ERDA Report

TORNADO-TYPE WIND ENERGY SYSTEM

SEMIANNUAL STATUS REPORT

by

James T. Yen

Research Department
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Bethpage, New York 11714

September 1977

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Division of Solar Energy

Approved by: Richard A. Scheuing
Director of Research

NOTICE

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EXECUTIVE SUMMARY

The Tornado-Type Wind Energy System is one of several advanced and innovative concepts being investigated under ERDA's Wind Energy Program as potential ways to reduce the cost and broaden the usability of wind energy. This system (see Figure 1) uses a large hollow tower to form an internal vortex, and the low pressure at the core of the tower provides an effective and low pressure exhaust reservoir for the turbine, which accepts a separate ram air inlet supply. The tower serves as a stationary and omnidirectional collector and concentrator capable of collecting immense amounts of wind energy and concentrating the collected energy into a high power density turbine. This system provides the unique advantages of a small, compact, vertical-axis, enclosed, and high efficiency turbine as well as a stationary, omnidirectional, and modularized tower. The components of the modularized tower can be mass produced on assembly lines, subassembled in the factory, and stacked up in the field thus providing for low-cost manufacturing, construction, and maintenance. These advantages also provide for fast delivery and an early return on investment. This wind energy system promises a structurally rugged and stable design for both on-land and offshore installations. Based on this design, large and low-cost multi-megawatt wind energy systems may be developed and constructed for the utilities, and small and economically competitive systems may be provided for individual farms and homes. We hope that this system will enable us to bring out fully the immense potential of wind energy.

This report summarizes work through the first seven months of Contract E (49-18)-2555. Analytical investigations of several very challenging fluid mechanical problems are being carried out. It will be some time, however, before all of the flow processes involved

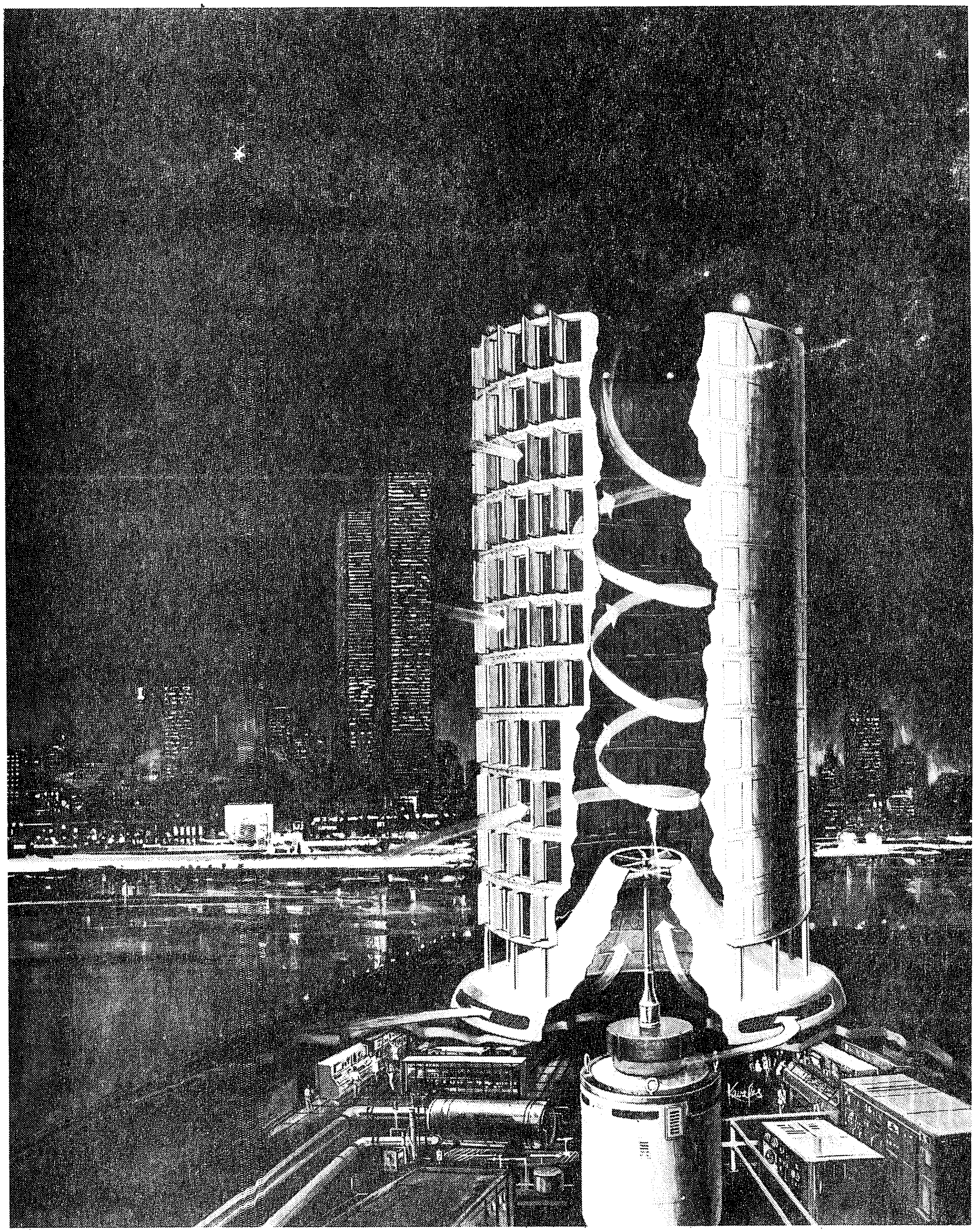

Fig. 1 Artist's Conception of a Large Tornado-Type Wind Energy System

will be known well enough to yield highly accurate analytical predictions of performance and to greatly improve our existing scaling laws. A variety of wind tunnel models have been designed and built and some testing at a small scale has been conducted using screens to simulate the turbines.

Although this investigation is still in its early stages, the prospect for the Tornado-Type Wind Energy System looks encouraging. Highlights and key issues are as follows:

- Detailed pressure surveys on the tower bottom wall with various screen-simulated turbines and small towers indicate that overall, the vortex is strengthened by the presence of the turbine as compared with the case when the tower has a solid bottom.
- Optimal turbine disk loading coefficients for maximum values of the power coefficient in small units tested are found to be between 2 and 5; it increases when the turbine size is reduced relative to the tower size.
- For these small screen-simulated turbines, the measured power coefficient based on the tower frontal area has reached a value of 0.064, as compared with 0.020 in our earlier results (refer to Ref. 2 in this report).
- Two independent simple flow field analyses (refer to Refs. 5 and 6) yield the same value of 1.54 for the theoretical maximum power coefficient based on the tower cross sectional area and 24.1 based on the turbine disk area when the turbine diameter is one-fourth of the tower diameter; these give us another indication that a very large

augmentation may be achieved with a sufficiently large vortex tower.

- A simple turbulence model including the stabilizing effects of the streamline curvature indicated that the vortex core diameter would decrease when the tower Reynolds number (based on the wind speed and tower diameter) is increased. As a direct result, the core pressure would be reduced and the vortex effect enhanced with increasing Reynolds number. One reason is that the inner core structure tends to remain laminar due to the stabilizing effects of the streamline curvature. Because of this effect, the predicted improvement in system performance with increasing Reynolds number is much stronger than previously expected, and is predicated on a more rational basis.

- Theoretical and experimental evidence indicate that turbines having exit swirls that are reinforcing to the vortex core have a highly beneficial effect on the overall system performance relative to screen exits.

- Beneficial effects of large size are expected in two areas; the vortex should strengthen because the core radius will grow more slowly than the tower radius as discussed previously, and the high velocity near the core causes a reduction in centerline density which in turn adds a bouyancy effect to the vortex pumping action. As a chimney, this latter effect increases with tower height.

1. INTRODUCTION

We have carried out investigations on the Tornado-Type Wind Energy System (see Figure 1) during the past seven months. Below we present a brief general description of this system, then a discussion of our analytical program in Section 3, and a technical report on our progress in Section 4.

As is well known, there are several major difficulties that have to be overcome by an innovative wind energy concept in order to develop a low-cost, rugged, and practical wind energy power plant capable of producing large amounts of power, e.g., 10 to 100 MW. The principal difficulty is caused by the basic fact that the energy density of wind is very low. With a usual system efficiency or a power coefficient of 30%, a collecting surface of around 200 m (600 ft) in diameter is needed for a wind energy power plant to collect sufficient amounts of wind energy for producing 10 MW with a 30 mph wind speed. This diameter is increased to around 600 m (1800 ft) if the wind energy power plant is to produce 100 MW. If the collecting surface is comprised of rotating blades as in the case of the conventional propeller- or Darrieus-type wind turbines, then the long rotating blades will encounter large dynamic stresses and require increasing stiffness/weight requirements to maintain dynamic stability. This adverse situation is accentuated since wind speed fluctuates with time, varies with altitude, and generally is turbulent in nature, and the magnitude of these variations increases with rotor size. For the propeller-type wind turbine, the blades are mounted on a horizontal shaft atop a vertical supporting tower. Dynamically, these blades interact strongly with both the earth's gravity field and the wake of the supporting tower as they move up and down in a vertical plane. It is a currently controversial point, but we believe with many others that around 60 m (200 ft) is roughly the practical upper limit for the blade diameter of such wind turbines before the costs of manufacturing and maintenance of the blades and the turbine escalate to unacceptably high levels. However, wind turbines with such a blade size (60 m or 200 ft) generate only around 1 MW with a 14 m/s wind. Hence, it is extremely difficult and expensive to make and install blades with large diameters of 200 m (600 ft) or beyond in order to generate 10 to 100 MW or more with a 14 m/s wind. As a result, we expect the unit-capacity of the conventional wind turbines will be limited by dynamic effects to around 1 MW; in contrast, the unit-capacity of fossil or nuclear fueled power plants can reach over 1000 MW.

To overcome this limitation, we first observe that the blades of the conventional wind turbines, either the propeller or the Darrieus types, serve two functions: as collectors for collecting wind energy and as converters for converting the collected wind energy into mechanical and electrical energy. The fact that they need and use a very large rotating collector is evidently a major cause for their severe dynamic stresses which impose an upper limit on their unit-capacity.

2. SYSTEM DESCRIPTION

In our Tornado-Type Wind Energy System, we will use a stationary collector for collecting immense amounts of wind energy, and then concentrate and convert the collected wind energy into mechanical energy using a compact vertical-axis turbine which is located near the ground. Details of this system have been discussed in Refs. 1 and 2.

Briefly, as seen in Figure 1, wind energy is collected by a stationary and omnidirectional collector comprised of a stationary tower fitted along its periphery with adjustable vanes which will be opened on the windward side and closed in the leeward side. Incoming wind will be guided by the vanes into forming a vortex within the tower. The low-pressure core of the vortex is situated directly above the vertical axis turbine so as to reduce the back pressure of the turbine. The underside of the turbine is connected to the ambient atmosphere through an omnidirectional bottom inlet. A well designed bottom inlet may raise the pressure within the bottom inlet to the ambient stagnation pressure, higher than the ambient atmospheric pressure.

It is well known that the core of a strong vortex can have a very low pressure. Hence, the vortex and the bottom inlet can maintain a very large pressure difference across the turbine. For example, for a 14 m/s (30 mph) wind the dynamic pressure $q_\infty = 1/2\ \rho\ V_\infty^2$ of the wind amounts to only 1/930 of the standard atmospheric pressure. Hence, if the vortex core pressure is at 5% below the atmospheric then a pressure difference of more than 45 q_∞ can be maintained across the turbine. In contrast, less than one q_∞ can be maintained by the wind across a conventional propeller-type wind turbine. Hence, a Tornado-Type Wind Energy System can produce a much larger pressure difference across, and a much higher power density from the turbine.

The increase in power density is usually expressed in terms of an augmentation factor which gives the ratio of the power output from a turbine and generator with the augmenting device such as our vortex tower, as compared with the power output from a same-sized turbine operating as a bare propeller-type horizontal-axis turbine under the same wind speed. The scaling laws worked out in Refs. 1 and 2 give an augmentation factor of 100 to 1000 for full-scale power plants while tests with a small and crude turbine at low wind speeds have given us an augmentation factor of around

10 based on the electrical power output. A major task ahead is to determine and maximize the augmentation factor achievable with different sizes of models and power plants.

There are many other practical issues that have to be resolved in order to produce a low-cost, rugged, practical and large unit-capacity wind energy power plant. Some of the augments indicating how and why we may resolve many of these issues with the Tornado-Type Wind Energy System have been discussed previously (Refs. 1 and 2). An updating and summarizing of these augments is presented in the Appendix.

3. PROGRESS TO DATE - EXPERIMENTAL INVESTIGATIONS

Detailed static pressure measurements on the tower bottom wall have been made in a small (0.61x0.92 m) wind tunnel at a wind speed of 5.7 m/s. The spiral cross-section tower has a height of 35 cm and an inner diameter of 13 cm. It employs a bell-mouthed pipe with screens to serve as a simulated turbine. For a 5.08 cm diameter pipe (tower diameter/turbine diameter = 2.5) the power coefficient based on the tower frontal area reaches a peak value of 0.053 at a turbine disk loading coefficient of 1.8; this translates to a peak value of 1.19 for the power coefficient based on the turbine disk area. For a 3.81 cm diameter pipe (tower diameter/turbine diameter = 3.3), a peak power coefficient of 0.064, also based on the tower frontal area, has been reached at a turbine disk loading coefficient of 4.0; this translates to a peak value of 2.50 for the power coefficient based on the turbine disk area. These results are shown in Figure 2; they represent a significant improvement when compared with the peak value of 0.020 obtained for the power coefficient reported previously in Ref. 2. These efforts will be continued using the larger 1.2x1.8 m wind tunnel which

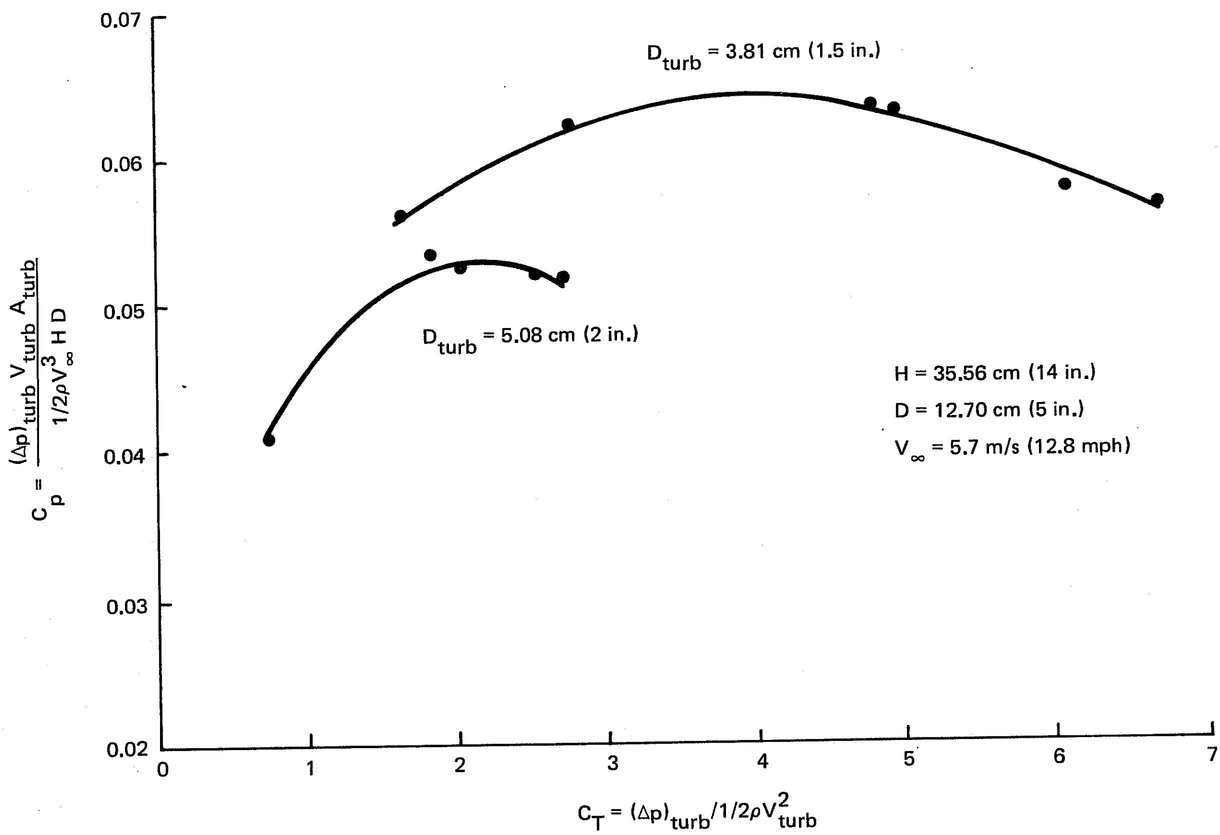

Fig. 2 Power Coefficient Based on Tower Frontal Area Versus Turbine Disk Loading Coefficient

makes it possible to use a higher and larger tower and to operate the tower in a vertical position so as to be able to continuously adjust the tower for centering with respect to the vortex.

Static pressure measurements with the simulated turbines have been compared with the corresponding measurements when the bottom of the tower is closed with a solid plug, as shown in Figures 3 through 7. It is found that in one of the quadrants around the turbine, the static pressure is reduced by as much as 50% while in the opposite quadrant the static pressure is raised up to 15% when the solid plug is replaced by the simulated turbine while the static pressure in the other two quadrants remains almost unchanged. Since a reduction in the static pressure implies a strengthening of the vortex (and vice versa), the overall effect is that the vortex is apparently strengthened by the simulated turbine. This surprising result may be explained through the following observations: First, the floor area occupied by the solid plug interacts through viscous effects with the vortex core and therefore represents a frictional loading on the vortex. When the solid plug is replaced with a simulated

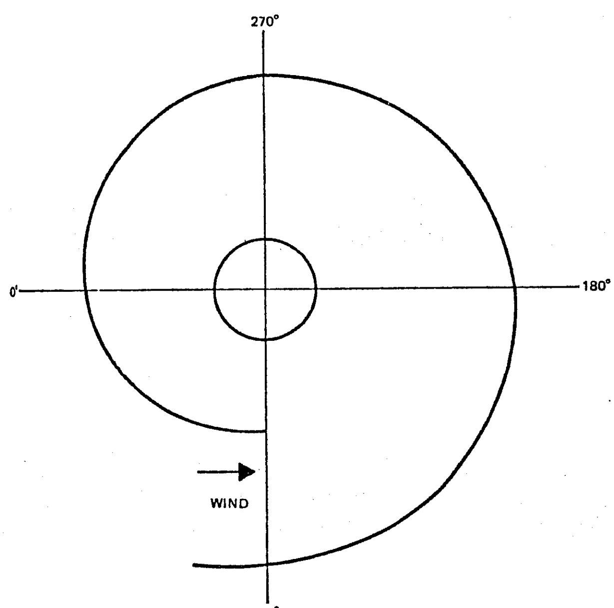

Fig. 3 Defining the Coordinate System for the Tower Bottom Wall

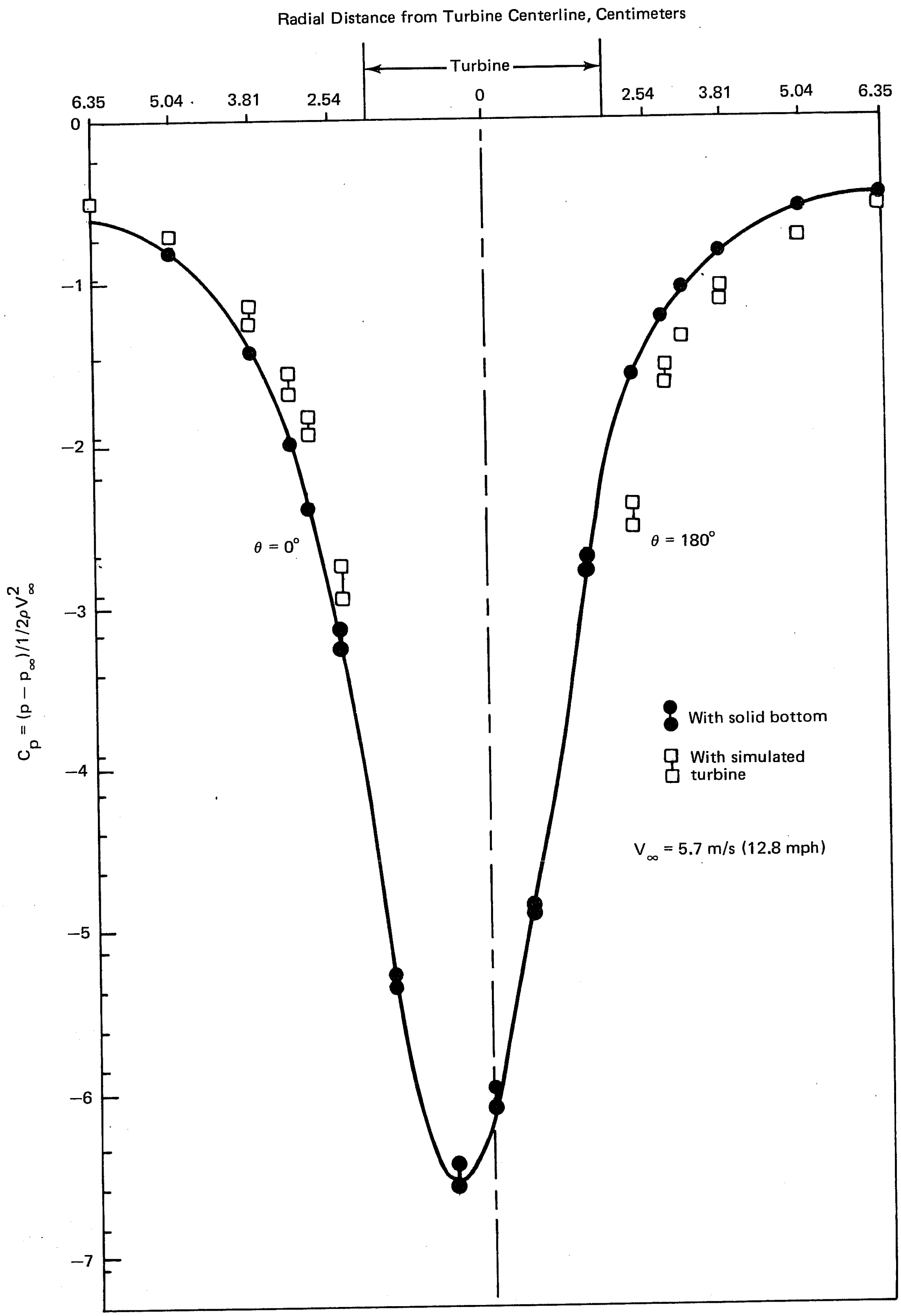

Fig. 4 Pressure Measurements on the Tower Bottom Wall With a Solid Plug or a 3.81 cm -diameter Screen-simulated Turbine (C_T = 4.77). Measurements are made along $\theta = 0^\circ$ and 180° as defined in Fig. 3.

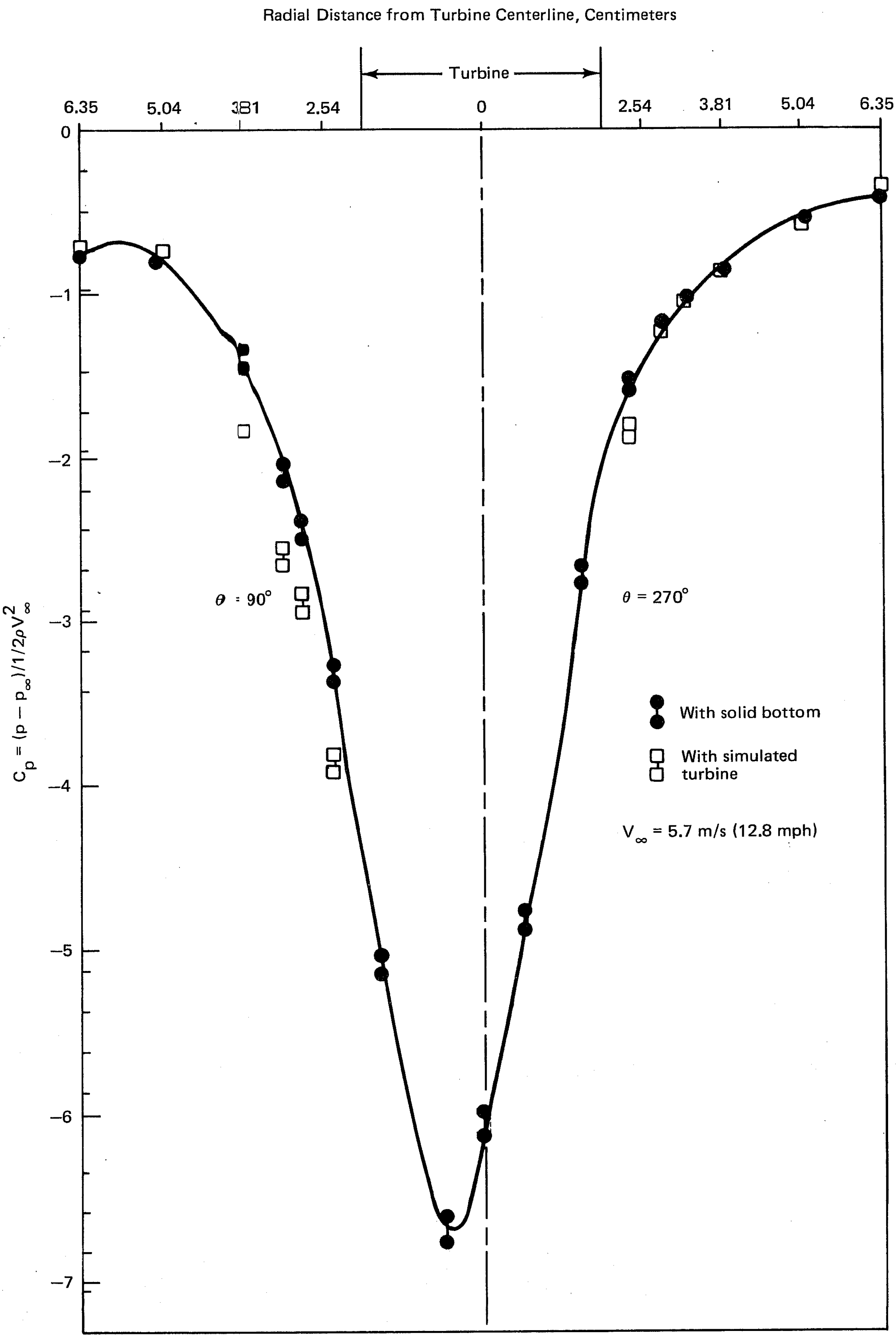

Fig. 5 Same as Fig. 4, except θ = 90° and 270°.

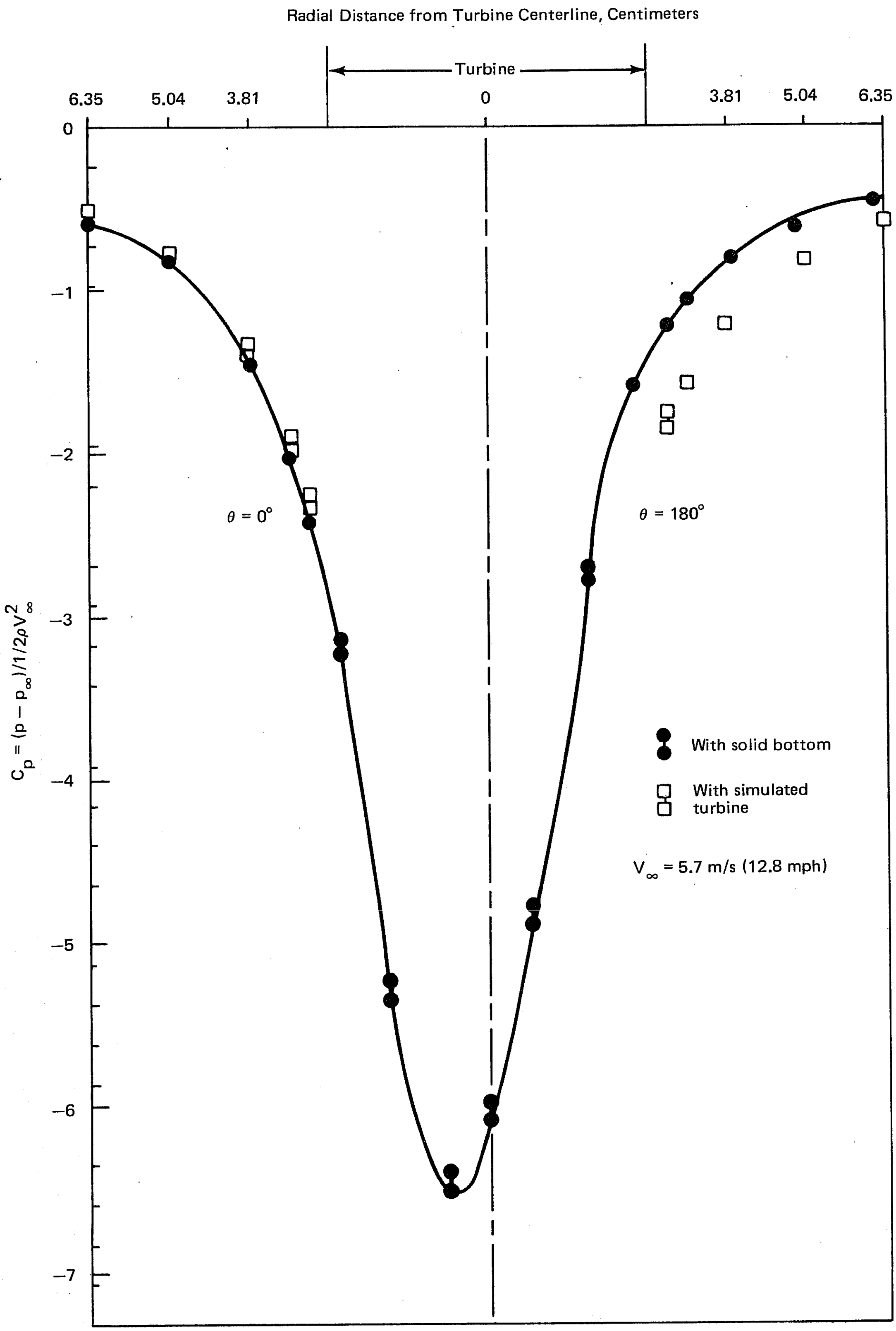

Fig. 6 Pressure Measurements on the Tower Bottom Wall With a Solid Plug or a 5.08 cm -diameter Screen-simulated Turbine (C_T = 1.78). Measurements are made along θ = 0° and 180° as defined in Fig. 3.

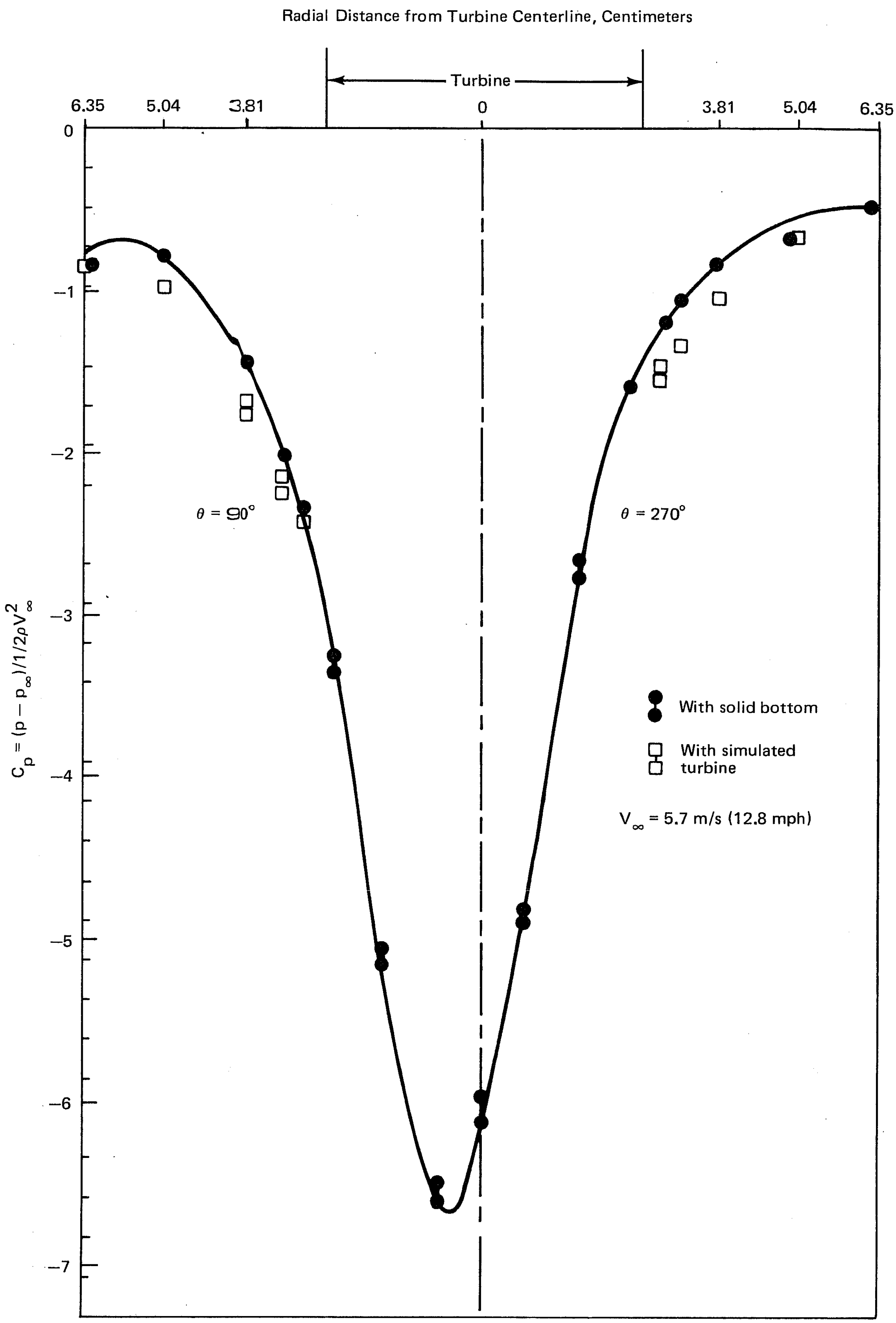

Fig. 7 Same as Fig. 6, except $\theta = 90^\circ$ and 270°.

turbine, this loading is removed. Second, the simulated turbine connects the vortex core with the ambient atmosphere which, in spite of the drop across the turbine, still injects air with a higher total pressure (i.e., a higher total enthalpy) than the vortex core. The turbine flow may therefore exert a favorable influence on the vortex core. Next, it is well known that a vortex is strengthened by enhancing the axial flow in its core, if the added axial flow is in the forward direction, i.e., in the same direction as the axial flow in the outer portion of the vortex. The turbine flow from the simulated turbine exhausts into the vortex core and pushes the vortex core in the proper forward direction and thereby tends to strengthen the vortex. These, and perhaps other effects we have not discovered, lead to the observed result that the vortex is strengthened by the simulated turbine as compared with the case with a solid-bottom tower, at least for some amounts of turbine flow. These effects are separate from any constructive effects of turbine exit swirl on reinforcing core flow.

The simulated turbine does not induce any swirling motion in its exhaust. The effect of this on the vortex cannot be ascertained with the present setup. By flow visualization, it is observed that the vortex extends into the simulated turbine and causes a swirling motion therein. This produces complicated interactions with significant pressure losses within the turbine exit. Due to the three-dimensional and fluctuating nature of the flow within the turbine exit, efforts to measure local static and total pressures have not yet given us meaningful results.

A major effort, which is outside the scope of the ERDA contract, involved the design, construction, and reduction of the fluctuations of the flow velocities in a new 1.2x1.8 m wind tunnel. Since the size of the laboratory is not sufficient to settle down and smoothen the exhaust from the wind tunnel to sufficiently low levels of fluctuations before it re-enters into the tunnel, large fluctuations were initially measured in the tunnel at an intensity of ± 13% about the mean speed with a 10 second averaging time. Following the advice of our consultant, Professor Mellor, vertical panels with adjustable flow passages were installed at the exhaust end of the tunnel to split the original "wall jet" produced by the tunnel exhaust into several nearly equal strength wall jets and thereby significantly reduce the peak velocities and energies of these jets. A smaller laboratory space is then capable of settling down these tunnel exhausts. These efforts, together with the installation of honeycomb sections at the entrance and exit ends of the tunnel, have reduced the fluctuations within the test section to an intensity of less than ± 2% about the local mean speed with a 10 s averaging time. Also, a spatial nonuniformity of ± 7% about the mean speed over the tunnel cross-section based on the same 10 s averaging time has been achieved as shown in Figure 8, although the mean speed has been reduced to 7.9 m/s from the previous 10.7 m/s.

However, as seen from Figure 8, the nonuniformity in the tunnel wind speed V is most pronounced in the lower portion of the tunnel where the test models will be located. Also, the measured power coefficients are made dimensionless based on a reference tunnel wind energy density $\frac{1}{2}\rho V^3$, and therefore a ± 7% nonuniformity in V would lead to an unacceptably large uncertainty in the power coefficient. For these reasons, an additional effort is being made aimed at a significant further reduction of the nonuniformity particularly within the lower portion of the wind tunnel.

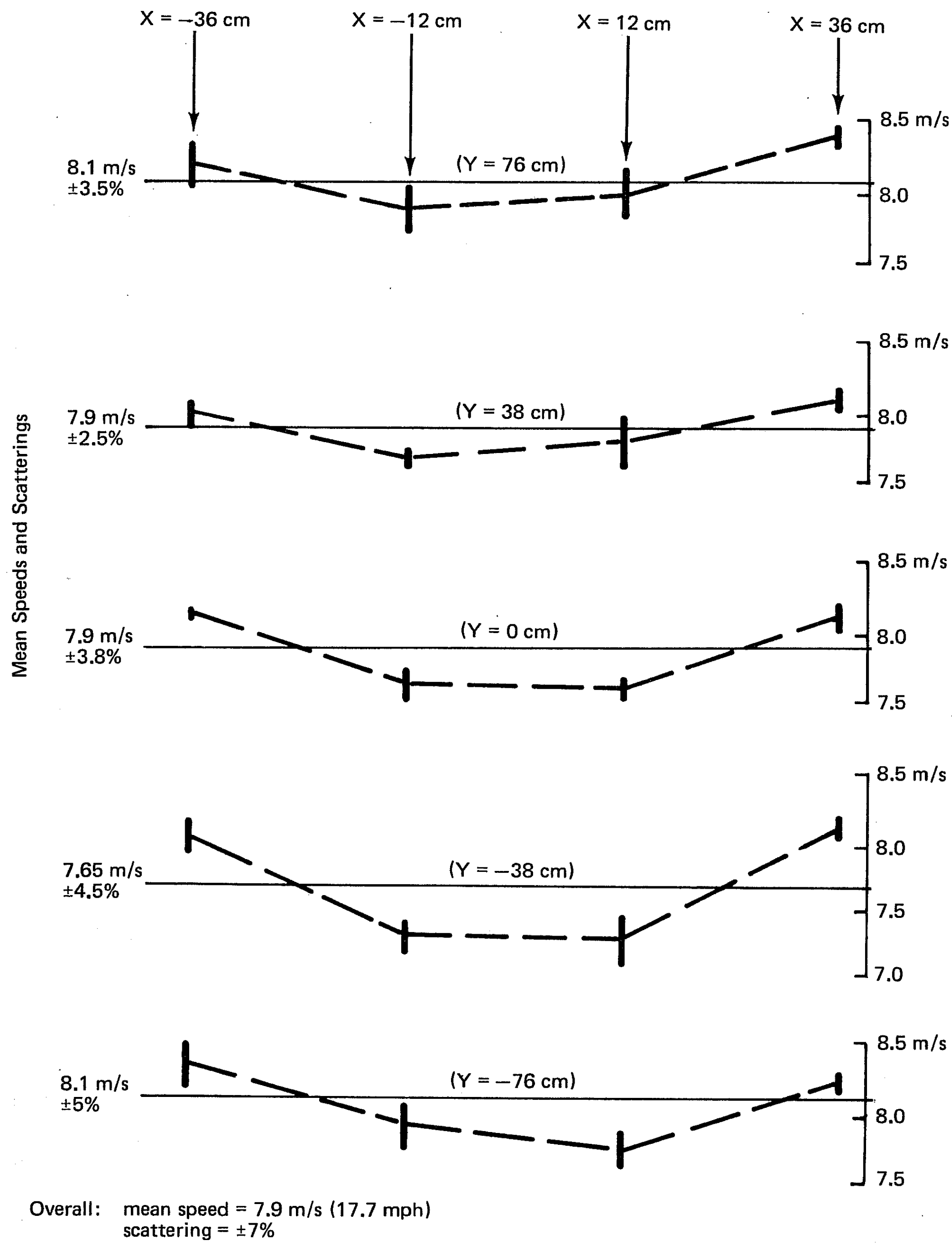

Fig. 8 Survey of Wind Speed Over a Cross Section for the 1.2 x 1.8 m Wind Tunnel; Averaging Time Constant = 10 seconds; X, Y Denote Locations of Individual Probes

Working turbines of 5.08 and 10.16 cm diameters have been designed and made with disk loading coefficients of 1.5, 2, 3, and 5 and with stator and rotor stages. Due to the small size of these turbines, it is not feasible to carry out detailed aerodynamic designs of the turbine blades since the chord Reynolds number of these blades ranges only around 10^4 while the existing aerodynamic data on lift and drag coefficients of aerofoil sections are valid only for Reynolds number of around 10^6 or larger. Improvements on our blade designs will be made after we test them in the 1.2 x 1.8 m tunnel.

Spiral cross-section towers of 35, 46, and 56 cm heights and of 53, 76, 91, and 107 cm heights have been made, respectively, for the towers of 13 and 26 cm inner diameter. A multivaned model of an 46 cm height tower has been constructed and will soon be tested in the 1.2 x 1.8 m tunnel. Experience gained from this testing will enable us to improve the existing design of a 91 cm height tower and to construct and test that tower in the 1.2 x 1.8 m tunnel.

4. PROGRESS TO DATE - ANALYTICAL INVESTIGATIONS

In this section, a brief discussion defines the basic problems confronting us in our analytical effort, followed by a presentation of the results obtained so far in our analytical investigations, and a summary of results obtained by the analyses of other investigators. Some progress made in our cost analysis is also presented.

It has become apparent that there are at least four major unresolved flow problems that must be understood in order to predict the output of a Tornado-Type Wind Energy System. These are:

a. Action of the tower surfaces to form the tower vortex

b. Effect of tower scale on the usable vortex pressure reduction

c. Processes in the wake by which the exhaust plume pressure rises from tower exit pressure to atmospheric far downstream

d. The way the vortex terminates on the tower floor to accommodate the turbine exhaust.

In addition to these key unsolved problems, there are many other problems of secondary effect that must be solved, such as the effect of tower side wall and floor friction, and the beneficial effect of core compressibility to produce a significant buoyancy effect for large towers. Despite a very large amount of definitive advice from a wide variety of sources, it is not clear to us how any of the aforementioned problems can be avoided if performance calculations are to be made. Unfortunately, neither is it yet clear how any of those same problems can be solved. Most of the analytical work performed on the project thus far has been on problem "d" above — the termination of the vortex around the turbine exhaust. Below is a brief discussion of each of these problems, and our current thoughts on their resolution.

FORMATION OF TOWER VORTEX

Many experienced aerodynamicists have challenged this concept on the grounds that Kelvin's theorem prohibits a core vorticity being formed from an irrotational free wind. Aside from the mundane argument that pressure, velocity, and visualizations all show a strong central vortex with a wide range of tower geometries, the answer lies in the bound circulation of the tower surfaces. Whether a continuous spiral wall or a cascade of inlet vanes, the tower surfaces must be subjected to lift forces in order to form the inlet flow into a vortex. If viewed in a horizontal cross section, the circulation around the wall surfaces must in the aggregate be equal and opposite to the circulation around the vortex core region, with proper allowance for the convection of core vorticity in the axial direction. When viewed as a complete three-dimensional lifting surface, the plume vortex is easily seen as the tip vortex that any finite span straight wing would produce. In this case the goal is to create a lifting surface that sheds all of its trailing vorticity at the tip.

The above analogies to conventional wing processes suggest that at least some understanding of the tower vortex formation could be gained by thin airfoil methods (i.e., methods using distributed singularities that are constrained by the requirement that the resultant flow must be paralled to surfaces). We have given thought to such approaches, but have not yet been able to pose a calculable model that contains the essential physics.

SCALE EFFECTS ON VORTEX STRENGTH

Problem "a" will determine the circulation on a vortex given the free wind velocity, tower geometry, and pressure distribution imposed at the top by the mechanics of the wake flow. An ideal potential vortex structure will always have a singularity at its center that is resolved by the turbulent shear stresses near the core in large vortex flows. Although one could expect the physical size of the turbulent core region to increase more slowly than tower diameter (Reynolds number) for constant wind velocity, this contention has proven quite controversial. If core radius were to remain completely constant (the ultimate in optimistic projection) the peak pressure reduction of the vortex would rise with Re^2. No such good fortune is expected, if only because the turbine exhaust streamtubes must be accommodated at the core; but it does seem reasonable to expect significant improvement in vortex augmentation with increasing Re. The only methods we know of to resolve this question are the testing of larger towers (we expect to do this later in the program), and large scale computation of vortex core turbulence structures using state-of-the-art models of turbulence, including the stabilization effects of the streamline curvature.

WAKE RECOVERY TO ATMOSPHERIC PRESSURE

The pressure distribution at the tower exit plane will obey the same radial characteristics as that inside the tower, but because it will be directly communicating with the incident flow, it must also match to the environment through the vortical wake structure. Empirical observation of these flows has repeatedly shown a sharp downstream curvature of a coherent vortex, followed by an apparent vortex breakdown after the vortex line has become (roughly) aligned with the wind vector, indicating that the exited vortex interacts strongly with the surrounding wind streams. Due to this interaction, a significant amount of energy is transferred from the wind to the vortex plume. No quantitative theory of this process yet exists, but to the extent that external wind kinetic energy can couple to the coherent structure of vortex plume to restore required total pressure to the wake core, it becomes possible for the exit plane total pressure level to be maintained well below atmospheric pressure. This means that there exists at least the possibility of harnessing wind streams about which no costly structure must be built.

TURBINE/TOWER INTERACTION

The details of the flow field surrounding the turbine exhaust at the bottom of the tower are very complex. At first it might seem possible to ignore this process to concentrate on the apparently more pressing questions laid out above; but this flow region apparently plays a very significant, and mysterious role in inducing tower axial flow. The following observations illustrate the point.

We have built two small demonstration units for illustrating the principles of the Tornado-Type Wind Energy System. They are alike in every important respect except size. A notable feature of both is that for convenience both fans used to supply simulated wind are shorter in height than the respective towers they are used with, so the top 25% or so of the tower stands above the boundary of the jet formed by the fam. One observer casually questioned us as to why the turbine so clearly exhausts into the tower, when the tower wake energizing process is clearly not available in this demonstration such that the total pressure inside the tower may become higher than that at the turbine inlet. It turned out to be a very good question, and to date the only answer we can find lies in the interaction between the turbine exhaust and the radial inflow in the tower floor boundary layer. It is not yet clear how this pumping effect takes place, but the simple fact that it does makes it a central part of the overall Tornado Wind Turbine process. Accordingly, most of the theoretical work on the project thus far has been devoted to the study of this flow process.

Analyses of the detailed flow fields at and near the bottom of the tower and around the turbine have been carried out. Even assuming a laminar viscosity, the three-dimensional flow fields are found to be highly complicated and the effort involves the solution of coupled partial differential equations. A rough laminar solution has been given by So (Ref. 3). He superimposes an inverted stagnation-point flow with the vortex and turbine flow. His numerical results on power coefficients agree remarkable well with our previous results as reported in our 1975 IECEC paper (Ref. 1). However, his flow velocity profiles do not change in shape in the axial direction. His solution may serve as a foundation for our effort. We divide the flow field into two regions: one situated around the turbine and above the bottom walls of the tower, and the other situated above the turbine itself. For the first or outer region, Weber (Ref. 4) has solved the flow using a momentum-integral approach. His solution is being matched to a solution which we have obtained for the inner region above the turbine using a singular-perturbation technique and by utilizing So's solution as a first iteration. Our consultant, Professor George Mellor, has given us another independent rough analysis of the system as a whole. He has obtained a power coefficient of 1.54 based on the tower cross-sectional area or 24.1 based on the turbine disk area when the turbine diameter is one-fourth the tower diameter; these give us another indication that a very large augmentation may be achieved with a sufficiently large vortex tower. The same results have been obtained by Hsu (Ref. 5) through an independent and different approach.

The analytical program has recently benefited from some new information, again supplied by Mellor. In this case, the issue is a simplified model for the structure of the turbulent shear flow near the center of the vortex. Strong streamline curvature can have very powerful damping effects on turbulence, and this effect has an important effect on vortex structure and scaling with increasing Reynolds number. Mellor (Ref. 6) has published a simplified turbulence model for use in situations for which streamline curvature is dominant. The model, which is supported by measurements reported by So and Mellor (Ref. 7), indicates that Reynolds stress is extinguished by curvature effects throughout most of the vortex core. Only in the outer part of the viscous core, just before the potential vortex structure prevails, is there a significant contribution to the total viscosity from turbulence. Since the model, though approximate, is fully closed, we can put it to work in various attempts to solve the vortex equations of motion so that we can predict both the effects of scale and the change of core radius along the tower. The former is vital to predicting improvement in performance with increase in size and the latter is important to choosing tower shapes and understanding tower processes. Results from this effort so far indicate that when the tower Reynolds number (based on the wind speed and tower diameter) is increased, the vortex core diameter would decrease, resulting in a reduction in the core pressure and a strengthening of the vortex. One reason is that the inner core structure tends to remain laminar due to the stabilizing effects of the streamline curvature. Because of this effect, the predicted improvement with increasing Reynolds number is much stronger than previously expected, and is predicated on a more rational basis.

Very little work has been done to date on cost projection. We have reexamined cost estimates made in 1975, but without a better picture of the aerodynamic performance it will be very difficult to project meaningful cost estimates for large machines. Some investigation of scaling laws for large static structures (without roof spans, which are very expensive) is needed. Presently, our best information on this subject indicates that cost varies with size for geometrically similar structures according to the following law

$$C = C_1 \, (D/D_1)^{\alpha}$$

where D is the characteristic linear dimension of the structure that costs C, D_1 and C_1 are the corresponding parameters of a known point design, and α varies in the range $1.5 < \alpha < 2.3$. This follows from a well-established empirical law that cost varies with the 0.77 power of weight for fixed designs. We expect that α will be in the lower range for the open-topped towers of interest, because historically the pacing technology in architecture of large structures has been the spanning of large areas with roof structures. We have bounded α by the two extreme variational possibilities: a) wall weight per unit area does not increase with size of structure ($\alpha = 1.54$), and b) wall weight is proportional to the characteristic size of the structure ($\alpha = 2.31$).

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APPENDIX

DISCUSSION ON SYSTEM ECONOMICS

There are many practical issues that have to be resolved in order to produce a low-cost, rugged, practical and large unit-capacity wind energy power plant. Major consideration here is to design a system which is low cost in materials, manufacturing, installation, and maintenance and which can stand up against occasional extreme wind speeds of severe storms. Some of the augments indicating how and why we may resolve many of these economic issues have been discussed previously (Refs. 1 and 2). Here, we update and summarize these arguments.

An inherent advantage of the Tornado-Type Wind Energy System is that it has a small, compact, enclosed and vertical-axis turbine and that its heavy components including the turbine, generator, gearbox, and flywheels are all located near the ground. Thus, these components can be installed, maintained, and replaced without the need for a large lifting crane. In contrast, a crane is always needed to install or replace the turbine, gearbox, and generator even for a small conventional propeller-type wind turbine, for example, a system which has 8-meter diameter blades for generating 15 KW with a 12 m/s wind speed. Eliminating the need for a large lifting crane means major savings in installation and maintenance, particularly for remotely located farms or households, or for people living in cities who can benefit by utilizing the strong winds atop high-rise buildings.

The fact that the new design has an enclosed turbine may also yeild important advantages since the blades will not interfere with TV signals and create ghost images on TV screens and, in contrast to exposed blades, they can greatly reduce problems with regard to accident insurance and fears of falling blades.

In terms of manufacturing and materials costs, the turbine of the new design has distinctive advantages. First, it can have rugged and fixed-pitched blades. The blades on the conventional propeller-type wind turbines have to be equipped with a variable-pitch hub so as to achieve "feathering" at extreme wind speeds due to strong gusts or storms. The main purpose is to protect the electrical generator since the power input from the wind rapidly increases as the cubic power of the wind speed. In the new design, the feathering can be done by adjusting the openings of the vanes mounted on the collecting tower. Hence, monolithic blades with fixed-pitch hubs can be employed resulting in a simple and high strength design with major cost savings.

We observe that the new design calls for a small, compact, vertical-axis, enclosed, and high-efficiency turbine located near the ground with an internal construction similar to that of a gas turbine. It will have a large, hollow, and cylindrical shaft fitted with many short and fixed-pitched blades, with at least one stator stage and a rotor stage, and capable of spinning at a higher rpm. The fact that the new design maintains a much higher pressure difference across the turbine calls for a higher turbine disk loading to be supplied by a combination of stator and rotor stages with high solidity blades. By employing a large, hollow, and cylindrical shaft and short and fixed-pitched blades, the turbine can be of both high-strength and light weight. Such a compact, rugged, and vertical-axis turbine can spin at a higher rpm close to the rotating speeds required for efficient electrical generators; thus the need for a large and expensive gearbox can be greatly reduced or eliminated. Such a turbine can also have a high tip speed ratio, and since it is enclosed within a duct, its "tip losses," which is a major loss mechanism for the conventional propeller-type turbines, can be essentially eliminated. It is well known that these turbines can be highly efficient, with a conversion efficiency of around 90% or better.

Turning now to the collecting tower, major economical gains can be achieved by a modular design. Thus, the tower is subdivided into many identical and independent layers or modules, each of which is limited to, e.g., 2 m in height. The vanes on each module will be independently controlled by small and identical motor-driven or aerodynamically powered controls under the command of a minicomputer. Thus, vanes at different altitudes can be opened at different directions and by different amounts to match with variations in the wind speed and direction with the altitude. Moreover, when wind speed exceeds a certain limit, e.g., 30 m/s, all of the vanes can be opened to relieve head-on wind pressure. Proper staggering of such vane openings can also result in damping through phase cancellation of any fluttering present due to interactions of the opened vanes with the extreme wind speeds. And by opening all the vanes, the vortex can be greatly weakened and the turbine can be shut down, so as to avoid "runaway" of the system at the extreme wind speeds. In other words, we can limit the maximum wind pressure loading that the tower structure has to sustain; and this means major savings in materials and costs. It is well known that for any large structure, the maximum wind pressure loading usually is a major factor in determining the actual material strength and thickness required to sustain the structure against the extreme wind speeds even if these winds occur only very infrequently.

The principal economic advantage of a modular designed tower should be savings in manufacturing and installation costs. Each layer or module of the tower will be composed of many identical components which can be mass produced and subassembled for easy transportation and final field assembly. For small units, the subassembled sections may be lifted by simple pulleys without the need for a large lifting crane. For large units, helicopters or blimps may be employed to transport and assemble such sections into complete power plants. Ane, when there is need for major maintenance, the modules may be "unstacked" and defective ones removed and replaced by new modules for fast and easy maintenance. Indeed, entire power plants may be disassembled and easily moved to new sites. Moreover, the components comprising the modules of each power plant are small in size and can be mass produced in large numbers and stored in warehouses for fast delivery against new orders. Thus, the modular design may greatly reduce costs in manufacturing, installation, and maintenance, and yield important savings in financial charges due to fast delivery and early return on investment.