Determination of velocity and size distributions of small falling water drops

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Geng, G.Q. and Mehuys, G.R. 1995. **Determination of velocity and size distributions of small falling water drops**. Can. Agric. Eng. 37:351-355. A new method to measure the fall velocity of small water drops and an improved method to measure their size distribution are discussed in this paper. The oil-microscope method is an improvement over the oil method of Eigel and Moore (1983) to determine small water drop sizes and their distribution, while a newly developed videocamera method was used to measure the fall velocity of small water drops. Both methods are simple and direct, and give quick and accurate results. The only equipment required for the oil-microscope method is a standard optical microscope. This method is especially useful to measure the size of very small water drops (less than 0.5 mm in diameter), which is not easily achievable by other methods. The smallest drop size measured in this study was 0.03 mm in diameter. The videocamera method requires only fairly standard equipment (stroboscope, videocamera, monitor, and videocassette recorder) and has the advantage of being appropriate for very small water drops. Both methods can be readily used either in the field or in the laboratory.

Cet article présente une nouvelle méthode pour mesurer la vitesse de chute de petites gouttes d'eau et une méthode améliorée pour mesurer leur grosseur. La méthode à l'huile et microscope est une amélioration de la méthode à l'huile de Eigel et Moore (1983) pour déterminer la grosseur des gouttelettes et leur distribution. La méthode proposée pour mesurer la vitesse de chute des gouttes d'eau utilise une caméra vidéo. Ces deux méthodes sont simples et directes, et procurent des résultats exacts rapidement. L'équipement requis pour la mesure des diamètres est un microscope optique ordinaire. Cette méthode est particulièrement bien adaptée pour mesurer de très petits diamètres (moins de 0.5 mm), qui autrement sont difficiles à déterminer. Le plus petit diamètre mesuré dans cette étude était de 0.03 mm. La méthode de mesure de la vitesse de chute des gouttes d'eau ne requiert que des équipements standards (stroboscope, caméra vidéo, téléviseur et magnétoscope). Elle aussi est bien adaptée aux très petites gouttelettes. Ces deux méthodes s'utilisent aussi bien au champ qu'au laboratoire.

INTRODUCTION

Detachment of soil materials from the soil mass is caused by raindrop impact and/or runoff shear (Ellison 1947a; Shainberg et al. 1992). Raindrop impact breaks down aggregates, which in turn generates sediment for transport, accelerates surface seal formation, decreases infiltration, increases overland flow, and leads to an overall increase in soil erosion (Ellison 1947b; Sharma et al. 1991). In studying the relationship between raindrop erosivity and soil detachment, kinetic energy has been the most commonly considered erosive parameter (Al-Durrah and Bradford 1982; Gilley et al. 1985; Lal 1990; Meyer 1981; Morgan 1985; Park et al. 1982; Sharma and Gupta 1989; Sharma et al. 1991). The kinetic energy of raindrops is usually calculated from the physical properties of natural or artificial raindrops. Ellison (1947c) described the quantity of soil particles splashed by raindrops as a function of the diameter and impact velocity of raindrops and rainstorm intensity. To calculate kinetic energy and investigate raindrop impact on soil particles, raindrop size and impact velocity must be known. Both drop size and fall velocity are also among those essential characteristics which are needed to design rainfall simulators (Bubenzer 1979; Tossell et al. 1987).

Techniques for measuring raindrop size and distribution have been summarized by Eigel and Moore (1983). They grouped them into five categories: stain methods (Gillespie 1958; Hall 1970), flour methods (Bazzoffi 1980; Carter et al. 1974; Kohl 1974; Laws and Parsons 1943), photographic methods (Laws 1941), momentum methods (Hudson 1981; Kinnell 1967) and immersion methods (Eigel and Moore 1983). Eigel and Moore (1983) reported still another method, called the oil method, which was an improvement on the immersion methods. The oil method is based on the premise that water droplets suspended in a less dense but more viscous fluid assume a near-perfect spherical shape due to the surface tension forces and the pressure distribution about the drops. Their drop collection medium was a mixture of STP Oil Treatment and Swan heavy mineral oil. Drop sizes were measured from photographs. This is a direct measurement technique that requires no calibration.

During the measurement of water drop sizes produced by low-intensity rainfall simulators, many of these methods were found to be either difficult to use or failed to give very good results if drop sizes were very small (less than 0.1 mm in diameter). The optical-array-shadowing method is suitable for measuring small water droplet sizes, ranging from approximately 0.01 mm to 0.62 mm (Frost and Lake 1981; Giles and Comino 1990; Lake and Dix 1985; Miller and Hadfield 1989). While this method is accurate, it requires complex equipment (optical array imaging probe and particle data processor with software package). To determine the size of very small raindrops accurately, simply and quickly, we improved Eigel and Moore's (1983) oil method by using a microscope instead of a camera.

Fall velocities of water drops were first measured by Lenard (1904) by suspending them in a vertical air stream and measuring air velocity at the point of suspension. The sizes of the drops were determined by a stain method. Laws (1941) measured the velocities of water drops with diameters between 1 and 6 mm falling in still air from heights of 0.5 to 20 m using optical techniques, which have been widely used in studies related to raindrop fall velocity. Gunn and Kinzer (1949) employed electronic techniques to measure fall velocities of water drops ranging in size from 0.07 to 5.8 mm in diameter. Their measurements were the most extensive and probably the most accurate (Mason 1971). Wang and Prupacher (1977) also used electronic techniques in a proof of their theory to calculate the terminal velocity of falling drops.

A popular method for measuring fall velocity has been the photographic method because of its simplicity. Morin et al. (1967) measured the fall velocity of raindrops with a still camera and a stroboscope as the source of light. Although the method is simple and direct, the camera hardly catches drops smaller than 0.5 mm in diameter. A method is described that uses a videocamera instead of a still camera to measure the fall velocity of small water drops.

DESCRIPTION OF THE METHODS

Water droplets were formed with two types of nozzle: Unijet nozzles with a 0.508-mm orifice diameter and Fulljet nozzles with a 1.59-mm orifice diameter, both from Spraying Systems Co., Toronto (Table I). The distance between nozzle and measuring level was 1.50 m and corresponded to the soil surface in simulation experiments. The nozzles covered a plot 4 m long by 0.8 m wide.

Drop Size

The oil-microscope method to measure drop sizes consists of three steps: (a) preparation of the collection medium; (b) collection of water drops and microscopic reading; and (c) calculation of water drop sizes.

The collection medium was the same as in the oil method described by Eigel and Moore (1983), i.e., a mixture of STP Oil Treatment and heavy mineral oil (available in most hardware stores and pharmacies, respectively). Details of the mixture characteristics and its preparation were described by Eigel and Moore (1983). Air bubbles must be avoided during the preparation of the collection medium because it is difficult to distinguish water drops from air bubbles in the collection medium. Glass petri dishes of 100-mm diameter and 10-mm depth containing a 1:1 ratio of oil treatment to mineral oil were placed in an array beneath a nozzle. The number of water drops collected in a dish depended upon the exposure time of the dish under a given nozzle at a fixed water pressure. Exposure time was limited to only a few seconds in this study. Drop population was thus kept small to avoid overlaying drops and make it possible to identify individual drops easily.

A standard optical microscope was used to determine raindrop size. To reduce the time between collection and reading, the microscope was set up in close proximity to the sampling position. A short interval between collection and reading is essential because drops, especially large ones, tend to settle on the bottom of the dish and deform. The largest drops in this study settled within one minute. The microscopic reading of the diameter of each drop was recorded for later size calculation. Drop sizes from several dishes located at different positions under a nozzle were measured in this way to obtain a drop size distribution over the plot. The microscopic reading was calibrated using a standard objective micrometer. Eye and objective lenses with an enlargement of 15 x 4 were chosen according to the small drop sizes anticipated. This yielded a scale of 3.4 units of reading for each 1 mm in length.

Drop fall velocity

The videocamera method to measure fall velocity consisted also of three steps: (a) set-up of equipment, (b) recording a videotape, and (c) analysis of images.

A sealed box was constructed to protect the videocamera from moisture and from stray light sources. A 20-mm (for Fulljet nozzles) or a 15-mm (for Unijet nozzles) diameter round passage on top of the box let raindrops through (Fig. 1). A stroboscope and the videocamera were placed inside the box 1.50 m below the nozzles on either side of the round hole.

The stroboscope's frequency was adjustable from 600 to 20,000 rpm. The frequency was chosen according to the videocassette recorder's speed. At the VCR's speed of 30 frames per second, through experimentation a frequency of 5,400 rpm on the stroboscope (three times the speed of the VCR) gave the clearest images. Theoretically, a 5,400-rpm frequency would produce three images on a single frame, which was the basis used to calculate the fall velocity of raindrops.

A VHS HQ videocamera with a macro lens was used because of the very small drop sizes. The videocamera lens was held horizontally in line with the hole in the box, while the stroboscope was set at a horizontal angle ranging from 40 to 50° between camera axis and direction of light (Fig. 1). At such an angle, the light striking water drops made them visible to the camera and kept the background dark so that only the drop images were caught by the videocamera. A recording of a template of standard scales was made prior to recording falling water drops and was used for calibration at the analysis stage. Videotapes of falling water drops were re-

Table I: Nozzle Specifications[z]

Nozzle type	Orifice diameter	Flow rate capacity (L/min at kPa)				Spray angle (degrees at kPa)		
	(mm)	69	103	138	207	69	138	276
Fulljet (1/8G2.8W)	1.59	1.06	1.25	1.44	1.70	120	120	120
Unijet (1/4TG0.3)	0.508		-	0.16	0.20	-	50	58

[z] Specifications as supplied by the manufacturer (Spraying Systems Co., Toronto).

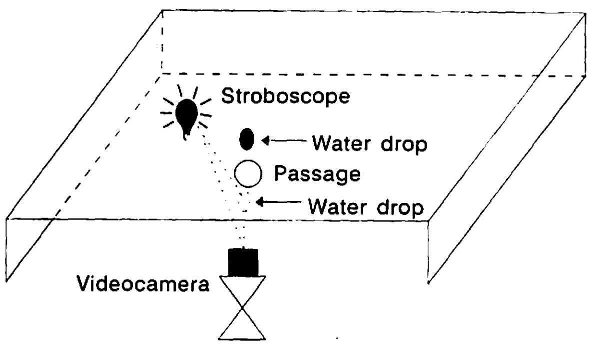

Fig. 1. Sketch of the experimental set-up for recording falling water drops onto a videotape.

corded in this manner at different locations in the plot under the nozzles.

Images were analyzed with a four-head VHS VCR and a flat-screen monitor. When the standard template appeared on the monitor screen, the image was frozen in order to compare distance on the template with its image on the screen. From this the scale ratio was determined. Images of falling drops were then frozen on the screen. The distance between two images was measured and the fall velocity was obtained by dividing this distance by the time interval between two images, and then multiplying by the scale ratio. The distribution of the fall velocity of raindrops was obtained by measuring the distances between many raindrop images at different locations.

RESULTS AND DISCUSSION

Size distribution

Figure 2 shows the overall distributions of measured drop sizes at a 1.50-m distance under Unijet and Fulljet nozzles. The size distribution of raindrops can be expected to vary considerably with the character of the rain (e.g., continuous steady rain, thunderstorms, or showers), with the type of cloud from which they fall, and also with the rain intensity (Mason 1971). For a given storm, the size distribution of raindrops is usually normal or approximately normal (Laws 1941; Laws and Parsons 1943). Size distributions of water drops obtained from spray nozzles also appear to be approximately normal. Because each distribution in Fig. 2 was the result of many measurements, it is assumed that the size distributions are very accurate. In addition, the accuracy of the measurement of the size of individual water drops is also good because of the use of the microscope at high enlarge-

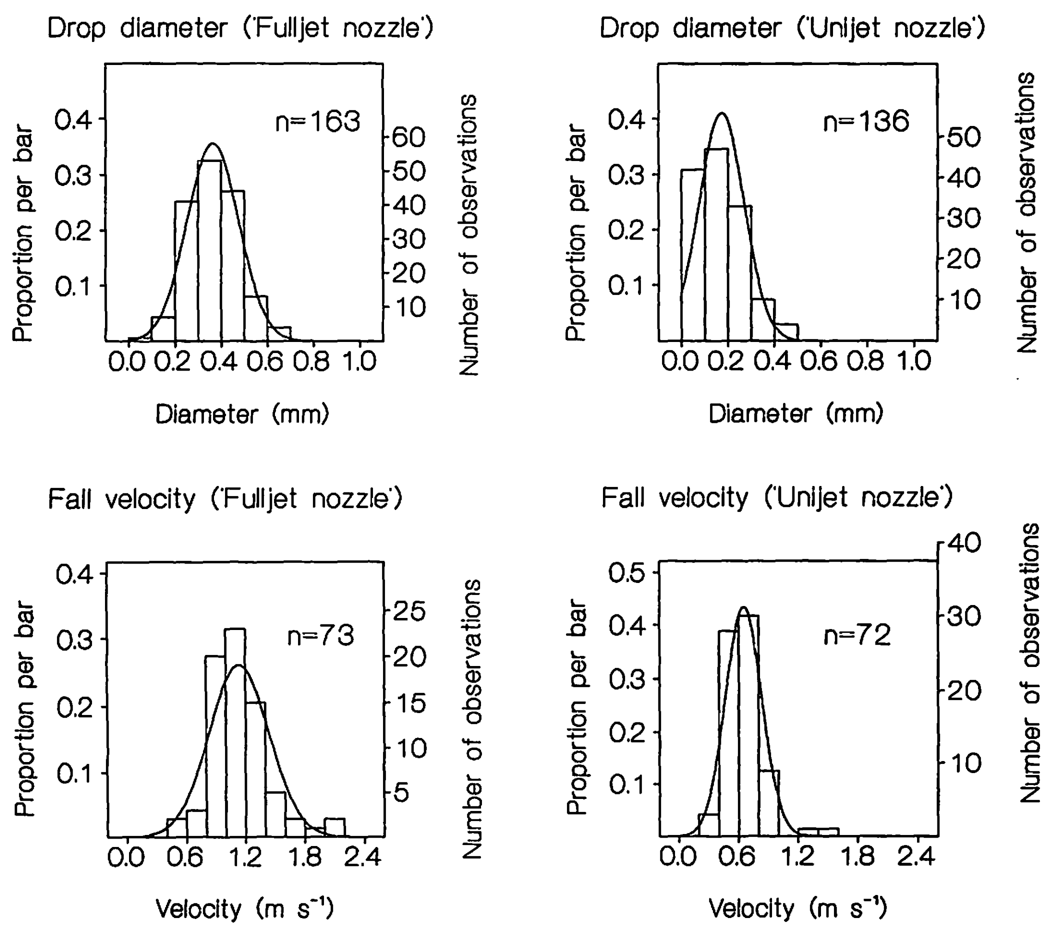

Fig 2. Drop size distributions and drop fall-velocity distributions under Unijet and Fulljet nozzles (n represents the total number of observations).

ment (60 times in this case).

The microscope-oil method has no practical lower limit since the microscope has the ability to measure very small drops. After touching the bottom of a petri dish, the spherical drop becomes flattened and hence its horizontal dimension increases and the accuracy of the determination decreases. When drop sizes become large, however, this speed of settlement in the oil mixture is faster than the time available for measurement. Under these experimental conditions, the oil-microscope method was difficult to use when drop size was larger than 0.7 mm.

Fall velocity distribution

Figure 3 is a photograph taken from the monitor screen and shows three images of a single drop on one frame at a stroboscope frequency of 5,400 rpm. Only the drops located within the focus of the camera show up clearly on the screen. Furthermore, if a drop hit the edge of the opening in the experimental box, it would not fall vertically. Therefore, it was easy to eliminate these drops from the measurement. Overall, Figure 2 shows approximately normal distributions for the fall velocity of water drops at a 1.50-m distance under Unijet and Fulljet nozzles, respectively. The videocamera method is easy to use. Because very small drops can be

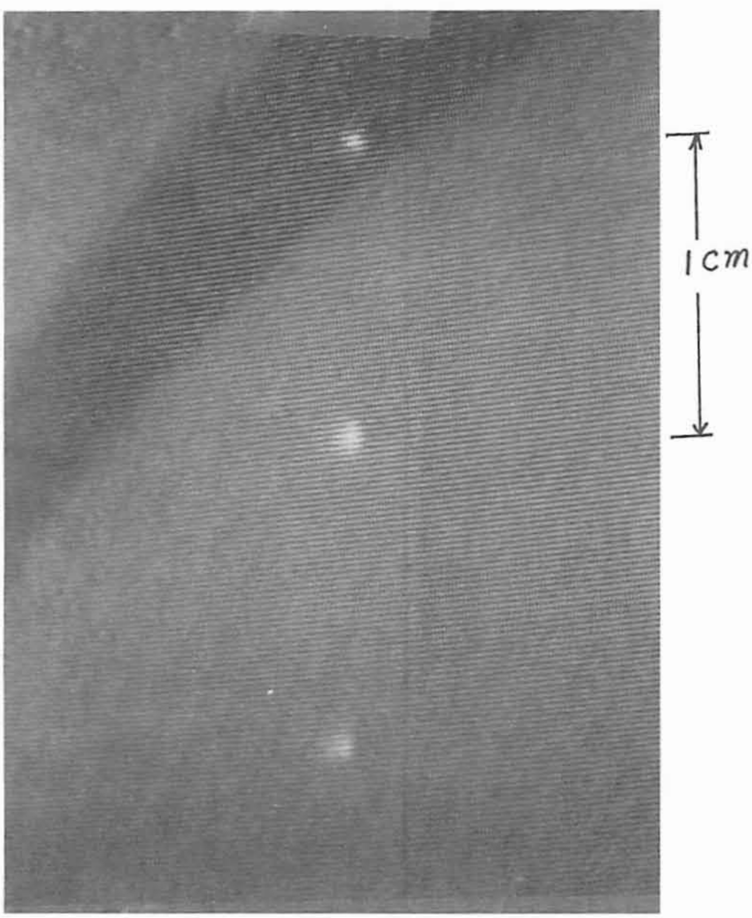

Fig. 3. Images of a single falling water drop on monitor screen. (The frequency of the stroboscope was 5,400 rpm.)

Table II: Comparison of fall velocities in relation to drop sizes

Method	Mean drop diameter (mm)	Mean fall velocity (m/s)
Videocamera	0.176[z]	0.65
	0.365[y]	1.14
Gunn and Kinzer	0.169	0.57
(1949)	0.197	0.70
	0.363	1.46

[z] Average drop sizes from Unijet nozzles.
[y] Average drop sizes from Fulljet nozzles.

caught by the videocamera, the velocity of a wide range of drop sizes can be measured.

Statistically, the average fall velocity can be thought of as being that of the average-sized drop. In this way, the results were compared with Gunn and Kinzer's (1949) measurements. According to Laws (1941), a fall distance of 1.50 m is sufficient for drops less than 0.5 mm to attain their terminal velocity. Since the largest measured water drop from Unijet nozzles was 0.47 mm in diameter, it was assumed that all drops from Unijet nozzles attained terminal velocity. Some water drops from Fulljet nozzles may not have reached their terminal velocity at the measuring distance, since about 20% of these drops exceeded 0.5 mm.

The mean diameter of drops from Unijet nozzles was 0.176 mm and their mean fall velocity was 0.65 m/s at the measuring level (Table II). Measurements by Gunn and Kinzer (1949) show that a drop with a 0.169-mm diameter had a terminal velocity of 0.57 m/s. Unijet nozzles showed good agreement with Gunn and Kinzer's measurement. The mean diameter of drops from Fulljet nozzles was 0.365 mm and their mean fall velocity was 1.14 m/s at the measuring level, appreciably less than Gunn and Kinzer (1949) obtained for a comparable drop size. The lower average fall velocity of water drops from the Fulljet nozzles was most likely because the larger water drops from these nozzles had not reached their terminal velocities at the measuring level (1.50 m). If the distance between the Fulljet nozzles and the measuring level was increased to enable all the water drops to reach their terminal velocity, a good agreement might have also been obtained between the videocamera method and Gunn and Kinzer (1949).

CONCLUSIONS

The oil-microscope and videocamera methods were developed to measure the size and fall velocity distributions of water drops. They are especially suitable for small water drops whose size and fall velocity are not easily determined with other methods. The smallest drop size measured in this study was 0.03 mm in diameter. Both methods are simple, direct and accurate. Neither require sophisticated technical means.

Both methods can be readily used in the laboratory or in the field. Although the oil-microscope method has no practical limit for small drops, it is not recommended for drops larger than 0.7 mm in diameter.

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