0	0.030–0.034	Increasing