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Performance Tests of Tornado-Type Wind Turbine Models

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ABSTRACT

Power coefficients (C_p) and pressure distributions in the vortex tower were measured for two Tornado-Type Wind Turbine (TTWT) models (one a circular-shaped tower; the other, a spiral) in a wind tunnel and in real environments. All the maximum C_p's measured were greater than one and ranged from 4.7 to 15.2 times the Betz limit of the conventional wind generators. These C_p's indicate that the TTWT machine is not only able to extract the total kinetic energy, but also part of the pressure (or internal) energy of the captured wind. The low pressure vortex core established in the wind tower can be maintained at a very low energy state for efficiently pumping the turbine's discharging flow. The static pressure drop from the ambient value measured at the vortex center of the tower ground floor ranged from 4.3 to 10.2 times the wind dynamic pressure when the turbine flows were plugged. Further improvement of C_p requires further vortex intensification and optimal geometric design.

INTRODUCTION

The Tornado-Type Wind Turbine (TTWT) was invented by Yen (1976, 1977) and further improved by Hsu and Ide (1982, 1983). The TTWT uses an intense vortex generated inside a tower to create a low pressure region for discharging turbine flow (see Fig. 1). The tower is mounted at the exit of a vertical-axis turbine. The vortex is generated by collecting wind through adjustable tangential ports at the tower inlet.

It is well known that conventional wind generators of horizontal or vertical axis can only extract a fraction of the kinetic energy of the captured wind (60% at most, theoretically) because the flow downstream of a wind generator cannot afford much more loss of its energy content than that. The vortex augmented wind machine is much more

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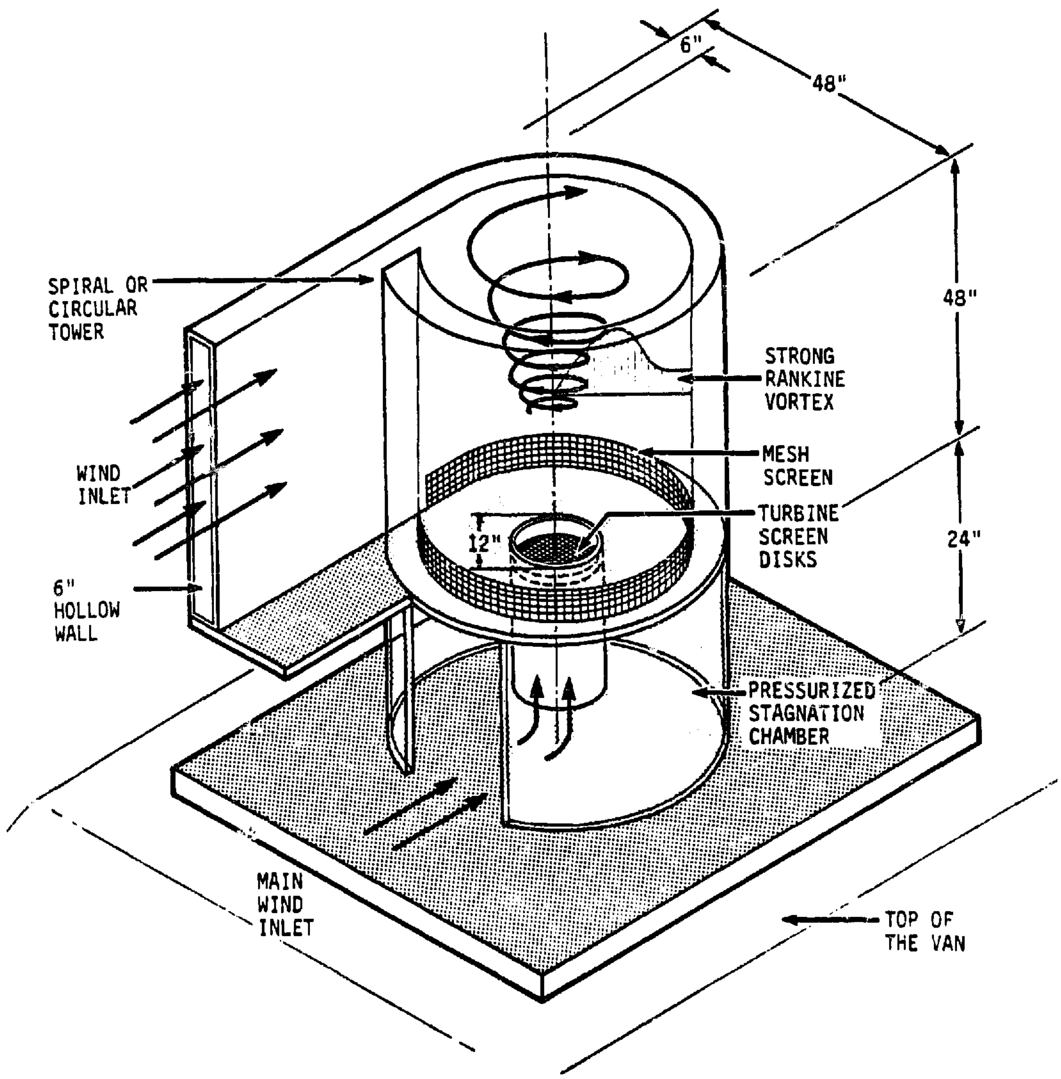

Fig. 1. Sketch of the circular TTWT test model mounted on a van.

promising because the concentrated viscous vortex core can be maintained at a very low-energy state for efficient turbine discharging flow.

Depending on the vortex concentration, the pressure drop from the ambient value in the vortex core can be very high, thus enhancing power extraction by the turbine through the viscous pumping action. The power coefficient, C_p, depends mainly on how low a pressure level can be created and maintained in the vortex core. The essential feature of the TTWT machine is that it is not only able to extract the total kinetic energy but also part of the pressure (or internal) energy of the captured wind (i.e., $C_p > 1$).

The TTWT machine offers other important basic merits, such as (1) omni-directional collection of winds by special design, (2) vertical-axis turbine to avoid aeroelastic fatigue problems, (3) ground location of the wind turbine for easy maintenance, (4) greater safety because of no rotating parts exposed in air, and (5) less noise because of noninteraction of the rotating parts with the wind.

Theoretical Background

Analytical studies on the C_p have been carried out by several investigators. Loth (1978) estimated the Betz-type limitation by considering conservation of angular momentum and assuming the existence of a Rankine-type vortex in the tower and approximately equal exit velocities at the turbine and the tower. So (1978) obtained an analytical solution for the turbine exit flow by assuming the existence of a Burgers one-cell vortex in the tower. The mass flow through the turbine disk was given in terms of a floating parameter, the numerical value of which cannot be properly determined (Johnston and Eaton, 1978). Johnston and Eaton (1978) and Hsu et al. (1978) independently obtained the same result from a simplified analysis: if the vortex core of a Rankine vortex is equal to the turbine disk area, the maximum C_p obtained should be proportional to the cube of the tower-to-turbine diameter ratio.

Rangwalla and Hsu (1982, 1983) extended So's (1978) analysis by optimizing the turbine mass flow as was done in Betz's analysis for conventional wind generators. They obtained very high C_p's provided that the vortex could be intensified to any desirable strength. Ayad (1981, 1983) made numerical computations of the flow field in the tower of Yen's spiral model by considering turbulence modeling and three-dimensional effects. The C_p's obtained were in good agreement with Yen's measured values when the measured static pressure data of Yen (1977) were used for determining the boundary values of the inlet velocity components in the computational domain.

Experimental Background

Yen (1977) tested a small TTWT model with a spiral tower and obtained a maximum C_p (based on tower frontal area) of 0.064 or a maximum C_p (based on turbine disk area) of 2.5 at a wind speed of 5.72 m/s. For conventional wind generators, the theoretical limit of the C_p based on frontal area or turbine disk area (they are equal in this case) is 0.593.

Hsu (1981) first tested a TTWT model with a circular tower and obtained a surprisingly low C_p (based on turbine disk area) of only 0.4 at a wind speed of 18.8 m/s. Volk (1982) also tested a model of a circular tower with 12 louvers around. Tangential velocity measurements in the tower indicated that the confined vortex rotated approximately as a solid body instead of a concentrated Rankine vortex, which had been assumed in all the previous theories. In this case, the C_p obtained should have been very low because, as realized by the author (1982), the C_p was comparable to that of a wrapped tower with no flow entering the tower through the louvers (essentially the chimney effect). However, the author reported a C_p of 2.6 at a wind speed of 5.9 m/s when the tower frontal area was used. This value had to be in error.

Hsu and Ide (1982, 1983) further tested several TTWT models of circular and spiral towers in a wind tunnel. This time they introduced radial inflow ejected from the tower inner walls near the tower ground plane. The C_p's of both models were greatly improved. The maximum C_p attained, on the basis of turbine disk area, was 3.8 for the circular model and 9.0 for the spiral model, both at a wind speed of 2.54 m/s.

Correction for C_p

Early researchers on vortex wind turbines followed the definition of C_p based on tower frontal area, as in the case of conventional wind generators, so that the C_p obtained for vortex wind turbines was only on the order of 0.10. This value was not attractive at all for any wind energy system. The correct C_p for a vortex wind turbine should be based on its turbine disk area. This is simply because the total energy flux of the wind captured for energy conversion is passing through the turbine disk area instead of through the tower frontal area. In the following discussion, C_p will be based only on turbine disk area.

The Necessity of Radial Inflow Supply

As mentioned before, Hsu (1981) and Volk (1982) have obtained surprisingly low C_p (about 0.4) for TTWT models of circular towers. Further analytical study by Rangwalla and Hsu (1982) confirmed this result under the conditions of a solid rotational vortex in the tower and a total pressure at the turbine inlet equal to the free-stream pressure.

Experiences in tornado simulation studies (Hsu et al., 1976, 1978) inspired the idea that radial inflow supply near the ground plane of the tower from the side walls is necessary to intensify the vortex from a solid rotational type to a Rankine type. Note also that the radial inflow is an inhcrent mathematical solution of the Navier-Stokes equations for the Burgers vortex.

It is understood now that simply guiding wind tangentially into a circular tower can form only a vortex of a solid rotational type. With the radial inflow supply near the ground plane of a circular tower and with the stagnation condition designed at the turbine inlet, the C_p may be greatly improved (1982, 1983). For a spiral tower, radial inflow is automatically present because of the continuously decreasing radii of the tower's curvature. The C_p's are expected to be high.

Provision for radial inflow by any possible means is the key to intensifying the vortex in the tower and thus to completing the genuine mechanism of tornado formation. The machine may now be correctly named a Tornado-Type Wind Turbine.

RESULTS AND DISCUSSION

Experimental Setup

Two plexiglas models were tested in a wind tunnel of 1.22 m × 1.22 m (4 ft × 4 ft). One tower was of circular shape with an inner diameter of 0.36 m (14 in.), an outer diameter of 0.43 m (17 in.), and a height of 0.58 m (23 in.). The other was spiral, R = exp(0.1θ), with an averaged inner diameter of 0.48 m (19 in.) and a height of 0.58 m (23 in.). The tower consists of a hollow, enclosed space between the inner and outer walls with a set of screens installed on the bottom part of the inner wall. Winds were led into this space and discharged into the tower for providing radial inflow. The turbine duct diameter was 0.1 m (4 in.) for both models.

In order to avoid blockage effect and ideal steady wind conditions experienced in the wind tunnel, we tested two TTWT models of much larger sizes in natural environments. The models were mounted on top of a 1972 Ford van, as shown in Fig. 2, driven at constant speeds on relatively calm days. A sketch of the circular TTWT model with the turbine diameter of 12 in. is shown in Fig. 1. Note that the main wind inlet was led into the circular stagnation chamber, then through a set of turbine screen disks, and further discharged into the low pressure region of the vortex core established in the tower for energy extraction. The secondary wind inlet was led directly into the tower for establishing a vortex flow in the tower. The third wind inlet entered the 6 in. wide hollow wall of the tower and exited through a set of mesh screens in order to provide radial inflow.

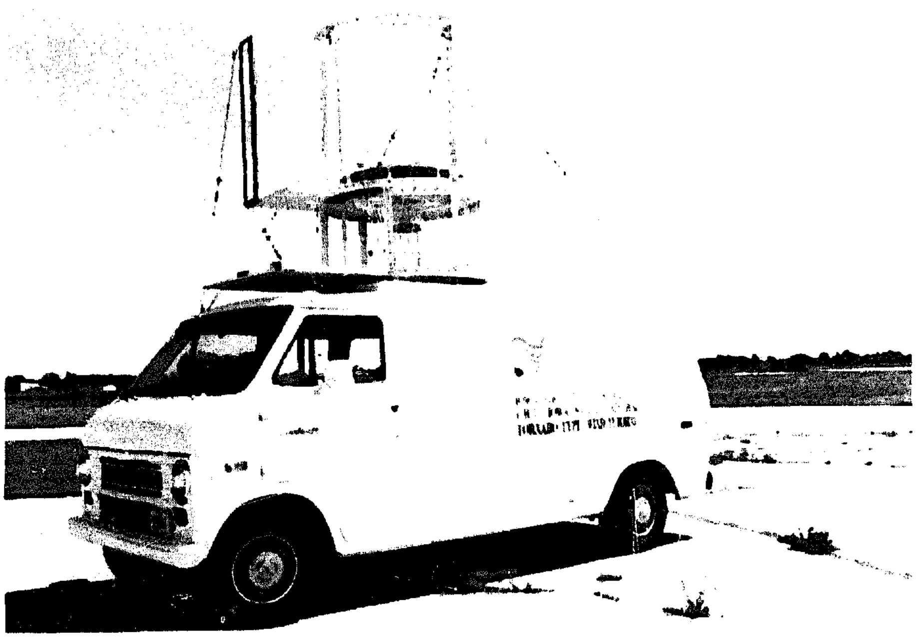

Fig. 2. The circular TTWT model mounted on a 1972 Ford van.

The spiral-shaped tower has the same outer tower radius of 0.457 m (18 in.) and same turbine diameter of 0.305 m (12 in.) as the circular one, but the inner tower radius gradually decreases to 0.229 m (9 in.), following the same spiral relation of exp (0.1θ) as the model tested in wind tunnel.

For performance tests in natural environments, the van was equipped with all instrumentation (mainly pressure transducers for measuring pitot and static pressures) together with data-acquisition systems (amplifiers, an analog-to-digital convertor, a Zenith microcomputer, and a Honda generator). Data measurements were recorded instantaneously for each wind speed by the Zenith computer. These data were further averaged for a representative wind speed.

For the measurements of C_p, the turbine load was simulated by a number of mesh screens (16×16 meshes per in.^{2}). The total pressure drop across the screens (Δp_t) was measured by two pitot probes installed below and above the screen, respectively, and $C_p \equiv wA_t\Delta p_t/q_\infty V_\infty A_t$ was directly evaluated where w denotes the averaged flow velocity measured through the turbine screens, q_∞ the dynamic pressure of measured ambient wind speed V_∞, and A_t the turbine duct area.

Wind Tunnel Results

The performance test results of TTWT models in a wind tunnel were briefly reported in Hsu and Ide (1983) and in more detail in Hsu and Ide (1982). They were not presented here except for the vortex pressure distribution on the tower floor. Figure 3 shows the static pressure drop, $(p_\infty - p)/q_\infty$, from the ambient value measured at the tower ground floor (with the turbine flow plugged) versus the radius of the tower for the spiral model at $V_\infty = 3.56$ m/s (7.96 mph) with and without radial inflow. A pressure drop $(p_\infty - p)$ of 9.1 and 10.2, respectively, times the dynamic pressure of the wind speed was produced at the vortex center without the radial inflow supply and with the radial inflow supply for the spiral model. As noted before, the spiral model is able to provide radial inflow by itself due to the decreasing radii of curvature. The increment of pressure deficit due to radial inflow supply accounts only about 12% in the present case. But for a circular model, the effect of radial inflow supply on pressure drop is much greater.

Test Results in Real Environments

The results of performance tests on the two TTWT models in real environments were reported in more detail in Hsu and Minachi (1988). Here, only a few best representative sets of data are presented.

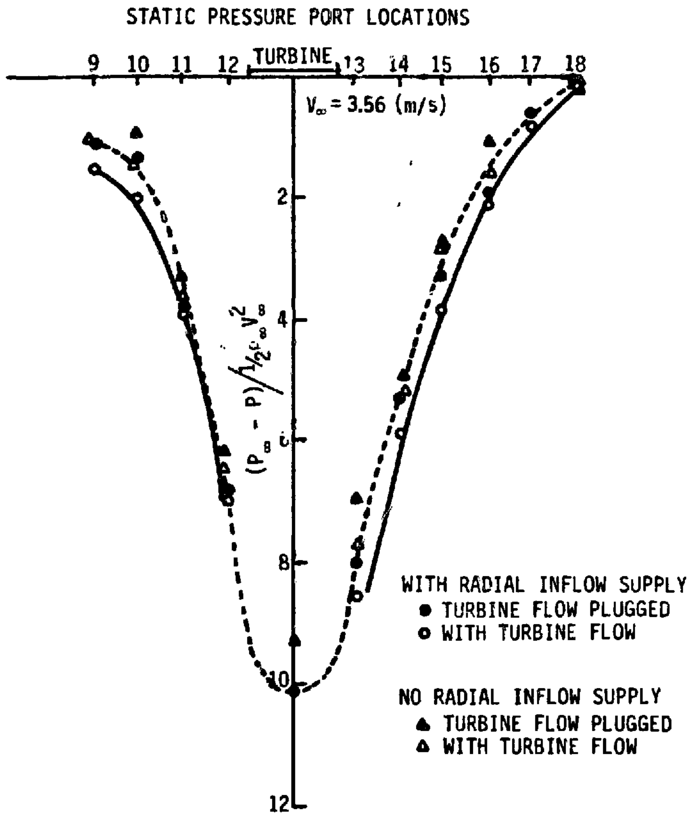

Fig. 3. Static pressure drop measured on the tower floor with and without the turbine flow plugged for the spiral TTWT model tested at a wind speed of 3.56 m/s in the wind tunnel.

The Circular Model

Figure 4 shows that the power coefficients, turbine intake velocity ratios, and total pressure drops were plotted versus wind speeds for the circular model. The averaged maximum C_p is 2.8 for the entire range of wind speeds (2 to 6 m/s or 4.47 to 13.4 mph) tested. The corresponding optimum turbine loading is five layers of mesh screen disks. The corresponding optimum number of side screens on the tower wall for providing radial inflow is four with a height of 4 in. and a circumference length of 60 in. with the same mesh screens as the turbine screens. Note that a large number of side screens was necessary to ensure a more uniform radial inflow discharging into the vortex tower.

The averaged maximum C_p of 2.8 is about 4.72 times that of the Betz limit of the conventional wind generators. This high C_p was contributed separately from the following improvements:

(1) Stagnant turbine intake condition

For a turbine intake flow of ambient pressure condition and a solid-rotating vortex in the tower, a C_p of only 0.4 can be obtained both from experiments (Hsu, 1981) and theory (Rangwalla and Hsu, 1982). Improvement of stagnant condition for the turbine intake flow

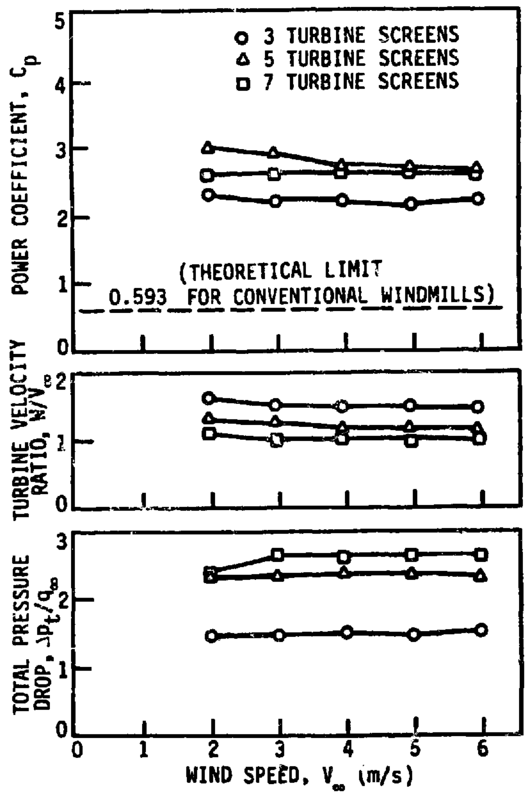

Fig. 4. Performance of the circular TTWT model tested in the real environment.

in the present case results in a gain of the wind dynamic pressure for the turbine inlet total pressure and an increase in C_p to 1.40.

(2) Venturi channel effect at the tower entrance

Because of this effect, the tangential velocity measured near the tower entrance was increased to 1.23 times the free-stream wind speed (or the ratio of the dynamic pressures was increased to 1.51). Consequently, the static pressure drop in the tower was enhanced by the same amount, which contributes directly to the increase in C_p.

(3) Vortex intensification due to supply of radial inflow

The effect on C_p due to supply of radial inflow to the vortex was measured. The averaged C_p in the range of wind speed tested was increased by a factor of 1.33.

Therefore, the total contribution of all the above improvements increases the C_p to a value of $1.4 \times 1.51 \times 1.33 = 2.81$ as shown in Fig. 4. Note that the averaged $(C_p)_{max}$ of the circular model in the range of wind speeds tested in the wind tunnel is also about 2.8 (Hsu and Ide, 1983).

Figure 5 shows the effect of radial inflow supply on the measured static pressure drop $(p_\infty - p)/q_\infty$ from the ambient value on the tower ground floor at $V_\infty = 3$ m/s (6.7 mph) for the circular model with plugged turbine flow. The static pressure drop increases from 3 to 4.23 times the wind dynamic pressure due to radial inflow supply, a gain of 41%. Also, it was estimated (Hsu and Minachi, 1988) that the maximum tangential velocity of the vortex was intensified by 29%

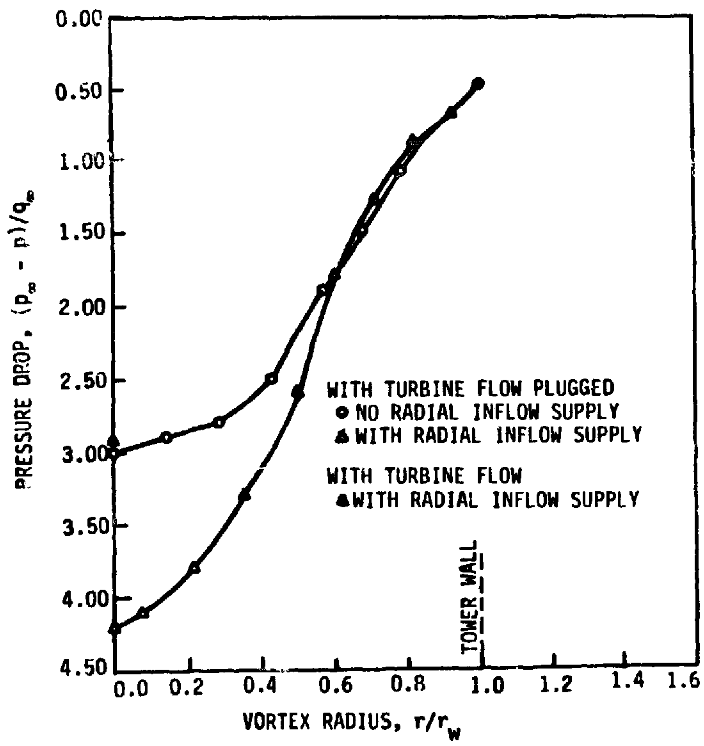

Fig. 5. Effect of radial inflow supply on pressure drop on the tower floor with plugged turbine flow for the circular TTWT model tested at 3 m/s wind speed in real environment.

because of the radial inflow supply, if a Rankine vortex was assumed, and by 16%, if a Burgers vortex was assumed. The location of the maximum tangential velocity was at 76% of the tower radius for the Rankine vortex and 72% for the Burgers vortex.

The feasibility of operation with burning solid waste was simulated with a limited amount of heat (400 W) supplied to a heating coil located on the tower floor. The averaged C_p was increased by at least 20% for the range of wind speed tested, and it mainly resulted from the increase in turbine intake velocity.

The Spiral Model

Because self-induced radial inflow is produced by the continuously decreasing radii of the spiral model's wall curvature, the C_p of this model showed better results with no radial inflow supply. One representative result is shown in Fig. 6 in which the power coefficients, turbine intake velocities, and total pressure drops were plotted versus wind speeds. The averaged maximum C_p is 4.0 for the range of wind speeds (2 to 6 m/s, or 4.47 to 13.4 mph) tested, which corresponds to 3 layers of turbine screen disks. However, while the C_p attained a maximum value of 6 at a low wind speed of 2 m/s (4.47 mph), it decreased sharply as wind speed was increased. This

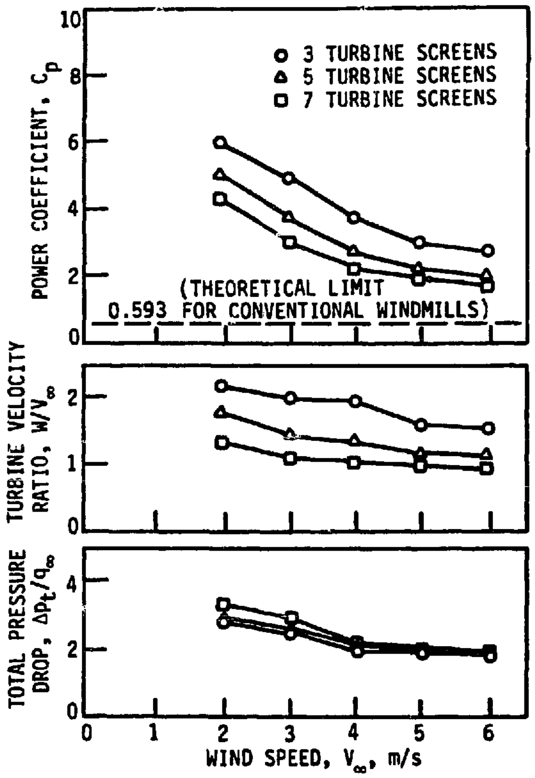

Fig. 6. Performance of the spiral TTWT model tested in the real environment.

decrease is probably due to some effect of pressurized* flow in the relatively small volume of the spiral tower. The volume of the spiral tower was reduced to only 50% of that of the circular tower because both towers had to fit onto the same existing stagnation chamber.

Note that the present C_p is much lower than that of the spiral model tested in the wind tunnel (C_p = 9) because of the different geometry of the two models. The model tested in the wind tunnel has a mean diameter of 0.48 m (19 in.) with a turbine diameter of 0.1 m (4 in.) while the present model has a mean diameter of 0.69 m (27 in.) but with a much larger turbine diameter of 0.3 m (12 in.), or a tower-to-turbine diameter ratio of 4.75 to 2.25 for the two models. A turbine with a larger tower-to-turbine diameter ratio should have a higher C_p because a relatively small turbine area occupies most of the low pressure region of the vortex core.

CONCLUDING REMARKS

The performance tests of the TTWT models in a wind tunnel and real environments have shown that the power coefficients of this

*Note that reversed turbine flow was observed when high speed wind entered a small TTWT tower of any shape.

vortex-augmented wind machine can be greater than one, ranging from 4.7 to 15.2 times the Betz limit of the conventional wind generators. This indicates that the TTWT machine is not only able to extract the total kinetic energy but also a portion of pressure (or internal) energy of the captured wind because a very low energy state can be maintained at the vortex core for efficiently pumping the turbine's discharging flow.

The power coefficients of TTWT machine can be further improved if the vortex can be further intensified and the geometrical configurations of the wind machine are optimally designed. Intensification of the vortex relies on more enhanced radial inflow supply. Optimal geometrical design includes a proper choice of the tower-turbine diameter ratio and of the size of the vortex tower in relation to the wind condition, more efficient design of the wind entrance region to the tower and of the diffuser section between the turbine and the tower, and increase in the size of the stagnation chamber.

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