Reprinted from Sixth ASME Wind Energy Symposium - Presented at The Tenth Annual Energy-Sources Technology Conference and Exhibition, Dallas, Texas, February 15-18, 1987

The American Society of Mechanical Engineers
United Engineering Center - 345 East 47th Street - New York, N.Y. 10017

INFLUENCE OF BLADE SURFACE ROUGHNESS ON THE PERFORMANCE OF WIND TURBINES

O. Yekutieli, Agricultural Engineer
Institute of Agricultural Engineering
Agricultural Research Organization
Bet Dagan, Israel

R. N. Clark, Agricultural Engineer
USDA, Agricultural Research Service
Bushland, Texas

ABSTRACT

Wind turbines operate in environmental conditions that can change the smoothness of the blade's surface. During testing of a 60 kW, 480 V, 60 Hz, 3-bladed fixed pitch horizontal-axis wind turbine for its performance, a power reduction due to insect debris accumulation on the blades was noticed. The reduction in performance was measured during the summertime at the USDA, Conservation and Production Research Laboratory, Bushland, Texas. Cleaning the blades improved the power output. Calculated monthly energy output for clean and unclean blades showed that, in this case, the energy reduction by insect contamination could have been about 20%. Power output reduction was caused also by accumulation of dust on the rotor's blades due to oil leakage. Examples of the power output before and after rain washed the dust are shown. The regular user of small wind energy conversion systems normally does not have the instrumentation to notice reduction in the power output. It is advisable to clean the blades periodically, especially during the summer, by scrubbing or washing with water in order to maintain a high performance.

INTRODUCTION

Wind turbines operate in environmental conditions that can change the smoothness of the blade's surface. The blowing wind can carry sand, dust, and insects which accumulate, in certain conditions, on the wind turbine blades. In low temperatures and high moisture, layers of ice can also accumulate on the rotor surfaces and change the airfoil characteristics. Blade roughness has a significant influence on the performance of small wind energy conversion systems (SWECS). Smooth blades perform better than rough blades, which results in a higher power output.

Airfoil surface roughness can be addressed at two stages for SWECS: 1) surface roughness at the stage of design, development, and manufacture; and 2) surface roughness during operation in the changing weather conditions. Stage 1 includes choosing the blade material (or the surface material to cover the blades) and the degree of blade surface finish. In the airplane industry, airfoil roughness plays a significant role and new improvements occur all the time. Modern airframe construction materials and fabrication methods offer the potential for production of aerodynamic surfaces without critical roughness and waviness (1). Also, with wind turbines, this stage is important, although not much information has been published.

Park (2) states that wind turbine blades made of aluminum offer a smoother surface and less air friction than fiberglass. After redesigning his rotor using aluminum skin, which was much smoother than the previous fiberglass surface, the performance improved. During the design stage, the predicted performance of the airfoil is selected, assuming, among other parameters, the roughness of the finished blade skin. Sometimes, the assumptions are too severe. For instance, Thomas and Richards (3) reports that the Mod-0 wind turbine performed better than predicted at the test windspeeds and that a possible explanation for these results is the fact that Mod-0 was sized assuming rough airfoils, while the actual airfoil was smooth.

The SWECS user has little influence on the first stage, maybe only by taking into account the behavior of the roughness problem among his other considerations while choosing and purchasing a new SWECS. But in the second stage, the user has a main part--to keep surface roughness to a low level in order to receive the anticipated power output.

Most of the information dealing with surface roughness has come from experience with the airplane's airfoil. Little information has come from the SWECS user's experience.

During testing of a horizontal-axis wind turbine for its performance by the USDA, Agricultural Research Service, Bushland, Texas, the results showed some influence of dust layers and insect debris accumulation on the power output of the wind turbine. The results indicate that surface roughness of the wind turbine blades can reduce, to some extent, the power generated by the rotor.

REVIEW OF EXPERIENCE WITH AIRPLANE BLADES

Surface Roughness and the Performance of the Airfoil

Drag of a wing is made up of profile drag and induced drag (which depends on the blade's geometry). The profile drag is due, principally, to surface friction. Among the desirable characteristics of an airfoil are a small value of minimum profile drag coefficient and a large value of lift coefficient to drag coefficient, C_L/C_D (4).

Surface roughness reduces the effectiveness of the airfoil. The extent to which roughness affects airfoil performance is dependent on the nature of the roughness, its size relative to the boundary layer thickness, the Reynold's number, and the airfoil type (5). The surface conditions influence both the lift and drag coefficients. Miley (5) gives an example of the effect of rough and smooth surfaces on four and five digit NACA airfoil performance. The results of maximum lift coefficients of smooth surface airfoils for 7×10^5 to 6×10^6 Reynold's numbers are higher than those for rough surfaced ones (1.2 to 1.6 vs. 0.8 to 1.3). At the same time, the drag coefficients for rough surface conditions are higher than those for smooth surface (0.014 to 0.010 vs. 0.08 to 0.06 for the above Reynold's numbers). These results were obtained in a wind tunnel with steady state conditions. The roughness used was 0.28 mm carborondum grains spread over the first 8% of the airfoil at the leading edge. In the unsteady case (as with wind turbines), roughness is likely to have a much more significant effect (6).

Another example is also given by Miley (5) on the higher performing six digit NACA airfoils. Here also the C_L is higher and the C_D is lower for smooth surface than for rough surface.

High performance airfoils are especially vulnerable to surface irregularities and roughness (5) and need more attention for exact contour and smooth surface. Abraham (4) indicated also that low-drag airfoils are very sensitive to roughness.

Insect Debris Contamination

Holms and Obara (1) deal with the application of natural laminar flow (NLF) on the wings for viscous drag reduction on production powered airplanes. They emphasized that the maintenance of NLF on the wings requires that the surface be kept free from critical amounts of surface contamination (i.e., insect debris or ice) in the operating environment. Holms and Obara (1) report that for a sample insect debris contamination pattern collected on an NACA 6 series airfoil, only 9% of the insect strikes were of supercritical height at cruise altitude, causing transition (in the boundary layer) at their location impact. In practice, the seriousness of insect debris contamination will likely be dependent on airplane mission characteristics. They suggest that for cases in which it is not practical to wipe the leading edge, the use of active methods of insect protection such as porous, fluid-exuding leading edges is needed which may serve the purposes of both insect and ice protection. They say that it is important to recognize that while sufficient insect contamination can seriously degrade airplane performance, the occurrence of serious contaminations likely will be infrequent for many combinations of place, time of day, time of year, airfoil geometry, and mission profiles. Most of the insects collide on the airplane wings only during takeoff or landing. However, with the SWECS blade, the problem seems to be more severe because the blades operate in the same zone of flying or wind-carried insects.

EXPERIENCE WITH WIND TURBINES

Wind Turbine Description

The horizontal-axis wind turbine had a 13.4 m diameter, three-bladed, fixed-pitch rotor mounted on a 29.9 m free-standing tower. The blades were fabricated from laminated epoxy-wood attached to a steel hub and covered with fiberglass. The rotor solidity was 0.075. Blade thickness was 17.5 cm at the root, tapering to 5 cm at the tip, with a twist of 5-1/2 degrees. The maximum blade chord was 61 cm and reduced to 51 cm. Rotor speed was 65 rpm at rated power.

The horizontal-axis wind turbine produced utility-compatible electrical power by employing a 480 V, 60 Hz, 3-phase induction generator.

Data Acquisition

Data for power and windspeed were collected at a rate of 4.4 Hz, averaged over 15 seconds. Temperature and barometric pressure were collected at a rate of 0.3 Hz. The windspeed was collected at two heights, 20 and 30 m, and averaged to 25 m, the height of the hub.

The results of standard power output vs. windspeed were calculated using the windspeed bin method (bin width of 0.5 m/s). The power was corrected to standard power using standard air density of 1.22 kg/m^3. Additional data was collected with a data logger, which had a 10-sec sampling rate averaged over 5 minutes. Windspeed and power were integrated over the 10-sec sampling period.

RESULTS AND DISCUSSION

Power Output Reduction by Insects

During the summer of 1985, insect debris accumulated on the wind turbine blades. In Fig. 1, the leading edge of one of the blades is shown with insect debris on it. No measurements were taken to determine the height and width of the contamination areas or for the roughness of the blade, but by comparing the finger on the right side of the picture, the relative size and density of the insect debris can be seen.

The blades were cleaned at the beginning of September 1985. After cleaning, there was some improvement in the power output compared to the

FIG. 1. Insect Debris on leading edge of wind turbine blade, summer 1985.

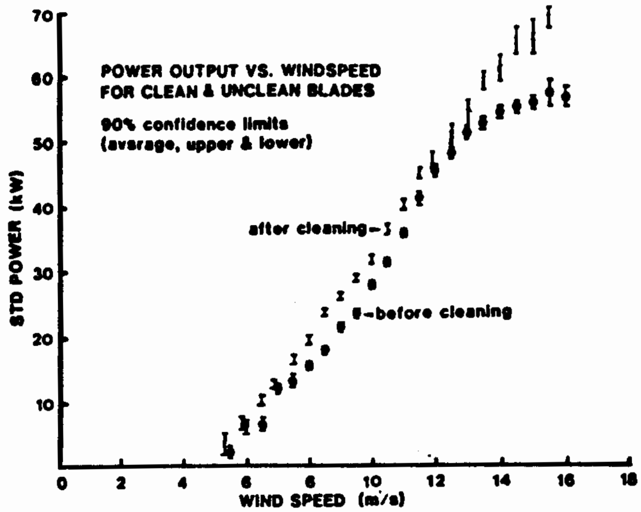

FIG. 2. Standardized electrical power output from a 13.4 m diameter horizontal-axis wind turbine, summer 1985.

performance before the cleaning (Fig. 2). In this figure, each curve includes the power mean and a 90% level of confidence, upper and lower limits (Tables 1 and 2). The power curve for uncleaned blades had a flat concave shape between windspeeds of 7 and 13 m/s, compared to the curve for cleaned blades, which is almost a straight line. For most windspeeds, the two curves or bands are going in the same direction; but around 13 m/s, there is a separation, and the differences between the power outputs increased from about 3 kW (13 m/s windspeed)

TABLE 1. Standard power output vs. windspeed bins, Aug. 9, 12, and 21, 1985. Blades covered with insect debris.

Windspeed m/s	No. of observations	Standard power (kW) 90% certainty limits	Standard deviation
5.5	53	2.52 ± 0.86	3.76
6.0	64	6.30 ± 1.06	5.10
6.5	82	6.87 ± 0.96	5.26
7.0	149	12.36 ± 0.81	5.98
7.5	143	13.58 ± 0.91	6.58
8.0	211	15.68 ± 0.69	6.13
8.5	248	17.72 ± 0.69	6.58
9.0	315	21.68 ± 0.62	6.64
9.5	313	23.76 ± 0.62	6.37
10.0	317	28.15 ± 0.66	7.12
10.5	278	31.71 ± 0.74	7.45
11.0	233	36.09 ± 0.79	7.35
11.5	178	41.79 ± 0.94	7.66
12.0	154	45.73 ± 0.83	6.21
12.5	161	48.24 ± 0.79	6.12
13.0	135	51.42 ± 0.81	5.74
13.5	110	52.96 ± 0.80	5.10
14.0	91	54.44 ± 0.80	4.66
14.5	62	55.43 ± 0.74	3.51
15.0	40	56.03 ± 1.02	3.86
15.5	10	57.65 ± 2.11	3.65
16.0	16	57.08 ± 1.41	3.72

TABLE 2. Standard power output vs. windspeed bins, Sept. 16, 17, 29, 1985. After cleaning the blades.

Windspeed m/s	No. of observations	Standard power (kW) 90% certainty limits	Standard deviation
5.5	16	3.69 ± 1.67	3.82
6.0	45	7.09 ± 0.98	3.91
6.5	126	10.51 ± 0.66	4.49
7.0	198	13.10 ± 0.55	4.69
7.5	215	16.83 ± 0.64	5.67
8.0	303	19.72 ± 0.63	6.39
8.5	444	23.88 ± 0.53	6.74
9.0	512	26.49 ± 0.49	6.82
9.5	588	29.28 ± 0.51	7.52
10.0	471	32.30 ± 0.63	8.34
10.5	346	39.96 ± 0.68	7.66
11.0	251	40.56 ± 0.77	7.36
11.5	188	45.37 ± 0.80	6.69
12.0	103	47.36 ± 1.25	7.71
12.5	65	51.24 ± 1.45	7.00
13.0	36	54.50 ± 2.13	7.57
13.5	45	59.43 ± 1.38	5.51
14.0	23	61.13 ± 1.95	5.49
14.5	8	65.59 ± 1.83	2.73
15.0	6	66.24 ± 1.60	3.16
15.5	2	69.08 ± 1.55	0.35

to about 11 kW (15 m/s). In lower windspeeds, between 8 and 11 m/s, the power output differences are almost 4 to 5 kW.

The power coefficient vs. windspeed curve for the cleaned blades was higher than for the uncleaned blades' curve (Fig. 3). The maximum C_p for the cleaned blades was 0.465 at 7.5 m/s windspeed. The maximum C_p for the uncleaned blades was 0.420 at 7 m/s. To show how much energy could be lost in a situation like this, let us assume that we have two rotors which have the curves of Fig. 2 cleaned and uncleaned blades' power output curves. Suppose these two rotors generate power for one month. Then, by knowing the windspeed distribution for this month and the power output for each windspeed, it is possible to calculate the monthly total energy (kWh). For

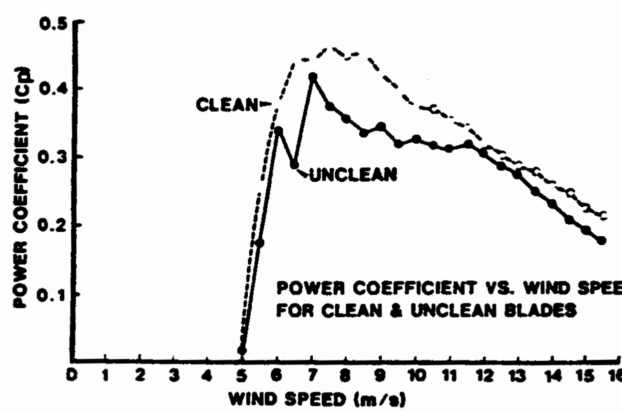

FIG. 3. Standardized power coefficients for a 13.4 m diameter horizontal-axis wind turbine, summer 1985.

these calculations, the actual windspeed distribution of September 1985, Bushland, was taken (Fig. 4). The calculated energy for the two rotors for each windspeed is shown in Fig. 5. The total calculated energy for the month for the cleaned blades was about 21% more than for the uncleaned blades (8,306 kWh for the cleaned blades, 6,868 kWh for the uncleaned blades). Actual energy read from the watt-hour meter was 8,115 kWh, not corrected for standard air density.

Frequently, a Raleigh frequency distribution is used to predict annual windspeed distributions. The frequency of occurrence F(V) of each incremental windspeed (Δv) centered at a wind velocity (V) can be expressed as:

$$F(V) = \Delta v \left(\frac{\pi}{2}\right)\left(\frac{V}{\bar{V}^2}\right) \exp\left[-\frac{\pi}{4}\left(\frac{V}{\bar{V}}\right)^2\right]$$

The annual number of hours operating at each increment will be F(V) x 8,760 (7).

For one month of wind turbine energy calculations, we used the Raleigh distribution with 720 month hours instead of 8,760 year hours. The mean windspeed ($\bar{V}$) for September 1985, Bushland, was 6.34 m/s, and the incremental dV was 0.5 m/s. This Raleigh windspeed distribution is also shown in Fig. 4. If this distribution was used for the energy calculations, the total energy for the cleaned blades would be about 18% more than for the uncleaned blades.

The above calculations were done on a monthly basis and not on an annual one because the insect problem is concentrated mostly in the summer and is not spread over the entire year. It seems that this problem can be more severe in sites with higher summer windspeeds or with higher amounts of insects in the air during this season.

By a relatively simple operation of cleaning the blades frequently, the insect problem can be avoided. Curley et al. (8) reports that after scrubbing the blades of their horizontal-axis wind turbine (September 1984, Davis, California), the power output, which was lower than the manufacturer's specifications before cleaning, then exceeded the specifications. The power output vs. windspeed curve for September was higher than the August curve,

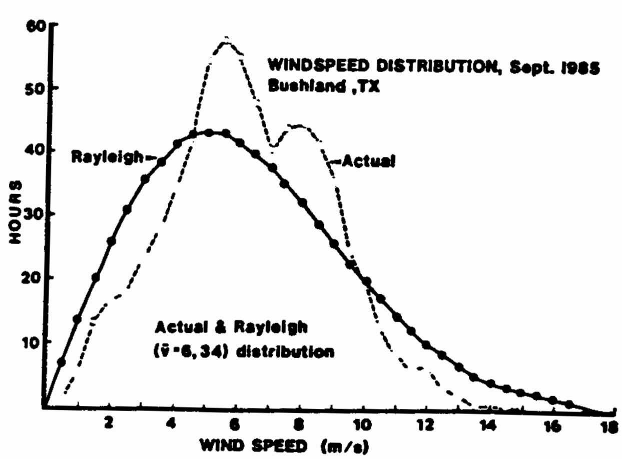

FIG. 4. Actual windspeed distribution for September 1985 measured at a height of 10 m in Bushland, TX. The Raleigh Distribution is shown for the same time period using the actual average windspeed.

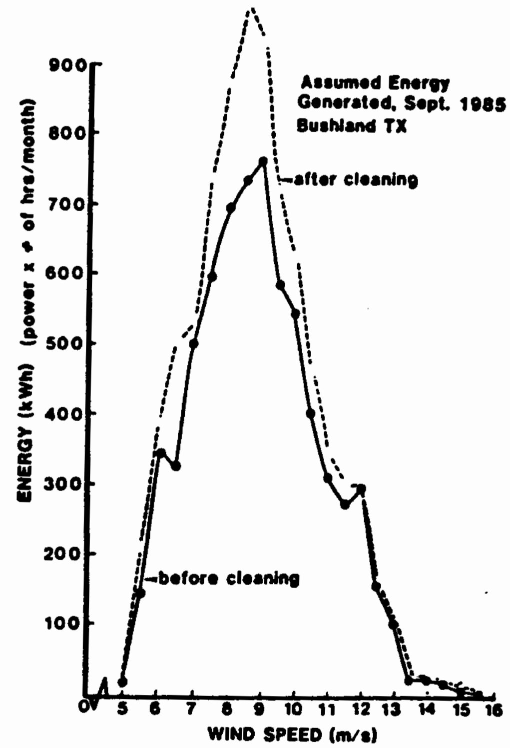

FIG. 5. Predicted energy production using power curves shown in Fig. 2 and windspeed distribution from Fig. 4.

especially in windspeeds higher than 8.9 m/s. It was not mentioned in the report whether the cleaning of the blades was because of insect or dust accumulation on the blades' surfaces.

Power Output Reduction by Dust Accumulation

Dust or sand particles which accumulate on the rotor blades can also reduce the power output. Data collected during November 1985 is shown in Table 3. These data show a power reduction similar to the reduction caused by the insects (Table 1).

In high windspeeds of 15 m/s and above, the power curve ceased to increase with increased windspeeds and the maximum power was about 53 kW. The maximum power after cleaning the blades in September 1985 was 69 kW in windspeed of 15.5 m/s.

The total amount of rain during November 1985 in Bushland, Texas, was 18 mm (0.71 inch) in four days: Nov. 1 — 2 mm; Nov. 2 — 7.3 mm; Nov. 14 — 7.3 mm; and Nov. 29 — 1.3 mm. This was not enough moisture to effectively clean the blades, and more dust accumulated between the rainy days.

Power Output Reduction by Dust Accumulation due to Oil Leakage

During the spring of 1986, there was a little leakage from the rotor transmission of the SWECS in Bushland and a thin layer of oil spread on the wind turbine blades. This leakage intensified the accumulation of dust and changed the smoothness of the blades surfaces. A little rain (17.6 mm) was enough to remove most of the dust and clean the blades till new dust layers accumulated. The accumulation of dust caused a reduction in the wind

TABLE 3. Standard power output vs. windspeed bins, November 1985. Blades covered with dust.

Windspeed m/s	No. of observations	Standard power (kW) 90% certainty limits	Standard deviation
6.0	142	6.172 ± 0.800	5.777
6.5	169	7.747 ± 0.795	6.260
7.0	144	10.042 ± 0.918	6.677
7.5	159	13.519 ± 0.839	6.415
8.0	121	16.260 ± 0.719	5.700
8.5	126	21.149 ± 0.819	5.593
9.0	120	24.727 ± 0.720	4.779
9.5	106	28.387 ± 0.695	4.338
10.0	80	32.061 ± 0.608	3.265
10.5	76	35.188 ± 0.626	3.221
11.0	50	38.121 ± 0.672	2.839
11.5	47	41.461 ± 0.579	2.363
12.0	26	43.429 ± 0.829	2.475
12.5	45	46.793 ± 0.508	2.029
13.0	32	48.205 ± 0.614	2.045
13.5	16	49.131 ± 0.865	1.924
14.0	16	50.249 ± 0.891	2.032
14.5	12	52.123 ± 1.032	1.989
15.0	13	52.720 ± 0.734	1.9511
15.5	5	54.108 ± 3.760	3.943
17.0	6	53.466 ± 0.022	0.094

turbine output, especially in high winds. Output results of two typical days, one before the rain and the other after the rain, are shown in Figs. 6 and 7 (data are presented by bins in Tables 4 and 5). With unclean blades (Fig. 6), the power output increased with the increase of the windspeed till about 12 m/s. Above this windspeed, the rate of output increase was reduced rapidly and above windspeeds of 14 m/s, the power curve flattened and the output stayed constant at about 35 kW.

After the rain, the dust was washed off and the power curve followed the windspeed curve (Fig. 7). In these graphs, the power outputs and windspeeds were 5 minute averages. In Fig. 8, the standard power output for these days vs. windspeed curves for clean and unclean blades are shown. Above 11 m/s, there is a separation between the two curves. The

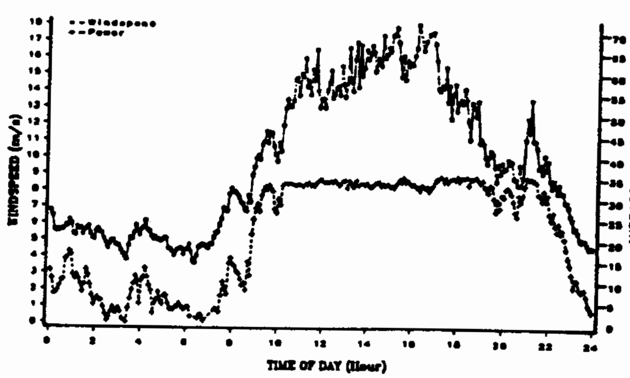

FIG. 6. Actual power production and windspeed for a 13.4 m diameter horizontal-axis wind turbine with dirty blades, April 13, 1986, Bushland, TX.

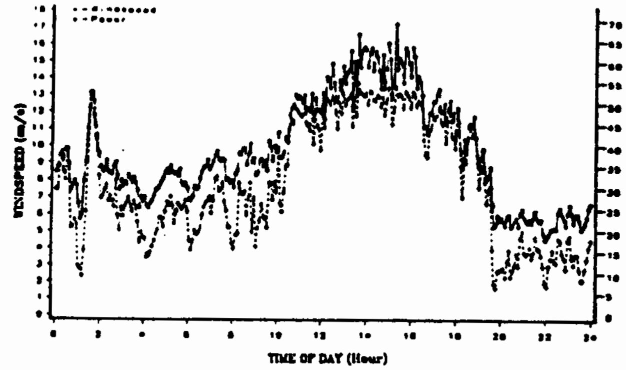

FIG. 7. Actual power production and windspeed for a 13.4 m diameter horizontal-axis wind turbine with cleaned blades (17 mm rainfall), April 17, 1986, Bushland, TX.

power of the clean blades continued to increase to about 65 kW in windspeeds of 18.5 m/s. The power of the unclean blades remained constant at about 41 kW with windspeeds above 13 m/s.

In the above examples, the blade's pitch angle was -1 degree. It seems that the dust accumulation increased the roughness of the blade surface, which caused separation in the boundary layer in windspeeds above 12 m/s. There was a thought that by changing the pitch angle to 0 degrees, the separation would be postponed to higher windspeeds and the influence of the dust accumulation on the performance between 8-14 m/s would be reduced. This was based on the fact that changing the pitch angle on this type of wind turbine could change significantly the power output (9). The results of uncleaned blades with 0 pitch angle are shown in Fig. 9.

Here, the power curve follows the windspeed curve till windspeed of about 12 m/s, after which the power curve flattened as we have seen before, but now the power curve is around 43 kW (not standardized power). It is a little bit higher than the 35 kW constant power which was reached with dusty blades in high winds with pitch angle of -1 degree. It is not clear if the higher constant power was due to the new pitch angle or because of less dust on the blades.

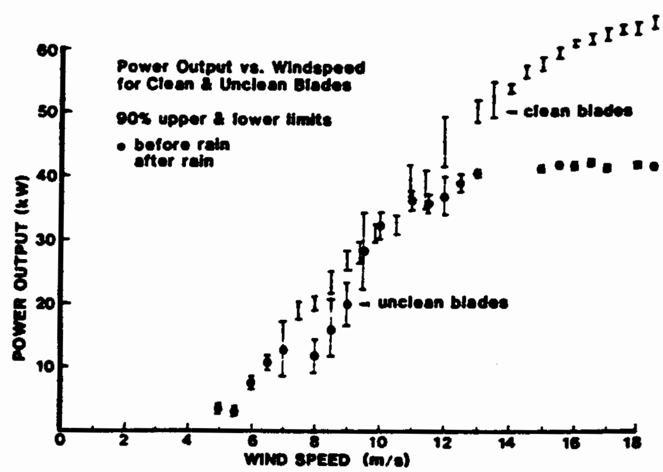

FIG. 8. Standardized power curves for clean and dirty blades for a 13.4 m diameter horizontal-axis wind turbine, Bushland, TX.

TABLE 4. Standard power vs. windspeed bins for dusty blades, April 13, 1986. (Each observation is 5-minute average.)

Windspeed m/s	No. of observations	Standard power (kW) 90% certainty limits	Standard deviation
5.0	15	3.36 ± 0.79	1.74
5.5	21	3.03 ± 0.82	2.17
6.0	26	7.39 ± 1.01	3.00
6.5	25	10.84 ± 1.12	3.26
7.0	7	12.72 ± 4.29	5.84
7.5	3	—	—
8.0	7	11.79 ± 2.63	3.57
8.5	6	15.87 ± 4.35	5.29
9.0	8	19.76 ± 3.90	5.07
9.5	5	28.01 ± 5.98	6.27
10.0	7	32.16 ± 2.10	2.85
11.0	11	36.01 ± 1.44	2.63
11.5	10	35.69 ± 1.63	2.81
12.0	5	36.74 ± 3.01	3.15
12.5	8	38.62 ± 1.90	2.08
13.0	5	40.24 ± 0.46	0.48
13.5	4	—	—
14.0	2	—	—
14.5	3	—	—
15.0	7	41.12 ± 0.59	0.79
15.5	13	41.84 ± 0.41	0.83
16.0	10	41.39 ± 0.45	0.76
16.5	13	42.04 ± 0.35	0.71
17.0	9	41.11 ± 0.71	1.15
17.5	4	—	—
18.0	8	41.46 ± 0.32	0.48
18.5	12	41.11 ± 0.29	0.56
19.0	8	40.64 ± 0.29	0.43
19.5	6	40.55 ± 0.22	0.26

The next day, there was a little rain that partly cleaned the blades, and constant power increased to about 50 kW with windspeeds higher than about 15 m/s. Later during the month (May 1986), there were few high speed winds; and, although there were several rains, it was not clear how much the new setting of the pitch angle increased the output of clean blades.

From these results, we can see that changing the pitch angle from -1 degree to 0 degrees did not solve the power reduction because of contaminated blades but postponed the windspeed which cause flattening of the power curve to somewhat higher speed, depending on the amount of dust which was accumulated on the blades.

SUMMARY

From the above examples, the influence of insect debris and dust accumulation on the power output of the SWECS is clear. A significant amount of energy is lost due to contaminated blade surfaces, and it is advisable to clean the blades as power reduction is noticed. The active methods of insect protection on airplane wings, such as fluid-exuding leading edges as suggested by Holms and Obara (1), seem impractical for SWECS blades, which are much narrower and thinner than airplane wings. Maybe a high pressure water spray could be used to clean the blades from ground level. The regular user does not have the instrumentation to notice power output reduction, so

TABLE 5. Standard power vs. windspeed bins for cleaned blades, April 17, 1986. (Each observation is 5-minute average.)

Windspeed m/s	No. of observations	Standard power (kW) 90% certainty limits	Standard deviation
7.5	12	18.87 ± 1.44	2.78
8.0	7	20.09 ± 1.10	1.49
8.5	9	23.18 ± 1.63	2.62
9.0	19	26.51 ± 1.42	3.57
9.5	20	27.84 ± 1.56	4.02
10.0	23	30.69 ± 1.33	3.70
10.5	20	32.21 ± 1.68	4.34
11.0	14	38.90 ± 2.32	4.90
11.5	8	37.71 ± 3.00	4.48
12.0	7	45.27 ± 3.96	5.39
12.5	3	—	—
13.0	7	50.22 ± 1.67	2.26
13.5	7	51.91 ± 2.75	3.74
14.0	14	53.77 ± 0.69	1.45
14.5	10	50.18 ± 0.91	1.56
15.0	13	57.52 ± 0.73	1.48
15.5	6	59.18 ± 0.84	1.02
16.0	7	60.43 ± 0.44	0.60
16.5	6	61.40 ± 0.75	0.91
17.0	6	62.12 ± 0.90	1.09
17.5	7	62.18 ± 0.53	0.72
18.0	7	62.90 ± 0.63	0.85
18.5	5	63.85 ± 1.03	1.07

it is advisable to clean the blades periodically during the summertime.

Contamination of wind turbine blade surfaces by insect debris or dust accumulation can reduce the performance. The monthly energy output was decreased by about 20% in data collected at Bushland, TX. Cleaning of the blades periodically by scrubbing or washing with water improved the power output to near normal condition. It is especially important in sites with little or no rain. Changing the pitch angle to receive more power did not reduce the problem of contaminated blades but postponed the power reduction to higher windspeeds.

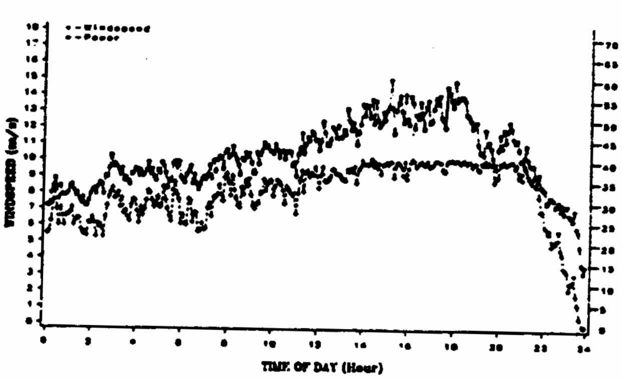

FIG. 9. Actual power production and windspeed for a 13.4 m diameter horizontal-axis wind turbine (pitch angle 0 deg) with dirty blades, May 3, 1986, Bushland, TX.

REFERENCES

1. Holms, B. J. and Obara, C. J., "Observations and implications of natural laminar flow on practical airplane surfaces," Journal Aircraft, Vol. 20, No. 12, p. 993, Dec., 1983.

2. Park, J., The Wind Power Book, Cheshire Books, Palo Alto, California, 1981, p. 33.

3. Thomas, R. L., and Richards, T. R., "ERDA/NASA 100 kW Mod-0 wind turbine operation and performance," Proceedings of the Third Biennial Conference and Workshop on Wind Energy Conservation Systems, September 19-21, 1977, Washington, DC.

4. Abraham, L. H., "Aeronautics," Marks Handbook for Mechanical Engineers, Seventh Edition, 1967. pp. 11-81.

5. Miley, S. J., "A catalog of low Reynolds number airfoil data for wind turbine applications," Dept. of Aerospace Engineering, Texas A&M Univ. February, 1982.

6. Stoddard, F. S., and Porter, B. K., "Wind turbine aerodynamics research needs assessment," U.S.D.O.E., January 1986, p. 18.

7. Soderholm, L. H., "Heating and cooling with wind energy," Solar and Wind System Workshop, October 18-19, 1983, Lincoln, Nebraska. Great Plains Agricultural Council Publication No. 109, p. 95.

8. Curley, R. G., Baumer, R. E., Thompson, J. F., Ward, D. M., Clement, L. D., Olson, K. D., Hanson, B. R., Fortis, T., and Rumsey, T. R., "Wind energy for irrigation pumping," California Energy Commission, Final Report, Contract N-500-82-047. Univ. of California, Davis. March 1985.

9. Vosper, F. C., and Clark, R. N., "Energy production and performance of a wind-driven induction generator," Transactions of the ASAE, Vol. 28, No. 2, 1985, pp. 617-621.