

# Ventilation Required to Entrain Small Particles from Leaves

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## ABSTRACT

Particles are blown from leaves when the wind at the height of the particles exceeds a minimum which is about 5 m/sec for some fungal spores. In the moderate winds typical within a canopy of leaves, the minimum is attained at spore height during brief changes in wind or puffs before the boundary layer grows to particle height. The requisite change in speed to remove spores occurs over a sizeable area only when the speed changes abruptly in a short distance in the direction of the wind.

The average wind near a leaf is slowed by viscosity. A study of the consequent time-averaged boundary layer explains the exchange of heat, water, and CO<sub>2</sub> by the leaf. The removal of microscopic particles from the leaf, however, is not explained by a study of this average boundary layer. The average is justified in the first case because of the thermal inertia of the leaf. On the other hand, because of the slight mass of  $\mu\text{m}$ -size particles, they respond to brief puffs. Thus, if 5 m/sec is required to remove a particle (1, 2, 4), then an average wind of fully 25 m/sec or 50 mph is required to force a speed of 5 m/sec within the boundary layer away from the leading edge, and yet moderate winds do in fact carry away small particles from the center of the leaf (2, 3). In this paper we demonstrate that an average view is misleading, and the required force on the spore occurs briefly during changes in wind speed.

## MATERIALS AND METHODS

Removal of particles from leaves and the structure of the turbulent eddies responsible for the removal were observed outdoors.

**Plant Material.** To observe particle removal, we used conidia of *Helminthosporium maydis* Nisikado and Miyake Race T because the strength of the attachment to their conidiophores is quite uniform (1). The fungus was reared on filter paper by a procedure described by Waggoner *et al.* (13). The spores were, on the average, 96  $\mu\text{m}$  in length by 17  $\mu\text{m}$  in diameter. The approximate spore volume, determined by assuming the shape to be a prolate ellipsoid, was  $1.5 \times 10^4 \pm 0.4 \times 10^4 \mu\text{m}^3$  and the projected cross sectional area of an average spore was  $1.28 \times 10^3 \mu\text{m}^2$ .

The strength of the attachment of these conidia to their conidiophores was determined by centrifugation, and the minimum air speed required for removal was estimated by the methods described in an earlier paper (1).

**Wind Measurements and Eddy Visualization.** To observe the rapid change in wind velocity along a flat surface, we constructed a special flat plate anemometer that revealed the location and speed of wind gusts by changing color. A sheet of black plastic,

0.0025 cm thick, was stretched over a 15-cm-diameter embroidery hoop, and a 1-  $\times$  10-cm strip of filter paper holding the spores was affixed in the plane of and along a chord of this circle (Fig. 1). To visualize regions of fast wind, the plastic (except under the filter paper) was coated with liquid crystals (Vari-Light Corporation, Cincinnati, Ohio) and exposed to wind which together with radiation and air temperature determined its temperature. These crystals preferentially scatter different wavelengths of white light and change color as their temperature changes within a prescribed range. Their use has been explained before (10). The thermal inertia of the thin plastic was slight. The characteristic time,  $t_1$ , for the plastic sheet to respond to a step change in ventilation is shown in the Appendix to be about 0.3 sec, which is also about the time for the crystals to respond to changing temperature.

We used several methods to maintain constant and uniform irradiation. The surface of the plastic sheet was maintained perpendicular to the sun's rays by turning the sheet or by a mirror. On overcast days an artificial light was used to warm the plastic. All methods worked equally well.

When the wind cooled the plastic from 16 C to 14.5 C, a progression of colors appeared: first blue, followed by green, yellow, red, and red-black. We measured the wind 0.5 cm from the sheet with a hot wire anemometer, determining the wind speed parallel to the sheet corresponding to a given air temperature and irradiation. Of course air temperature also experiences turbulent fluctuations according to the vertical temperature gradient and the gust wavelength (12). Within one gust, however, temperature was nearly uniform and changes in color caused by these fluctuations could not be detected; *i.e.*, when a gust caused the crystals to turn red they remained uniformly red essentially for the duration of the gust. This could be because temperature fluctuations occurred faster than 0.3 sec or because their magnitude was insufficient to change the color. In either case, air temperature fluctuations had no influence on our observations.

Observations were made in the center of an 0.8-ha, mown field. Horizontal wind speed was measured at 0.2-, 0.4-, 0.8-, and 1.6-m height with sensitive cup anemometers and was recorded at 0.5-, 1-, or 5-min intervals. In addition, the wind speed and direction were measured at 0.7-m height with a Gill propeller anemometer and a vane, respectively.

Whenever an area of the plastic became the color corresponding to a 4.2 to 5 m/sec air speed (green to red) a mark was made on the recorded output of the propeller anemometer. A sketch was made of the shape and extent of the colored area. Then spore removal over the surface of the strip was evaluated under a microscope by a worker who had not observed the location of the eddy.

## RESULTS

Spores were removed from a sizeable area of the strip (Fig. 1) when the average wind was about 2 m/sec (Table I). However, the force required to detach conidia by centrifugation (1) is about  $0.75 \times 10^{-2}$  dynes, which spore dimensions and the law

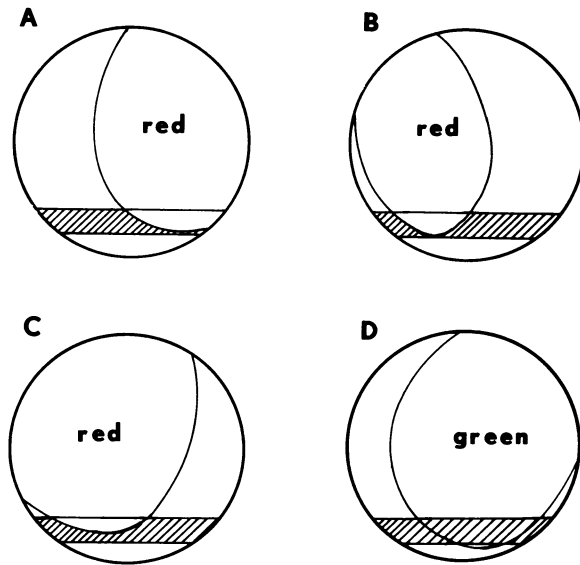


FIG. 1. Diagram of the liquid-crystal-covered plastic sheet and the strip of fungus-covered filter paper. The colors indicate areas cooled by a gust of wind. The white area of the strip indicates where spores were removed by the gust while the hatched area of the strip indicates where spores remained. The wind was from the left.

for air drag on a cylinder (11) indicate requires a wind of about 5 m/sec for removing the spores. This apparent contradiction is resolved by measuring the instantaneous wind speed, near the surface of the plate.

Figure 1 shows the region of the flat plate anemometer where the cooling by wind was greatest (the colored area) and also where spores were removed. Since the wind was from the left of the diagram, it is clear that the "leading edge" of the coolest region did not always correspond with the windward edge of the plastic. In experiments A, B, and C the spores were removed from a region that was red, corresponding to a speed at 0.5-cm height slightly greater than 5 m/sec. Spores were not removed from the strip outside of this coolest region where the wind was only about 2.5 to 3 m/sec. In experiment D, the green area corresponded to a wind of about 4.2 m/sec. In this case, no spores were removed.

It must be emphasized that the wind was not measured at particle height but rather at 0.5 cm from the surface, well outside the fully grown boundary layer which was about 0.12 cm high at the point of measurement (ref. 11, p. 15). In view of the thickness of this boundary layer, even a 5 m/sec wind at 0.5 cm from the surface of the plastic does not guarantee that the spores at a height of 150 to 200  $\mu\text{m}$  will experience a wind fast enough for removal. However, the liquid crystals allowed us to measure a striking characteristic of the wind structure that revealed how the spores could experience the full force of the wind. The changing color of the crystals in response to changing ventilation showed that the transition from the highly ventilated red area (Fig. 1) to the region of low ventilation took place within a very short distance—only 1 mm. We shall show in the next section how this abrupt transition explains the removal of spores over a large area when the speed of the bulk air is only moderate.

#### DISCUSSION

The key to understanding how the spores were liberated in these moderate winds resides in the unsteadiness of the wind and in the rate of growth of the fluid boundary layer near the surface. When a fluid over a surface is started suddenly, the velocity very near the surface at the instant of starting is equal to the free

stream velocity (11). Immediately thereafter, because of viscosity, a region of quiescent fluid, the boundary layer, begins growing outward from the surface. Since a wind of about 5 m/sec is required for spore removal and since the highest wind that we observed was also about 5 m/sec, liberated spores must have been removed quickly, *i.e.*, before the boundary layer had grown to spore height. It is shown in the Appendix that the speed at spore height is reduced by 5% in a time,  $t_2$ , of only  $10^{-3}$  to  $10^{-4}$  sec. The brevity of this exposure is certainly striking and, as we shall show below, it characterizes the kind of gust capable of spore removal. Although our estimate of a 5 m/sec wind for spore removal utilizes a drag coefficient valid for steady state flow (11), it is appropriate because the time,  $t_3$ , for the flow around the spore to reach steady state is shown in the Appendix to be much shorter than the time for the boundary layer to grow to particle height.

The cushioning effect of the thick steady boundary layer is well known. Hirst and Stedman (7) have also described a mechanism for wiping out the boundary layer after it is developed. They suggested that the air at spore height could reach a high velocity as a result of the radial spread of splashing rain drops, the "rain tap and puff" mechanism.

The fact that a sizeable area was cleaned of spores indicates that the transition zone from low to high ventilation must have swept over the surface faster than the  $10^{-3}$  to  $10^{-4}$  sec calculated above for the boundary layer to grow to spore height. We can estimate this time by knowing the spatial variation of the wind speed between the cooler and warmer regions of the plastic. If the spatial variation of the wind speed,  $U$ , takes place in a small distance,  $\delta x$ , then, at a fixed point this velocity variation is swept over that point by the wind in a time of the order of  $\delta x/U$ . Hence, we require that the sweeping time,  $(\delta x/U)$ , be of the order of  $10^{-3}$  to  $10^{-4}$  sec. From measurements with the hot wire anemometer, we found that a change in wind of about 2.5 m/sec caused the crystals to change from blue to red. Moreover, the observed width of the transition from blue to red and thus the ventilation change was 1 mm. Therefore,  $(\delta x/U)$  was about  $10^{-4}$  sec and the transition zone could indeed have swept over the surface in advance of significant boundary layer growth.

The extent of spore removal far from any leading edge in Figure 1 is in marked contrast to the more limited removal near an edge when the airspeed was not changing so abruptly (14).

Table I. Wind Observations at 0.8-m Height Showing Decrease in Recorded Speed with Increase in Averaging Time

In experiment C, for example, the fastest minute observed was about 20% greater, and the fastest burst was about 120% greater than the average for 1 hr. Rows d and e give the number of times the wind equalled or exceeded twice the hourly average and twice the average for a minute. Obviously, the wind was steadier during experiment A than during experiments B to D.

	Windspeed			
	Experiments			
	A	B	C	D
	<i>m/sec</i>			
a. Fastest hr	1.6	1.7 <sup>1</sup>	1.8	1.6
b. Fastest min	1.8	2.3	2.2	
c. Fastest 2 sec	3.3	4.8	4.0	4.8
d. No. of occurrences per hr when $c/a \geq 2$	1	22	10	21
e. No. of occurrences per hr of $c/b \geq 2$	0	2	5	

<sup>1</sup>0.5 hr.

It is important to recognize that the patterns of cooling and spore removal shown in Figure 1 are not those expected from two-dimensional boundary layer flow (10) but are rather a consequence of three-dimensional flow which, in general, leads to complex patterns of removal (2). These patterns are brief, remaining about 2 sec, and are rare, occurring at most once or twice per hr in the 1.6 to 1.8 m/sec winds in the field. The upwind edge of the cooled regions does not correspond to the leading edge of the plastic sheet but rather to the region of attachment of the eddy during the passage of the gust.

So far we have shown how a moderate wind of 5 m/sec at 0.5 cm from the leaf surface could be felt at particle height. However, it must be remembered that this speed of 5 m/sec was not the average wind velocity but only occurred in brief gusts. As shown in Table I, there is a marked difference in speed when averaged over 1 min or over a couple of seconds. Although short puffs were observed with the liquid crystals, they clearly cannot be observed by conventional cup anemometers. Because it is not practical, in general, to monitor wind even on a minute-by-minute basis, some criteria to estimate critical gusts from hourly, 3-hourly, or daily wind data must be developed. Studies of the wind within a crop such as those made by Huss (8) for wind in the open should help supply the required relationships.

In conclusion, we have explained how spores can be removed when the average wind is only 2 m/sec. The removal occurs as a rare event when a puff of 5 m/sec or more passes over the spore-bearing surface and the transition from low to high ventilation takes place within 1 mm. Consequently the spores can experience the 5 m/sec wind for a short while, and hence be removed, before the boundary layer has grown to particle height; moreover, the spores can then be swept from a sizable area.

#### APPENDIX

The time,  $t_1$ , for the plastic sheet to respond to a sudden change in ventilation can be written (5) as

$$t_1 = \frac{\rho c b}{\bar{h}} \quad (\text{A1})$$

where  $\rho$ ,  $c$ , and  $b$  are the density ( $\text{g/cm}^3$ ), specific heat ( $\text{cal/g C}$ ), and the thickness (cm) of the plastic sheet, and  $\bar{h}$  is the heat transfer coefficient associated with the ventilation. The spatial average heat transfer coefficient  $\bar{h} = 2h$  where  $h$  is evaluated at a distance  $x$  and is given by (9, 10)

$$h = 0.453 \beta k Pr^{1/3} \left( \frac{U}{\nu} \right)^{1/2} \quad (\text{A2})$$

Here  $k$ , the thermal conductivity of air, is  $5.8 \times 10^{-5}$  cal/cm sec C, the Prandtl number,  $Pr$ , is 0.7, the kinematic viscosity,  $\nu$ , of air is  $0.15 \text{ cm}^2/\text{sec}$ ,  $U$ , the wind speed, is 500 cm/sec, and the numerical coefficient,  $\beta$ , representing the effect of turbulence, varies between 1 and 2.5 (10). For typical values of  $\rho$  and  $c$  for our 0.0025-cm thick plastic sheet (6) and for an average  $x = 5$  cm, we estimate that the response time of the plastic  $t_1$  is between 0.5 and 0.3 sec.

The time  $t_2$  required for the boundary layer to grow above the plastic sheet can be estimated from the solution for the flow above a flat plate impulsively started from rest (see ref. 11, p. 72). The velocity along the plate,  $u$ , in a coordinate system fixed to the plate is

$$\frac{u}{U} = \text{erf } \eta \quad (\text{A3})$$

where  $\eta = y/2(\nu t_2)^{1/2}$ . Here  $y$  is the distance into the fluid from the surface, and  $U$  and  $\nu$  have the same meaning as above. From the centrifugation experiment we estimated that an air flow of about 5 m/sec was required for spore removal, and since we observed speeds that were only slightly in excess of this, we require the time  $t_2$  for the speed at spore height to be reduced but little, say by 5% of  $U$  and  $u/U$  or  $\text{erf } \eta$  be about 0.95. This time,

$$t_2 = \nu^{-1} (y/2\eta)^2 \quad (\text{A4})$$

is between  $10^{-3}$  and  $10^{-4}$  sec with  $y = 0.02$  cm and  $\eta = 1.4$  (see ref. 11, p. 73, Fig. 5.5).

The time  $t_3$  required for a boundary layer to grow around the spore can be estimated from the solution for the component of velocity along the surface of a cylindrical body started impulsively from rest and given by Schlichting (11) as

$$\frac{u}{U} = \text{erf } \eta + t \frac{2U}{R} \cos \frac{x}{R} \eta_1 + \dots \quad (\text{A5})$$

where the first term on the right is the same as the right hand side of equation (A3), and the second term in this time expansion enters because the free stream velocity varies with distance  $x$  along the body. Here  $R$  is the radius of the spore and  $\eta_1$  is a graphical function of  $\eta$ . The time at which this expansion diverges gives an estimate of the time necessary for the flow to reach its steady state. Because  $\text{erf } \eta$  and  $\eta_1$  are of the same order (11), we find that the small time expansion breaks down, *i.e.*, the second term becomes as large as the first when

$$t_3 \frac{2U}{R} \text{ is about } 1 \quad (\text{A6})$$

or when  $t_3$  is about  $10^{-6}$  sec. That is, after  $10^{-6}$  sec, the flow around the spore has nearly reached its long-time or steady limit. Thus we are justified in taking the steady drag coefficient to compute the drag.

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