Experimental Determination of Droplet Impaction on Canopy Components of Balsam Fir

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ABSTRACT

The capture efficiencies of balsam fir [Abies balsamea (L.) Mill] canopy components for monodisperse glycerin droplets were measured in a low-speed wind tunnel. Droplets were produced at sizes and wind speeds typical of cloudy conditions in a windy, subalpine environment. Capture efficiencies (CE) were evaluated on the basis of the Stokes number (STK) (an inertia parameter). Regression analyses produced a cubic equation relating CE to the independent variable, STK, with an R^2 of 0.78. The data demonstrated a decline in CE when STK > 10, a departure from current theory. Droplet re-entrainment is suggested as a possible cause for this behavior. The utility of these data for modeling cloud droplet deposition is discussed.

1. Introduction

Subalpine balsam fir forests of the northeastern United States are frequently immersed in wind-driven clouds (Reiners and Lang, 1979). This condition is believed to lead to significant deposition of water beyond that measured by incident precipitation gages (Schlesinger and Reiners, 1974; Olson et al., 1981). Furthermore, cloud droplets generally contain much higher concentrations of dissolved substances than does incident rain (Georgii and Wözel, 1970; Tomlinson et al., 1980) so that impaction of cloud droplets may represent an important source of chemical inputs to these subalpine systems.

To evaluate the role of cloud droplet capture in these subalpine forests, we characterized the impaction behavior of cloud droplets on components of balsam fir canopies under realistic conditions of droplet size, wind velocity and turbulence. This paper describes the procedure and results of this characterization.

The theory of droplet impaction has been studied by Chamberlain (1975) and others. Capture efficiency (CE) is a function of the inertia of a droplet and the flow around an obstacle. Droplet inertia can be expressed as the stop distance (SD), i.e.,

\[ SD = \frac{\rho_d d^2 u}{18 \rho_a \nu}, \]

where \( d \) is droplet diameter; \( \rho_d \) and \( \rho_a \) are the densities of droplet and air, respectively; \( u \) is the wind speed; and \( \nu \) is the kinematic viscosity of air. If the droplet has a SD nearly equivalent to, or less than, the length scale of the air flow disturbance around an obstacle, it will follow the streamline of air flow. If its SD is larger than the disturbance, it will deviate from the streamline and impact on the obstacle. The relationship between SD and the flow disturbance is expressed by the Stokes number (STK), a non-dimensional inertia parameter given as

\[ STK = 2SD/l, \]

where \( l \) is the critical dimension of the obstacle, the diameter in this case.

Experimental results have not always followed theoretical predictions of impaction. Theory predicts that CE will continuously increase with increasing STK (Chamberlain, 1975). Data from Belot and Gauthier (1975) and Gregory (1951) show increasing CE with increasing STK up to specific maxima, and then decreasing CE at higher values of STK. It was against this background of theory and empirical results that we experimentally characterized CE for droplets by canopy components of balsam fir.

2. Methods

A closed-circulation wind tunnel was constructed with an internal test section 15 cm long and 21 cm by 21 cm in cross section perpendicular to the flow. The tunnel produced wind speeds up to 810 cm s\(^{-1}\) but experimental runs in this study were limited to wind speeds of 50, 170, 340 and 725 cm s\(^{-1}\).

Monodisperse glycerin droplets tagged with uranine (sodium fluorescein) were produced by a vibrating orifice aerosol generator (TSI 3050 with TSI 3054 aerosol neutralizer) and dispersed into the airstream 50 cm upstream from the test section. Glycerin was chosen because, unlike water, the size of droplets is not significantly affected by temperature or humidity, thereby simplifying operation of the

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wind tunnel. The density of the tagged glycerin droplets was 1.35 mg mL$^{-1}$, resulting in aerodynamic behavior equivalent to larger water droplets of unit density. Actual diameters of glycerin droplets were corrected and expressed as equivalent aerodynamic diameters of unit density water droplets according to the equation,

$$d_e = (1.35d_w)^{1/2},$$

where $d_w$ is the actual glycerin droplet diameter. Equivalent aerodynamic diameters ($d_e$) of 4, 15 and 32 µm, which fall within the range of cloud droplet diameters (Chamberlain 1975), were used for our experiments.

The simulation of the aerodynamic behavior of water droplets by glycerin droplets was also tested empirically. This was done by comparing trajectory deviations of water and glycerin droplets in a high-velocity airstream. This test was made with a single-stage, single-jet impactor designed and built at the U.S. Army Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire. With this impactor, a droplet-laden airstream is sucked through a 1 mm orifice perpendicular to the center of a gelatin-coated microscope coverslip. Air exits around the perimeter of the coverslip as the high-inertia droplets impact on the gelatin film. We found that the impaction zones on the cover slip were the same for glycerin and water droplets of equivalent aerodynamic diameters indicating that their trajectories and aerodynamic behaviors were indistinguishable. These similarities were observed at intake velocities up to 1500 cm s$^{-1}$, giving us further confidence that the glycerin droplets were satisfactorily simulating water droplet behavior in the wind tunnel.

Target materials used in these experiments were representative of the bulk of surface-area components of balsam fir canopies. These included bare twigs of three size classes (0.2, 0.5 and 1.5 cm diameters), and needle-bearing twigs. The length scale for bare twigs was assumed to be the diameters of individual target twigs. The length scale for needle-bearing twigs was set at 0.1 cm, one-half the needle width. This length was chosen on the following grounds. First, close examination of smoke flow through needle-bearing twigs by Wedding et al. (1978) and by us revealed that smoke passed through the needle array without visible flow separation. This indicated that needle-bearing twigs did not act as aggregated obstacles but rather as arrays of individual obstacles or collectors. Thus the needles were the unit-collectors, not the aggregated array. Second, we reduced the length scale to one-half the needle width because the various orientations of needles with respect to airflow produce target silhouettes equivalent to about one-half needle width. The reader is cautioned that this reasoning may not be appropriate for species with different needle-cluster morphologies.

Samples of these component types were cut to 10 cm lengths and placed in the center of the test section. They were exposed to the urine-tagged glycerin droplets for 5–30 min at fixed wind speeds and droplet sizes. After the appropriate exposure times, the target samples were removed and rinsed with deionized water to elute the deposited glycerin. The fluorescence of a subsample of the rinse water was determined with a Turner Model 430 Spectrofluorometer. Microscopic examination of captured droplets showed that the droplets remained on the surfaces of the target materials and were not absorbed, permitting thorough removal with rinsing. Further verification of the completeness of the tag washoff was provided by sequential rinsing of sample material, which showed no additional fluorescence removed after the first rinse.

The flux rate of droplets in the target zone was measured before and after each run by sampling the airstream isokinetically through a membrane filter. The filter was rinsed and the fluorescence of the rinse water determined as described above. The removal of the tag was checked by sequential rinsing, and found to be complete after one rinse. The amounts of fluorescence captured by both the filter and the target material were divided by the cross-sectional areas of the filter and the target (projected to the vertical plane), respectively. These area-corrected deposits were divided by the duration of the run to determine the flux of fluorescent particles. The capture efficiency (CE) was expressed as

$$CE = \frac{\text{flux of uranine to target}}{\text{flux of uranine to filter}}.$$ (4)

3. Results and discussion

A total of 289 separate determinations of capture efficiency (CE) were made in the wind tunnel with a variety of target specimens, droplet sizes and wind speeds. The capture efficiencies were plotted against the appropriate Stokes number (STK) for each of four component types. Polynomial regressions were then run on the log-transformed CE vs STK data sets. With an $F$ test, we tested the null hypothesis that the separate regressions were not statistically different; that is, that the populations of target materials all showed the same relationship between CE and STK. We were unable to reject the null hypothesis at the $p = 0.05$ level and therefore pooled the data to calculate a composite regression equation:

$$\ln(CE) = -1.842 + 0.903 \ln(STK) - 0.110[\ln(STK)]^2 - 0.035[\ln(STK)]^3,$$ (5)

$$n = 289, \quad R^2 = 0.78, \quad \text{SEE} = 0.77$$

where $n$ is the number of observations, $R^2$ the multiple coefficient of determination and SEE is the stan-
The standard error of estimate of ln(CE). The graph of Eq. (5) is plotted in Fig. 1 with the averages of runs at single STK’s.

Fig. 1 portrays the rising curve of CE with STK followed by a decline at STK > 10. The rising arm of the curve follows theoretical patterns (Chamberlain, 1975) but the descending arm does not. The reality of this descending arm is partially supported by the relatively high $R^2$ of the regression (0.78). Belot and Gauthier (1975) attributed the decrease in CE at high STK to re-entrainment of aggregated particles that were dislodged from needle surfaces by mechanical agitation at wind speeds of 1000 cm s$^{-1}$. Gregory (1951) considered re-entrainment to be caused by blow-off resulting from the thinning of the viscous boundary layer at high velocities. A thinning boundary layer provides less of a “cushion” to absorb momentum, so that droplets might bounce off more readily (Chamberlain, 1975). In our study, blow-off and bounce-off can be particularly important due to the surface roughness of twigs and the complex wakeflows within needle-bearing twigs; surface roughness and upstream turbulence can dramatically reduce boundary-layer thickness (Lighthill, 1963).

At STK > 60, CE would be expected to increase again as increasing drop size would enhance interception. In this range, droplets whose centers lie outside of the projected area of the target could make grazing contact as they passed by and would be captured. Droplets may also shatter on impact (Chamberlain, 1975) producing smaller droplets with lower STK, conceivably in the range of high CE. Our data do not permit extrapolation above STK = 60.

Below STK = 0.06, CE should continue to decrease until STK < $10^{-4}$ where the small droplet size allows diffusion to contribute to capture (Chamberlain, 1975). Although our data show a possible increase in CE at STK < $10^{-2}$ our regression equation should not be extrapolated to this region because of the limited data at this end of the set.

Models such as those by Bache (1979) and Shuttleworth (1977) include estimates of CE based on theory modified by experimental evidence. They project, however, a leveling off of capture at high efficiencies for high STK values. This may represent an error in their estimation. The droplet sizes and wind speeds that correspond to the region of decreasing CE (STK > 10) can represent a substantial portion of the water flux from clouds in a windy environment. Models based on asymptotic or monotonically increasing CE in this region will overestimate water input. Applications of these relationships for estimating droplet capture must take this unexpected behavior at high STK into account. At the same time, a satisfactory reconciliation between such empirical results and theory is needed.

The data reported here supplement the very limited experimental data published on droplet capture by canopy components (Merriam, 1973; Wedding et al., 1978). That the droplet capture characteristics of twigs of different sizes and needle-bearing branches are explainable by a single expression suggests that
these results may be generalized to a broader range of coniferous canopy components if the appropriate length scale is specified. More experimental measurements of this sort are needed to test the generality of this expression.

We have used Eq. (5) in a model of cloud droplet deposition to balsam fir forests (Lovett et al., 1982) which predicts significant hydrologic and chemical inputs from cloud water in these ecosystems. Experimental data such as those presented here should be useful in assessing the importance of cloud deposition in other systems as well, by providing empirical parameter estimates for micrometeorologic models.

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