Deposition Efficiency of Different Droplet Sizes for Citrus Spraying

M. Salyani, S. L. Hedden, G. J. Edwards
ASSOC. MEMBER ASAE   MEMBER ASAE

ABSTRACT

THE purpose of this study was to develop a methodology for fast and accurate assessment of deposition efficiency for foliar spray applications. Two criteria were used to evaluate deposition efficiency: percent of material deposited on leaf surfaces and, percent coverage of water sensitive targets. Using this methodology, the highest deposition efficiency on washed citrus leaves was obtained when spray droplets were approximately 400 μm in diameter.

INTRODUCTION

Young (1979) has identified several stages during which sprayed materical can be lost due to drift and deflection from the target surface. The major portion of the losses occur during droplet formation (atomization), transport to target, and impact with the target surface. Other losses and wastages occur in subsequent stages so that only about 1 to 3% (Hall, 1985) and often less than 0.1% of pesticides applied to crops reach target pests and contribute towards pest control (Pimentel and Levitan, 1986). The misdirected pesticide could potentially become a serious health hazard if it was allowed to pollute air, soil, water, and food resources. Therefore, it is important to reduce application losses and environmental contaminations; thereby increasing the efficiency of the spraying operation.

Losses involved in droplet transport and impaction contribute greatly towards the overall application inefficiency and are believed to be related to the size of the pesticide droplets. Small droplets drift beyond the target area while larger ones tend to bounce off the target surface and fall to the ground. Retention of a particular droplet size is dependent on the spray characteristics, atmospheric conditions, physical properties of pesticides, and surface characteristics of the sprayed targets. It is desirable to understand the relationship between droplet size and deposition efficiency so that droplet size can be changed and maximum deposition efficiency in spray applications can be achieved.

The objectives of this study are:

1. To develop a methodology for fast and accurate assessment of deposition efficiency of foliar spray applications.
2. To identify an optimum droplet size for deposition on citrus leaves.

PREVIOUS WORK

Many researchers have attempted to find an optimum droplet size for spray applications, but due to the complexity of the transport and deposition process, the wide distribution of droplet sizes within a specified diameter range, differences in the characteristics of spray targets, and effects due to atmospheric conditions the reported data is inconsistent and lacks a common basis. Therefore, the delivery efficiency of existing spray equipment is basically unknown. Himel (1969) concluded that the optimum diameter for insecticide spray droplets is in the range of 20 μm; while his many citations report optimum droplet sizes ranging from 10 to 350 μm. Akesson and Yates (1981) have stated that, for agricultural spraying, elimination of droplets below 50 μm in diameter would reduce airborne transport to a minimum. They considered droplet sizes within the broad range of 20 to 2000 μm as desirable for various uses of insecticides, herbicides, etc. Dubs et al. (1985) used three different chemicals and three different droplet sizes (67, 115, and 210 μm in diameter) to study the effect of droplet size on deposition efficiency. Their tests were aligned perpendicular to the wind and all tests were conducted simultaneously. By chemically analyzing the vegetation after the tests, they found that the 115 μm spray droplets had the highest deposition efficiency. Spillman (1984) studied the deposition of droplets on both horizontal and vertical leaves. He concluded that droplets that were 250 μm in diameter, or larger, had the highest deposition rate on horizontal leaves, while droplets in the range 20 to 50 μm, with a minimum wind velocity of 3 m/s, had the best deposition on vertical surfaces, stems, and undersides of leaves.

The need for monodisperse or uniform sized liquid droplets in spray research has led to development of several uniform droplet generators. The theoretical basis was explained by Rayleigh (1878). He showed that a liquid jet is basically unstable and by inducing a disturbance wave on the liquid jet the breakup of the liquid can be controlled. Schneider and Hendricks (1964), Threadgill et al. (1974), and Reichard et al. (1986) had described uniform droplet generators based on Rayleigh's principle but they differ in their means of imposing a disturbance on the liquid jet.

Reichard et al. (1986) used a uniform droplet generator and high speed photography techniques to study several factors that influence the deposition of spray droplets on various leaves. Their observations of

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The authors are: M. SALYANI, Assistant Professor, University of Florida, IFAS; S. L. HEDDEN, Agricultural Engineer; USDA-ARS; and G. J. EDWARDS, Assistant Professor, University of Florida, IFAS, Citrus Research and Education Center, Lake Alfred, FL.

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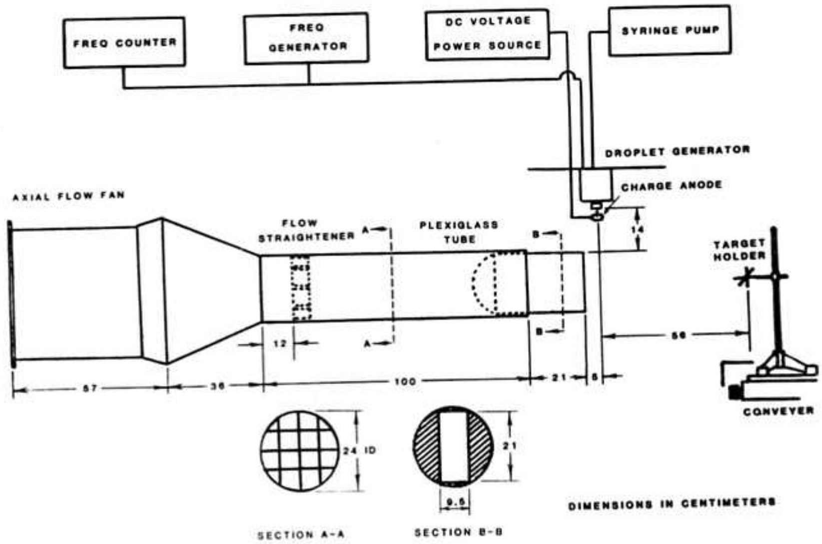

Fig. 1—Overall sketch of the test apparatus.

several high-speed motion pictures of droplet impaction show a marked difference on droplet deflection among leaf surfaces.

EQUIPMENT AND METHODS

Test Apparatus

A vibrating orifice aerosol generator (Thermo-Systems, Inc., Model 3050)* was modified so that uniform-sized droplets of up to 1000 μm in diameter could be generated. The generator uses a frequency controlled disturbance to break a cylindrical liquid jet into uniform-sized droplets. If the liquid flow rate and the vibrating frequency are adjusted properly, the droplet diameter (d) can be calculated from the following formula:

$$d = \left(\frac{6}{\pi}\cdot\frac{Q}{F}\right)^{1/3} = \left(\frac{6}{\pi}\cdot V\right)^{1/3} \qquad \text{. . . . . [1]}$$

where

Q = flow rate
F = frequency
V = volume of the droplet

Several orifice sizes were used to generate different droplet sizes. The size of uniform droplets, generated from any orifice, could be varied about 25% by changing the operating frequency. Droplet size could not be changed by varying the liquid flow rate because the frequency must be adjusted to match the flow rate. The appropriate flow rate and frequency ranges for each orifice size were determined by trial and error using a video camera and recording system (PANASONIC—WV-341P) and a strobelight (STROBOTAC—TYPE 1531A). The flow rates were controlled by a compact infusion pump (HARVARD APPARATUS—Model 975) and the frequencies were generated using a sine/square wave generator (B+K PRECISION—Model E 3108).

An axial flow blower fan (DAYTON—Model 4C259A) was connected to a plexiglass tube (24 cm I.D.) to provide air transport of droplets towards the deposition targets. The average air velocity near the targets (measured by ALNOR—Model 6000 A velometer) was 15.0 m/s (2,950 ft/min) which was within the range of commercial orchard sprayers used in citrus spraying. A sketch of the test set-up and instrumentation is shown in Fig. 1 and air velocity profiles near the targets are shown in Fig. 2.

Droplets were discharged so that they could be carried horizontally and in a narrow band, about 50 mm wide, towards the targets. The droplets were charged by 1200 to 2000 VDC potential (BIO RAD—Model 2000/200 power supply) in order to be dispersed within the band. The targets were adjusted vertically to ensure proper alignment with the center of the droplet stream.

A target holder was made to hold eight targets at different angles (90, 45, and 10 deg) with respect to the

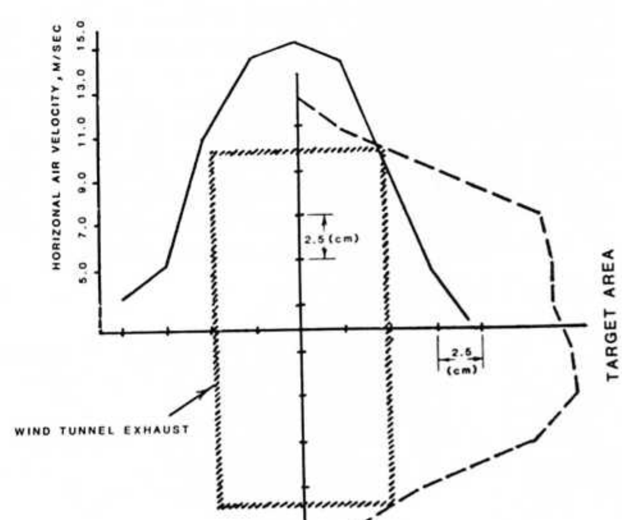

Fig. 2—Air velocity profiles and the wind tunnel exhaust superimposed.

*Trade and company names used in this paper are solely for providing specific information. Their mention does not constitute a guarantee of their products or an endorsement over other products not mentioned.

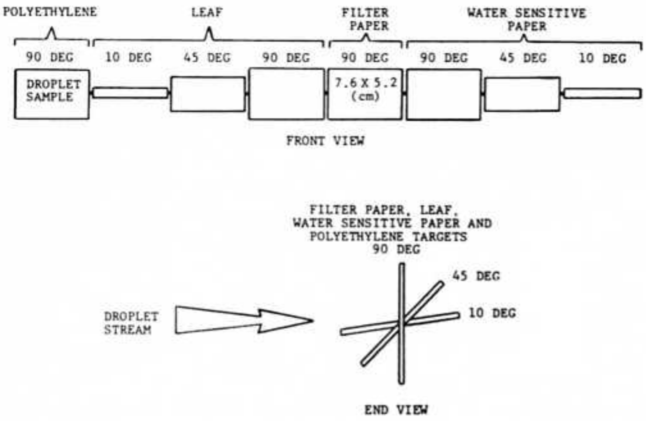

Fig. 3—Positions of various targets on the target holder.

droplet stream. The targets were made of: filter paper (WHATMAN NO. 4), orange leaves, water sensitive paper (CIBA-GEIGY), and plastic (4 mil polyethylene). The positions of each target are shown on Fig. 3. The filter paper targets were cut to 7.6 x 5.2 cm dimensions and masking tape was applied to its back surface to ease handling and minimize water evaporation. Leaf targets were made from citrus leaves that were washed and cleaned of surface mildew or deposits. Leaves were cut in 5.2 x 3.8 cm pieces and two pieces were then randomly chosen and adhered to masking tape to form the same size target as the filter paper. The targets had approximately 40 cm^2 of surface area, about the size of an average citrus leaf.

Test Procedure

Prior to each run, the liquid feed pump and signal generator were operated until the flow had stabilized. A filter paper target was then placed inside a plastic Zip-Loc bag (7.5 x 10 cm) and weighed on a high resolution (0.1 mg) balance (METTLER H30) to obtain its tare weight. Three bags, for leaf samples, were also weighed. Then, all eight targets were mounted at their respective locations on the target holder. When the liquid flow and droplet discharge were considered stable, the high voltage supply and the blower fan were turned on, the conveyer (Fig. 1) was started, and the targets moved across the stream of droplets at 0.228 m/s (0.747 ft/s). As soon as all the targets passed by the droplet stream, the conveyer was stopped. The filter paper and then the leaf targets were removed from the target holder, placed in the pre-weighed Zip-Loc bags and sealed to prevent evaporation. The bags containing the targets were then weighed. The leaf targets were then taken out of the bags, dried by an absorbant tissue and weighed again. Simultaneously, the polyethylene target, containing droplets on its surface, was removed from the holder, placed under a microscope (BAUSCH & LOMB), and 12 droplet diameter readings were taken.

Six orifice plates were used with the droplet generator. The nominal sizes of the orifices and their corresponding calculated and measured droplet sizes are given in Table 1. The calculated values (Dc) were obtained using equation [1]. The flow rate and frequency values correspond to the condition of uniform droplet generation. The measured droplet mean diameters and their respective standard deviations are obtained using three different methods:

1. Droplets captured on polyethylene targets as hemispheres.
2. Droplets collected on a high viscosity microscopy immersion oil (CARGILLE) as slightly flattened spheres.
3. Droplets submerged in oil (Automatic Transmission Fluid, CHEVRON) as spheres.

To obtain equivalent spherical droplet diameters (Dl) from hemispherical droplets, the readings were multiplied by a factor of 0.79 (cubic root of the ratio of hemispherical and spherical droplet volumes = $\sqrt[3]{0.5}$). The latter two methods gave direct diameter measurements but were laborious. The averages of the three measurements are as the droplet sizes reported in this test (Dm). The fluids used in the test were water (distilled) and water with 0.1% surfactant (ORTHO X-77 Spreader, CHEVRON).

The size and number of droplet traces on the water sensitive paper targets and the percent of the image area covered by droplets were analyzed using a video image analysis system (MEASURIONICS Linear Measuring Set or LMS). The LMS system consisted of a video camera, VHS recorder, image processor, Apple II computer, disk drive, and a printer. Video images consisted of 49,152 pixels arranged in 192 horizontal and 256 vertical rows. The use of water soluble fluorescent dyes, including Rhodamine B, Fluorescein, and Uranine did not produce sufficient contrast for droplets to be seen clearly on the leaf surface using the image analysis system. Therefore, only water sensitive targets were used for the image analysis.

Two criteria were used to express the deposition efficiency. The first was the percent of droplets by weight retained on the target leaf surfaces. To obtain this

TABLE 1. DROPLET SIZES GENERATED BY VARIOUS ORIFICE SIZES

			Droplet size				
				measured*			
Orif. size, μm	Flow rate Q, mL/min	Freq. F, kHz	Cal'd Dc, μm	D1 $\bar{D}_{10}$/sd, μm	D2 $\bar{D}_{10}$/sd, μm	D3 $\bar{D}_{10}$/sd, μm	Dm, μm
102.9	2.94	15.0	184	209/18	217/16	180/20	202
153.2	2.94	4.0	286	320/35	295/12	296/31	304
202.9	4.16	3.7	329	395/9	418/26	428/60	414
253.7	5.88	2.7	411	498/38	502/56	493/47	498
355.6	8.32	2.6	467	756/63	770/106	762/104	763
432.1	11.77	2.1	563	—	—	960/141	960

*D1, D2, and D3 are obtained using the methods 1, 2 and 3 respectively.

$\bar{D}_{10}$/sd = length mean diameter/standard deviation

TABLE 2. PERCENT DEPOSITION ON LEAF TARGETS*

Targets:	90 deg, 45 deg, and 10 deg			90 deg and 45 deg			90 deg		
				Fluids†					
Drop size, μm	W/S, %	W, %	S, %	W/S, %	W, %	S, %	W/S, %	W, %	S, %
202	73.4b	71.8b	75.1a	81.6c	81.4c	81.9b	79 6c	78.5d	80.8c
304	74.5ab	72.3b	76.8a	86.1abc	83.3bc	89.0ab	85.6bc	84.0c	87.3bc
414	78.9a	79.7a	78.2a	91.4a	94.1a	88.8ab	94.4a	95.0a	93.8a
498	76.3ab	74.6ab	77.9a	90.6ab	90.4ab	90.7a	92.1ab	92.8ab	91.3ab
763	72.9b	72.8b	73.0a	85.3bc	86.0abc	84.5ab	86.3bc	87.0bc	85.5bc
960	75.8ab	77.3ab	74.2a	84.3c	86.5abc	82.0b	85.1bc	87.8bc	82.5c

*Means followed by same letter in each column are not significantly different (5% level) using Duncan's Multiple Range Test

†W = water only; S = water + surfactant; W/S = average of both fluids

percent, it was assumed that the droplet flow was uniform and filter paper targets retained 100% of the impacted droplets. The amount deposited on the filter paper and leaf targets were obtained by several weighings described earlier. Therefore, deposition efficiency is obtained from the following relationship:

$$DE = 100 \frac{DL}{DF} = 100 \frac{(DL1-DL2-DL3)}{(DF1-DF2)} \quad \ldots\ldots\ldots [2]$$

where

- DE = deposition efficiency, %
- DL = deposition on leaf targets, mg
- DL1 = weight of sprayed leaf target plus bag, mg
- DL2 = weight of the bag, mg
- DL3 = weight of the dried leaf target, mg
- DF = deposit on the filter paper target, mg
- DF1 = weight of the sprayed target plus bag, mg
- DF2 = weight of the target plug bag before spraying, mg

The second criterion for expressing deposition efficiency was the percent of target area covered by droplets. The image analysis system described earlier provided this percentage directly.

RESULTS AND DISCUSSION

The data were analyzed using multiple linear regression models in which the fluid type, droplet size, and target angle were the indepenent variables and deposition efficiency was the response variable. There were four replications for each of the droplet sizes studied. When all of the data were considered, the model was highly significant ($R^2 = 0.83$). The effect of droplet size on deposition efficiency was not significant; however, the effect due to target angle was significant (5% level). We believe that this is primarily due to low deposition on the 10 deg angle targets. When the data corresponding to the 10 deg angle targets were not included in the analysis, droplet size effect was significant, but R-square values were lower. The effect due to fluid type, i.e., water on water with surfactant, was not significant in any of the analyses.

Table 2 shows the results of Duncan's Multiple Range Test for the different analyses. Deposition efficiency of some droplet sizes were significantly different (5% level); however, between adjacent size categories there was generally no significant difference. The 414 μm droplets, by and large, showed the highest efficiencies (Fig. 4).

Analyses of percent coverage data, obtained by image analysis of the water sensitive targets, showed a significant effect due to droplet size and the target angle ($R^2 \geq 0.84$). Table 3 shows the results of Duncan's Multiple Range Test for the effect of droplet size on percent area covered. The coverage is based on the same

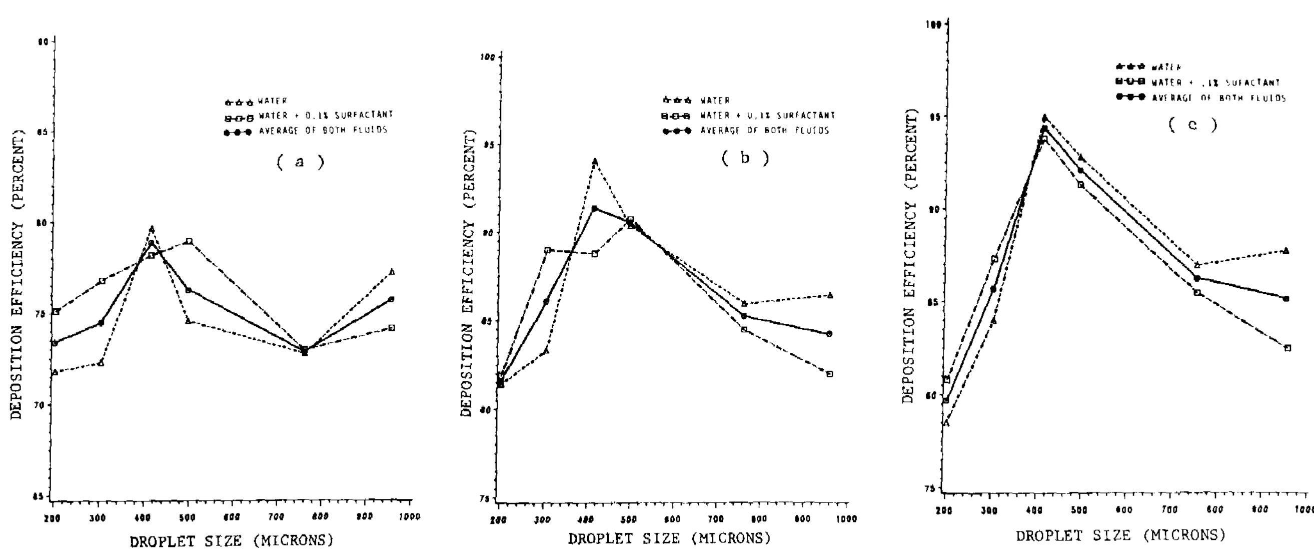

Fig. 4—Deposition efficiency vs. droplet size: a) using data for all target angles, b) using data for 90 deg and 45 deg targets, c) using data for 90 deg targets only.

TABLE 3. PERCENT AREA COVERAGE ON WATER SENSITIVE PAPER TARGETS*

Drop size, μm	Target angles: 90 deg, 45 deg, and 10 deg, %	90 deg, and 45 deg, %	90 deg, %	45 deg, %	10 deg, %
202	4.9b	5.7b	5.8b	5.5b	3.4b
304	7.3a	7.7a	8.3a	7.1a	6.6a
414	4.4b	4.7c	4.8cd	4.6bc	3.7b
498	3.5c	3.8d	4.2d	3.4c	3.0b
763	4.5b	4.8c	4.9cd	4.7bc	3.9b
960	4.6b	5.0bc	5.5bc	4.5bc	3.8b

*Means followed by same letter in each column are not significantly different (5% level) using Duncan's Multiple Range Test.

flow rate for all droplet sizes. In this case, the 304 μm droplets showed significantly higher coverages than other sizes (Fig. 5).

The percent deposit data showed a high correlation with the percent coverage data ($R^2 \geqslant 0.83$). This relationship indicates that either of the selected criteria or some combination of both may be used to express the efficiency of deposition. However, because of the difference in surface characteristics of leaf and water sensitive paper targets, no specific relationship is given at this time.

The image analysis system had limitations in obtaining droplet counts. The adjustment of the gray level on images affected the outcome of measurements. Therefore, unless the system is used for comparative measurements (with one time adjustments), poor repeatability and accuracy should probably be expected from the analysis. In addition, the output of the system is dependent on the degree of contrast in the image. High contrast will result in high accuracies.

The analysis of video taped pictures of droplets in motion by the LMS system was found to be practical. However, proper lighting of droplets was found to be essential for obtaining accurate readouts.

Mean diameters obtained from image analysis of droplet traces, on water sensitive papers, were larger than the mean droplet sizes used to make those images (due to the spreading effect). The spread factors (ratio of the diameters) ranged from 1.6 to 2.6. For droplet sizes of less than 400 μm and the light application rates, the water sensitive paper was a fast and easy method for estimating droplet size of sprays.

The main objective of this paper was to describe a technique developed to assess deposition efficiency for foliar spray applications. This work is a pilot study and will be followed by more detailed and comprehensive studies in order to understand the effect of droplet size on deposition efficiency of citrus spraying. Therefore, the purpose of the conclusions presented here is to point out trends which were observed and to identify areas in which further research is needed.

CONCLUSIONS

The weighing method for deposition assessment was found to be fast, repeatable, and accurate, provided that targets are handled with speed and care. The simplicity, speed, and low cost of the technique permits a large number of samples to be taken and replicated sufficiently to insure reproducible results. Using this methodology, the highest deposition efficiency on washed citrus leaves was obtained when spray droplets were approximately 400 μm in diameter.

Image analysis of deposition on water sensitive targets was found to have a limited use in droplet size measurement.

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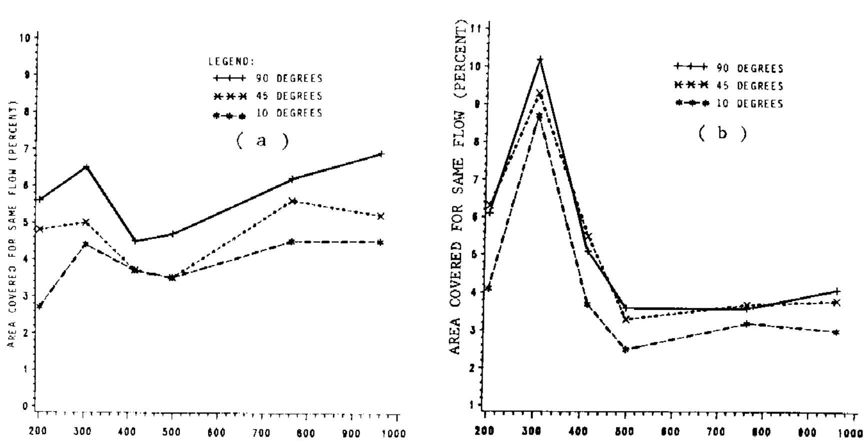

Fig. 5—Area coverage vs. droplet size: a) using data for water plus 0.1% surfactant, b) using data for water only.