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A Tilting Wind Tunnel for Fire Behavior Studies

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The combined effects of wind velocity and slope on wildland fire behavior can be studied in the laboratory using a tilting wind tunnel. The tilting wind tunnel requires a commercially available fan to induce wind and can be positioned to simulate heading and backing fires spreading up and down slope. The tunnel is portable and can be disassembled for transport using a full-size pickup truck. Vertical velocity profiles indicate that the average turbulence level is about 15 percent of mean wind velocity.

Retrieval terms: heading fire, backing fire, slope, rate of spread, wind velocity

Wind velocity and topography are important factors affecting many aspects of a wildland fire. Research examining the effects of wind and slope on fire behavior has been conducted since at least the late 1930s.[1] The research has been both field and laboratory based. Field-based research programs have been extensively used in many countries including Canada and Australia.[2] Advantages of the field-based approach are that wildland fire behavior is studied on a scale that is very close to the actual phenomenon. A disadvantage to this approach is that control over experimental conditions is difficult to achieve and isolation of the effects of individual factors may not be obtainable.[3]

Laboratory-based research has been widely used in the United States to isolate and examine the individual factors affecting fire behavior. A potential disadvantage of laboratory-based research is that scale effects may exist. For example, the ratio of radiative and convective heat transfer in a laboratory study may not be equal to the ratio observed in full-scale wildland fires. The theory of similitude and scaling relationships have been widely used in fire modeling as well as other disciplines with success.[4,5,6,7] Laboratory results must be validated at near-field scale to ensure against any scaling effects if similitude has not been preserved.

Laboratory studies of wind effects on fire behavior have traditionally been studied in wind tunnels or similar devices capable of inducing wind. Ten wind tunnels of various types, the majority of which were located in the United States, that have been used for fire research have been described.[8] Three of these tunnels are part of the two USDA Forest Service forest fire laboratories in Macon, Georgia and Missoula, Montana. Other smaller wind tunnels have been constructed to examine various fire behavior phenomena.[9,10,11]

Studies of the effects of slope on fire behavior range from examining fire spread along single fuel particles to field-scale tests.[12] Laboratory tests using constructed fuel beds have commonly been used to study slope effects on fire spread.[13,14,15] However, these experiments have examined only the effects of slope and thus were conducted under calm air conditions. The combined effects of wind and slope on fire behavior have not been examined in a laboratory setting.

To examine wind and slope effects concurrently under controlled conditions, a wind tunnel that can be tilted is necessary. The wind tunnels that are housed at the Forest Service combustion laboratories are fixed in the buildings and cannot be tilted. Small wind tunnels can be tilted and can be used to examine wind and slope effects concurrently.[10,11,16] Most wind tunnels are simply long boxes consisting of four rigid, immovable sides. For a fire of sufficient size, the buoyancy exhibited by the flame could be influenced by the presence of a roof.[17] A fixed position wind tunnel with a movable roof designed not to impede a flame's buoyancy has been described.[18] A wind tunnel with a moving or open roof is untraditional; however, this design has been used in at least one other wind tunnel.[11]

A small wind tunnel was designed to incorporate several design features: 1) tilt, 2) wind flow from either tunnel end, 3) flame buoyancy unimpeded by a fixed roof, 4) low cost, 5) portability and 6) low inflammability. Air flow characteristics were of concern because of the potential impact of flow characteristics on fire behavior, and the similarity of air flow to other wind tunnels used in fire behavior research. If air flow was similar to other wind tunnels, results from studies in the present wind tunnel could be included with results from experiments in other wind tunnels. Flow similarity to actual wildland conditions was not a design criterion. Several of the wind tunnels described above have been designed to produce a uniform vertical velocity profile. A uniform vertical velocity profile is one in which air velocity does not change appreciably beyond some vertical distance above the wind tunnel floor. Wind velocity variability of < 5 percent has been achieved in wind tunnels used for wildland fire behavior studies.[18,19]

This note describes a tilting wind tunnel and its air flow characteristics.

WIND TUNNEL

Dimensions of the wind tunnel and supporting braces are 4 m L by 1.5 m H by 1.2 m W; dimensions of the tunnel itself are 3.7 m L by 1 m H by 0.9 m W *(fig 1)*. Total cost of the wind tunnel was less than $1,500. The tunnel can be easily disassembled and transported using a full-size pickup truck. The frame of the wind tunnel and the supporting rails were fabricated from 0.95 cm aluminum angles and 0.64 cm flat aluminum. The base and side panels at both ends of the wind tunnel were 1.91 cm exterior, fire-treated plywood that was finished on the inside. Four removable 0.64 cm tempered glass panels comprised the middle 2.4 m section *(fig. 2)*. Access for placing fuel beds and video recording of fire behavior required removable clear glass. The roof was made from heavy fiberglass cloth and was collected on rollers at either end of the wind tunnel. The rollers were manually

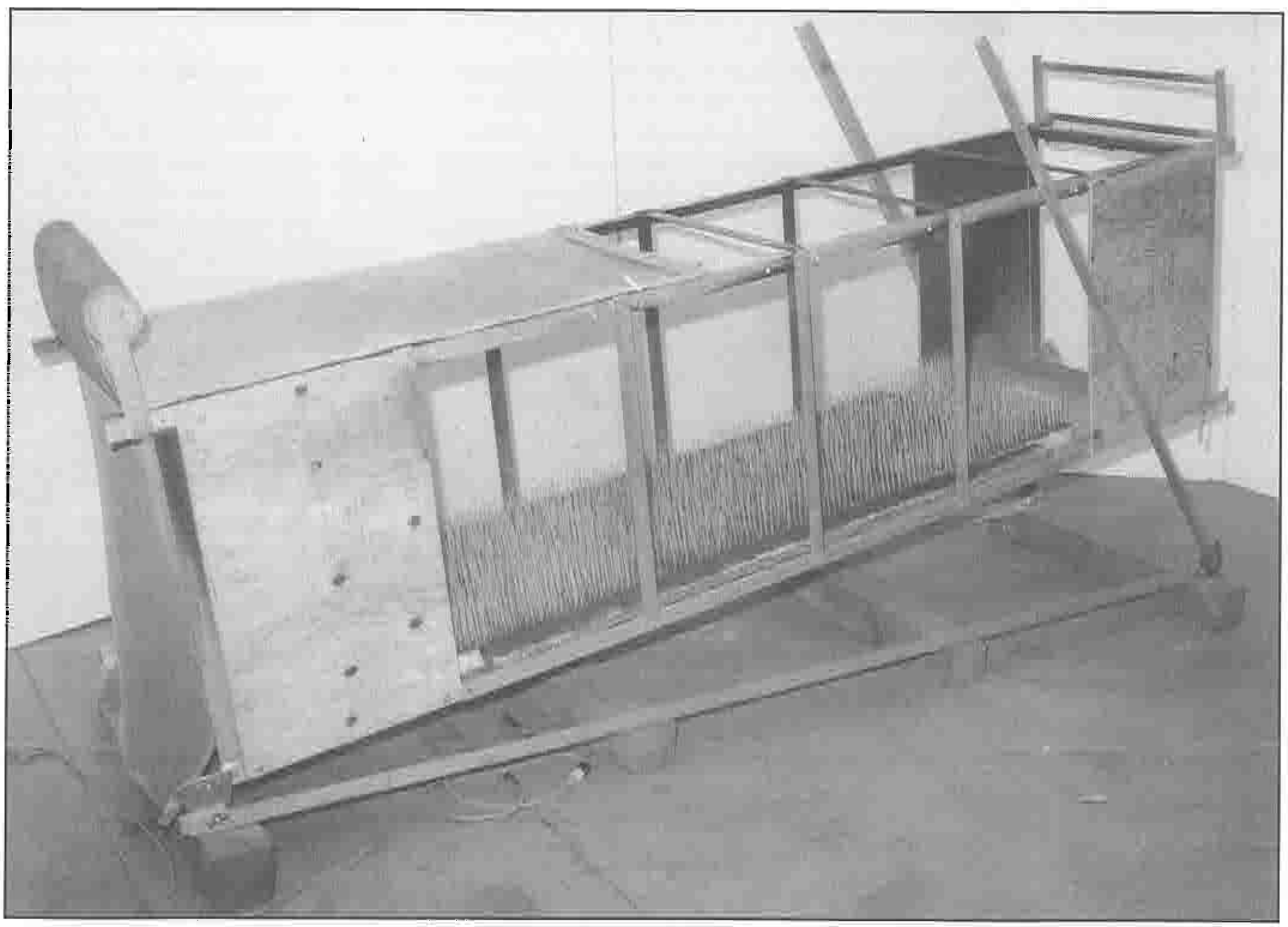

Figure 1—Open-topped, tilting wind tunnel used in fire behavior studies. Note screens at left end of tunnel.

controlled *(fig. 1)*. The base of the wind tunnel in the level position was about 20 cm above the ground. This space allowed access into the wind tunnel via drilled holes for instrumentation.

Fuel beds were placed on soft insulating fire brick *(fig. 3)*. This type of fire brick is commonly used in ceramic kilns and can be easily drilled and cut with standard wood working tools. Total width of the brick base is 0.686 m and total length is 2.515 m. The bricks were centered in the middle of the wind tunnel. Lumber (5.1 cm by 10.2 cm by 2 m) covered with aluminum foil flush with the top surface of the brick was used to fill the two channels on either side of the brick base. Additional brick could have been cut to fill the channels but the lumber accomplished the same task at a much lower cost.

The wind tunnel pivots on one end and is tilted by raising the opposite end that is then supported by rails fashioned from the aluminum angles *(fig. 1)*. The wind tunnel, including the fire brick base and windows in place, weighs about 180 kg; some form of mechanical device is required to raise and lower it. A single person can safely position the wind tunnel by using a chain hoist. Once the rails are bolted into place, the wind tunnel is self supporting. Any angle from 0° to nearly 90° can be achieved with sufficiently long rails. For angles greater than 45°, precaution should be taken to secure both the fire brick and fuel beds in place to prevent sliding or safety hazards.

Wind was induced by a commercially available three-blade, 0.75 m diameter, rotary fan. The fan is free standing and can be placed at either end at any desired distance. In the present configuration, the fan must be placed on some form of support for the downslope orientation. In order to smooth out oscillations and turbulence in the wind flow caused by the rotary fan, removable screens and filters are placed in an end of the wind tunnel. For downslope wind flow, the screens are placed at the upslope end of the tunnel; for upslope flow, the screens are placed on the downslope end of the tunnel. With the screens in place, the actual usable length of the wind tunnel (the test section) is about 2.5 m.

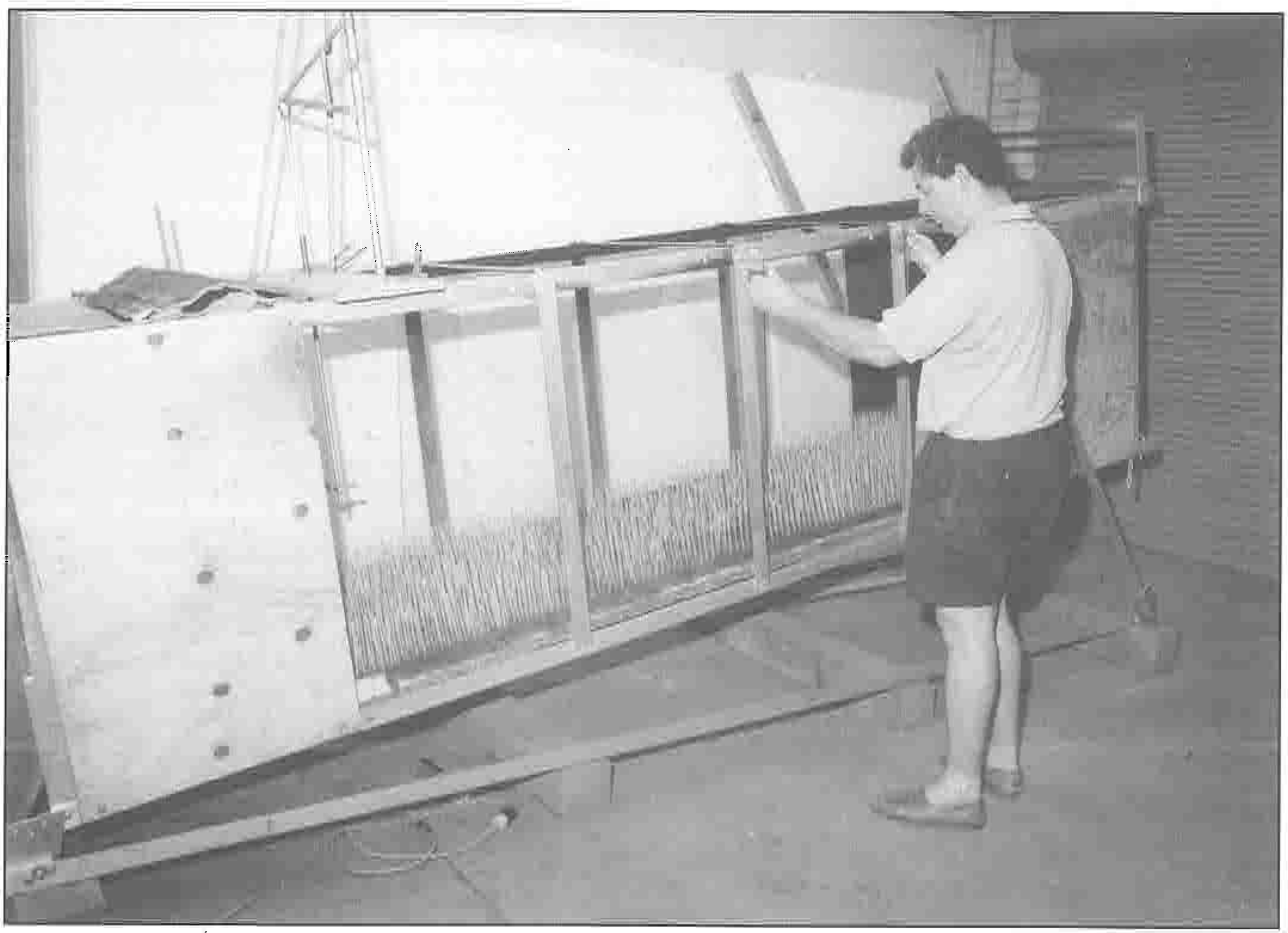

Figure 2—Removable tempered glass panels provide access to wind tunnel interior and permit observation of experiments.

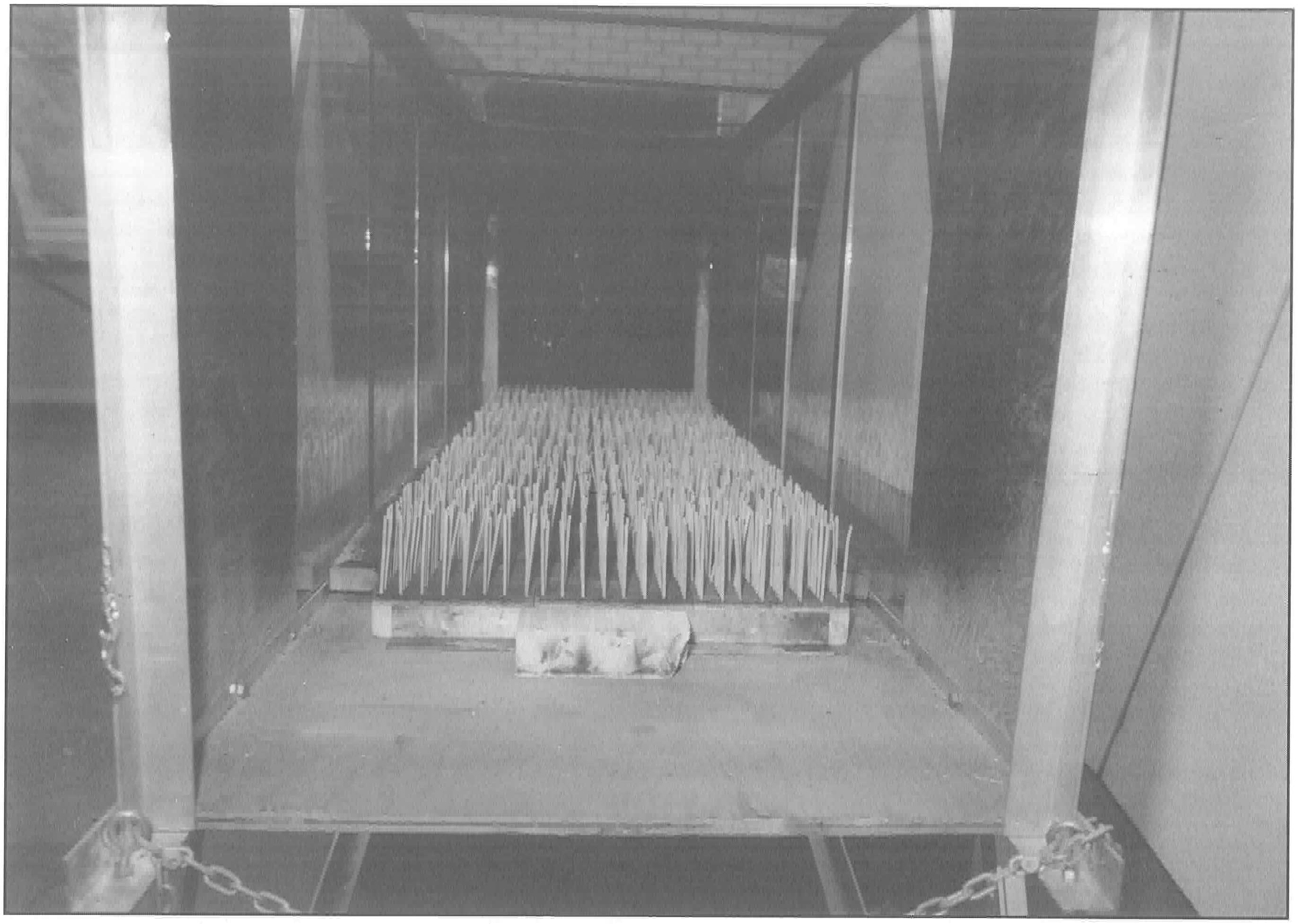

Figure 3—Fuel bed of birch sticks placed in soft insulating brick. Observe aluminum-covered lumber on both sides of brick base.

VELOCITY PROFILES

In order to interpret the results of laboratory fire behavior tests using wind tunnels, the flow characteristics within the tunnel must be known. Chief among these characteristics are the velocity profile and turbulence level. Air flow is strongly affected by the type of blower and filter system used.

Velocity profiles were determined for a study examining the effects of wind and slope interaction on wildland fire behavior. Two wind speed settings were crossed with five slope angles (-17.0°, -8.5°, 0.0°, 8.5° and 17.0°). These angles are equivalent to slopes of -30, -15, 0, 15 and 30 percent. The following sign conventions were used in this study: negative wind velocities indicate backing fire (fire spread into the wind), positive velocities indicate heading fire (fire spread with the wind); negative slope percentages indicate fire spread down a slope, positive percentages indicate spread up a slope. The fan blew horizontally and was placed 1.5 m from either end of the wind tunnel. A single fan speed was used; wind velocity was regulated by using two sets of filters.

A hot wire anemometer was used to make a single vertical transect of the wind tunnel at the tunnel midpoint for all slope angles. Accuracy of the anemometer was within 5 percent of the flow velocity. The tunnel roof was extended to the midpoint so that half of the tunnel was enclosed. Wind velocity was sampled with the anemometer starting at a height of 6.35 cm above the brick base. The vertical distance between subsequent sample points was 1.6 cm. Maximum vertical height for most profiles was about 67 cm above the brick base. Wind velocity was sampled every second for 30 seconds at each height. Mean wind velocity was estimated at each sample point. Temporal and spatial variability were estimated using root mean squared errors (standard deviations). Spatial variability was estimated with the standard deviation of the mean velocity at each height about the mean of means. Temporal variability was estimated by calculating the mean standard deviation for the 30-second samples. Transects were made without a fuel bed so that flow characteristics of the tunnel alone could be determined.

RESULTS AND DISCUSSION

With the exception of the -30 percent slope setting, most velocity profiles were relatively uniform *(fig. 4)*. There was some indication of inverted wind profiles (wind velocity decreasing with height) for the low and high velocity -30 percent slopes. High velocity profiles for the 15 and 30 percent slopes indicated increasing velocity with height as might be expected with a boundary layer above the brick base. Both the inverted profile and the potential boundary layers might be caused by the positioning of the fan relative to the tunnel entrance. Velocity stream lines were not parallel to the main axis of the wind tunnel for all nonzero slopes.

Mean wind velocity for each of the five slopes did not vary greatly *(table 1)*. The largest mean differences within low and high velocity settings were 0.08 and 0.11 m/s, respectively. Spatial variability (CV_1) was generally less than 15 percent of the mean velocity. The exceptions to this were the low wind speed setting for the -30 and -15 percent slopes. Spatial variability for each wind and angle setting can be seen in *figure 2*. Temporal variability (CV_2) was greater than 10 percent for the low velocity setting and less than 10 percent for the high wind setting.

Variability (turbulence) in the velocity profile can be reduced by improving the straighteners (screens and filters). Turbulence in other wind tunnels has been reduced from 30 percent to 1 percent by using a series of screens and reducing blower speed.[18] A flat velocity profile was observed in the Forest Service wind tunnel in Macon, Georgia; flames from experimental fires exhibited laminar properties so a trip screen was utilized to generate a turbulent layer.[20]

The potential effects caused by tilting the wind tunnel could possibly be removed by connecting the fan to the tunnel entrance via some form of flexible ducting. This must be done carefully because some fan/tunnel configurations result in fire burning into the fan-induced flow. If the fire's buoyant force is greater than the force of the wind, then hot flame gases could potentially bathe the fan and damage it. Another potential solution would be to ensure that the fan-induced flow is parallel to the long wind tunnel axis.

Although the present configuration of the wind tunnel resulted in variability of about 15 percent of the mean flow, this turbulence level was viewed as acceptable for the present experiment. Turbulence levels of larger, more costly wind tunnels used in fire behavior research are < 5 percent.[19,20]

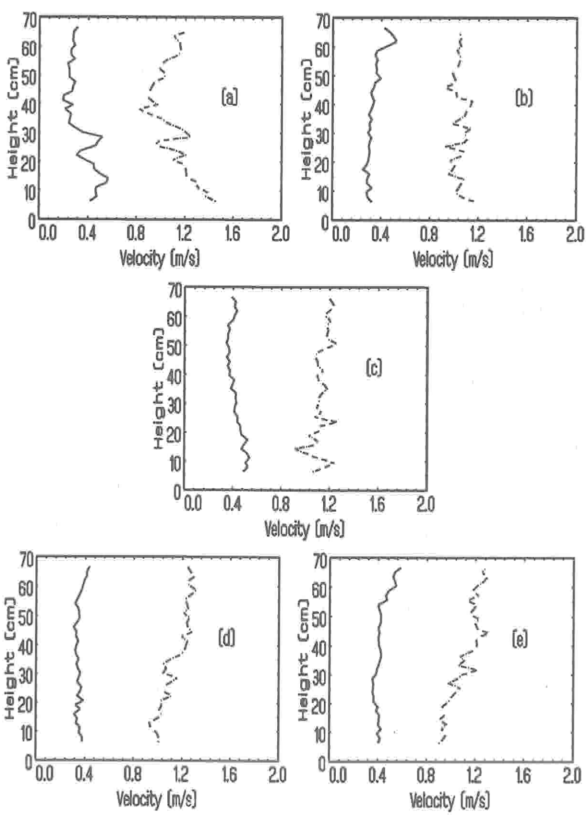

Figure 4—Profiles of mean velocities at low and high wind velocities for five slope percentages: (a) -30 pct, (b) -15 pct, (c) 0 pct, (d) 15 pct and (e) 30 pct. Solid line denotes low wind velocity, broken line denotes high wind velocity. Negative slope percent indicates downslope flow.

Table 1—***Estimated mean velocities and turbulence levels in a tilting, open-topped wind tunnel for two wind velocities and five slope settings.***

Slope[1] (percent)	Wind velocity (m/s)	RMS_1[2]	CV_1[3]	RMS_2[4]	CV_2[5]	n[6]
-30	0.34	0.108	31.8	0.060	17.6	39
	1.11	0.152	13.7	0.093	8.4	39
-15	0.34	0.061	17.9	0.047	13.8	39
	1.04	0.060	5.6	0.102	9.8	39
0	0.42	0.054	12.9	0.059	14.0	43
	1.14	0.074	6.5	0.108	9.5	43
15	0.35	0.029	8.3	0.053	15.1	39
	1.15	0.116	10.1	0.102	8.9	39
30	0.42	0.055	13.1	0.044	10.5	39
	1.11	0.127	11.4	0.106	9.5	39

[1] Slope percent is defined as 100 * (ratio of vertical change to horizontal change). Negative value indicates flow in downslope direction, positive value indicates upslope direction.

[2] Root mean squared error (standard deviation) of velocity across vertical profile (m/s).

[3] Coefficient of variation for RMS_1.

[4] Mean root mean squared error (mean standard deviation) based on n samples of 30 observations.

[5] Coefficient of variation for RMS_2.

[6] Number of sample points in profile. Profile begins at 6.35 cm above brick base with vertical increments of 1.6 cm.

APPLICATION

Improved understanding and experimental measurement of combined effects of wind velocity and slope angle on wildland fire behavior require experiments designed to examine these two factors concurrently. These experiments can be conducted in a tilting wind tunnel. Fairly uniform velocity profiles were achieved by using window screen, air filters, and a commercially available rotary fan. Root mean square flow turbulence was less than 15 percent of mean wind velocity for eight of ten wind speed/tunnel angle configurations.

ACKNOWLEDGMENTS

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