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INVESTIGATION OF DIFFUSER-AUGMENTED WIND TURBINES
PART I

Executive Summary

R. A. Oman
K. M. Foreman
B. L. Gilbert

January 1977

Work Performed Under Contract No. EY-76-C-02-2616

Research Department
Grumman Aerospace Corporation
Bethpage, New York

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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INVESTIGATION OF DIFFUSER-AUGMENTED WIND TURBINES†
PART I — EXECUTIVE SUMMARY

by

R. A. Oman

K. M. Foreman

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Prepared for

Wind Energy Conversion Branch
Division of Solar Energy

Fluid Dynamics
Research Department
Grumman Aerospace Corporation
Bethpage, New York 11714

Approved by: Charles E Mack, Jr.
Charles E. Mack, Jr.
Director of Research

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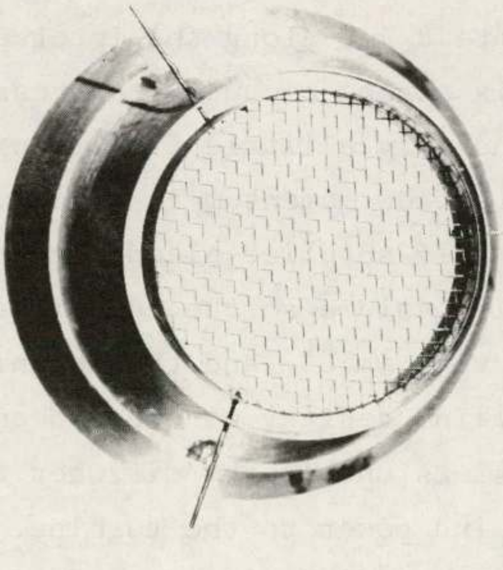
a) (left to right) 20°, 30°, and 40° half angle models each with an area ratio of 2.78



b) baseline configuration; 30° diffuser with an area ratio of 2.78 (screen installed $C_T = 0.37$)

Figure 2 Boundary Layer Controlled (BLC) Diffuser Models studied analytically the use of the interior supporting struts as guide vanes, or stators, ahead of the turbine blades, and have assessed the economic tradeoff of the DAWT against ordinary WECS.

A large number of models for diffuser designs have been tested in a small wind tunnel. Several configurations of each of two effective types of diffusers (ring wings and boundary layer controlled) have been investigated. Of these, we have chosen the most cost effective configuration as a baseline design. A wind tunnel model of our present baseline diffuser is shown in Fig. 2. In our tests, the aerodynamic effects of different turbines are simulated by interchangeable screens. The model shown is a boundary layer controlled type, conical diffuser with a 60° included cone angle and an area ratio of 2.78.

For boundary layer control we have taken advantage of a situation which is unique to the application of diffusers in wind machines, the plentiful supply of high energy air just outside the diffuser's walls. In Fig. 3 we illustrate the boundary layer control technique . Boundary layer separation is avoided by allowing external high energy air to create a jet along the internal wall heading downstream. The jet flow is strong because the pressure is subatmospheric inside the diffuser, and only a little flow is needed because the jet acts exactly where extra flow momentum is needed. In the wind turbine application, the externally supplied bleed air is only a minute fraction of the main diffuser flow volume so the additional equipment cost and performance penalty is very small, and the technique is particularly effective. In the baseline design, we use two annular slots in the diffuser wall. These slots enable the diffuser to produce almost a doubling of available wind power to the turbine. In addition to the pressure recovery inside the diffuser, the rapid flow divergence continues long after the end of the duct. Thus we get much more of an effective diffuser than we pay for in physical equipment.

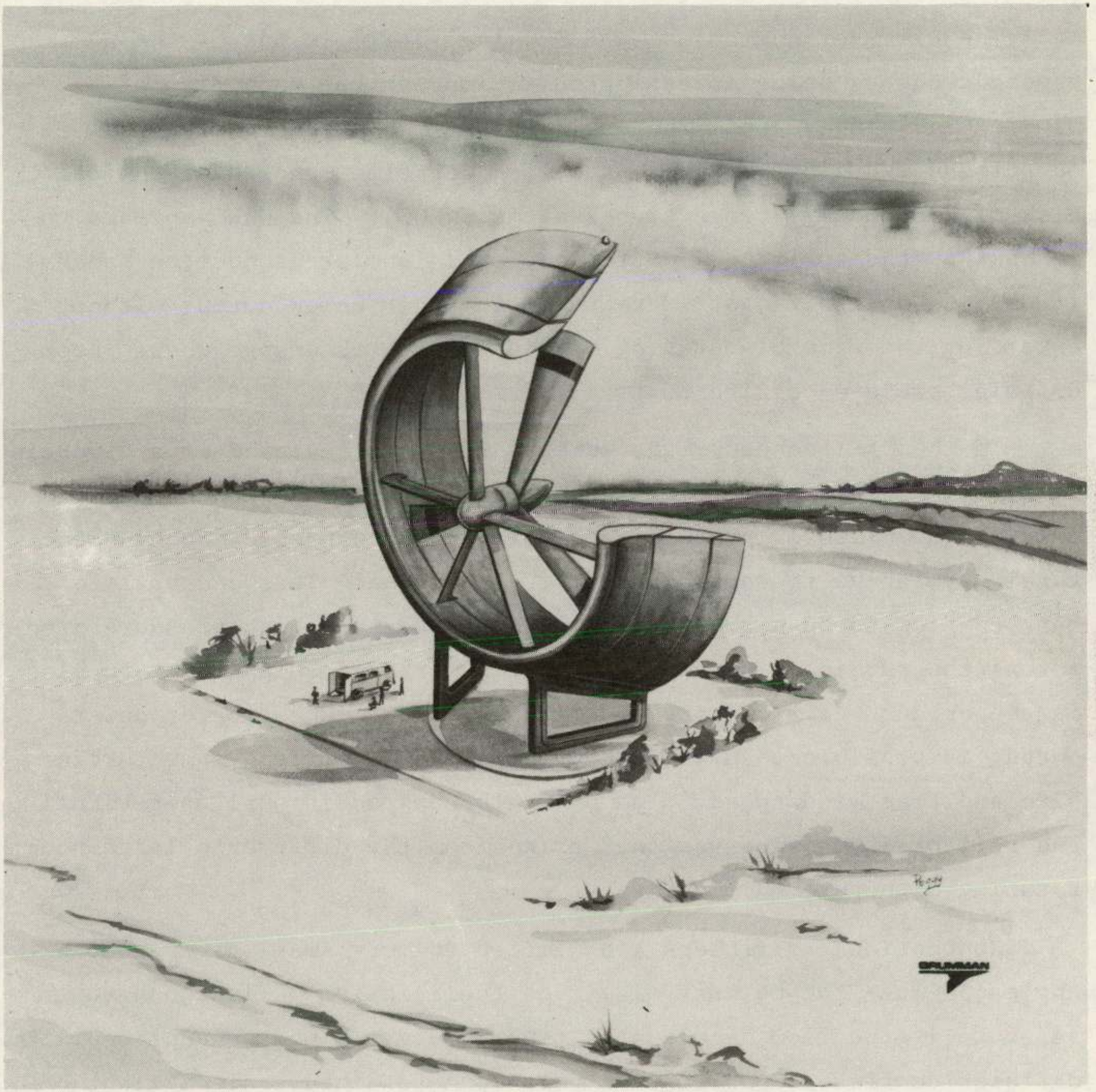


Figure 1 Conceptual Installation of a DAWT with 60 Meter Diameter Turbine

PROJECT SUMMARY

The Diffuser Augmented Wind Turbine (DAWT) is one of the advanced concepts being investigated to improve the economics of wind energy conversion. The project is aimed at increasing the output and reducing the cost, the off-duty time, and the technical risk of wind energy conversion systems (WECS). The DAWT appears to be best suited to large WECS for commercial power production because it permits a significant increase in the unit power output without extending the size of rotating machinery into the range where rotor dynamics cause excessive costs.

In the DAWT concept, the turbine rotor is enclosed in a diverging duct called a diffuser (see Fig. 1). By recovering exhaust kinetic energy, the diffuser produces a greatly reduced pressure behind the turbine relative to that behind a free turbine. This causes more mass to flow through the turbine with at least as much pressure drop across the turbine. Because the wind power available to the turbine is the product of flow rate and pressure drop, much greater power output is possible than for a conventional WECS at the same turbine size and free wind speed. The DAWT also has additional operational and reliability advantages that arise from the diffuser's large non-rotating structure.

Conventional diffusers are limited to very small divergence angles because the boundary layer on their inside walls tends to separate if the flow decelerates too rapidly. Since conventional diffuser configurations must be very long to achieve significant area change, they are prohibitively costly to construct. Therefore, our research goal has been to apply modern techniques to reduce radically the size of the diffuser without sacrificing its performance, thereby producing a cost-competitive DAWT. We have also

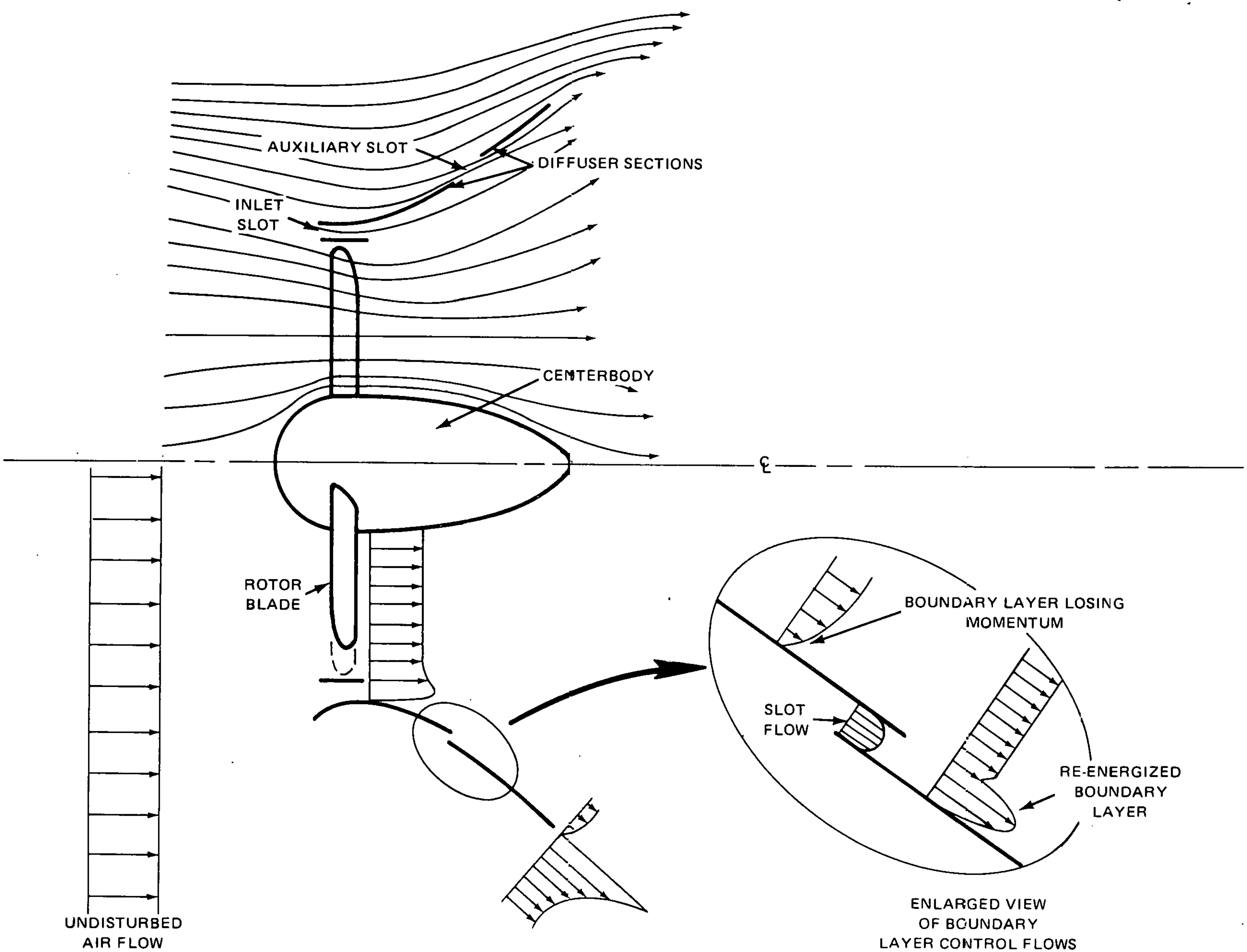


Fig. 3 Flow Patterns and Velocity Profiles in a BLC DAWT

The dominant factor in the evaluation of DAWT configurations is the cost of the energy produced. The DAWT can be considered economically viable only when the diffuser component costs, in production quantities, are offset by improved productivity, such that the overall electrical generation system cost is reduced. While the compact baseline diffuser design produced only a fraction of the augmentation possible with much larger diffuser, it presents a more cost effective solution for wind energy conversion. A comparison of the estimated costs for the same rated power based on rough structural designs shows that the DAWT can be as much as 50% cheaper than conventional WECS for turbine diameters greater than 35 meters.

Our analysis has shown that it is possible to employ variable stators with a constant speed, fixed pitch turbine rotor, but that this control policy results in lower off-design power than would result for the same rotor without a variable stator.

The key issues for further development of the DAWT concept are further improvement of the aerodynamic output of diffusers while minimizing structural cost, demonstration of performance at larger scale and with actual turbines, and further design and costing refinements.

EXECUTIVE SUMMARY

INTRODUCTION

There is consensus that the major unresolved technical problem in the design of conventional Wind Energy Conversion System turbines (WECS) for very large power systems is in the blade dynamics of large diameter rotors. Because of this fact, integration of wind generators into a national or regional power grid is inhibited by the unacceptable reliability of very large units or the economic liability of many smaller units of comparable total power output. This technical factor interacts with the economic constraints associated with matching supply and demand schedules in variable wind, the low power density of wind, the high development risk of new system concepts, and the capital-intensive nature of wind power systems.

Many of these capital and performance restrictions of WECS can be reduced or eliminated by enclosing the wind turbine rotor in a suitably shaped duct. The nonrotating duct structure provides a compact diffuser section behind the rotor that produces a power augmentation of considerable magnitude (typically 1.5 to 2 times) for a given size rotor, as well as dampening gusts, lowering cut-in wind speed by raising the level of axial velocity significantly, and eliminating tower wakes.

Ducted wind turbines have been suggested periodically for over half a century. Early investigators tended to underrate the concept by various combinations of analysis and/or conceptual errors, failed to anticipate low pressures at the shroud exit, and assumed that diffusers would have to be very long and costly to avoid boundary layer separation. Early in 1960, an Israeli group (Kogan) repeated correctly much of the earlier analytical development and proceeded to some experiments concerning performance of two dimensional diffusers, duct inlet contour effects on axial misalignment of the incoming flow, and performance of short axisymmetric diffusers with exit plane ejectors.

Later studies by Igra showed that the exit plane of a Diffuser-Augmented Wind Turbine (DAWT) has, in fact, the greatly depressed pressure level that was hoped for in order to obtain large augmentation effect. Evidence is now clear that base pressure reductions on the order of $\frac{1}{2}$ the wind dynamic pressure result from both viscous and inviscid interaction, and this kind of base pressure reduction raises the diffuser augmentation significantly. The diffusers in this application have the unique feature that a plentiful supply of high energy air exists just outside the diffuser wall. However, the aerodynamic benefits of the DAWT must overcome the highly visible cost of the shroud structure. Therefore, the focus of our research has been the technical challenge of extracting sufficient fluid mechanic performance from a very compact diffuser that will be cheaper to build than the incremental cost of larger diameter wind turbines to produce the same rated power. Such short diffusers are cost-competitive designs because they will result in reduced capital expense of electrical energy generation by wind energy conversion.

DIFFUSER AUGMENTATION THEORY

The results of one dimensional momentum theory applied to a DAWT show that the power available to a perfect ducted turbine can be made to increase significantly by a high exit/rotor area ratio, a high diffuser efficiency, an optimum ratio of inflow disk to free stream velocity, and a strongly negative base pressure coefficient. Optimistic values of diffuser efficiency and base pressure coefficient, operating with optimized disk loadings, lead to analytical predictions of augmentation ratio as high as 4 in the limit of infinite area ratio. Augmentation ratio is the ratio of power output of an ideal DAWT rotor to that of an unshrouded ideal rotor of the same size and in the same wind. Since structural cost increases rapidly with shroud area ratio, the most cost-effective DAWT will operate at modest area ratio, and a correspondingly smaller augmentation ratio. Our present baseline configuration optimizes at an area ratio of 2.8, and has delivered augmentation ratios as high as 1.9.

DIFFUSER DEVELOPMENT

Several different diffuser concepts have been suggested for a DAWT. The design criteria of a maximum subatmospheric pressure at the exit plane, a large pressure recovery within the diffuser, and the smallest possible structural cost imply that need for functional diffusers with equivalent half angles much greater than the conventional 3° to 6°, which are dictated by boundary layer separation. Nevertheless compact diffusers for DAWT must maintain effective performance characteristics. We have chosen what appear to be the two most promising design concepts for further study. The first of these employs repeated injection of external air for boundary layer control. External high energy air from the wind is injected tangent to the wall, thereby adding axial momentum to the boundary layer. The additional momentum helps the boundary layer fluid to flow against the severe adverse pressure gradient and frictional losses that are present in the wall region of large angle diffusers. This can prevent the flow from separating from the wall, the primary cause of the failure of flow in large angle diffusers. The second diffuser concept is the use of a diffuser constructed from short ring airfoils. Each ring airfoil produces a local aerodynamic pressure and velocity field as a result of the section contour. The low pressure along the internal ring surface induces more flow through the turbine. By the use of high lift wing contours for the rings, or by use of flaps, appreciable augmentation is obtainable.

Experiments have been conducted in a low speed, low turbulence level, free jet tunnel facility. The core region of a 29.2 cm diameter free jet flow is used as the test section in which uniform wind conditions are simulated. A velocity of 13.0 m/sec (43 fps) was used for the tests. Models were mounted slightly downstream of the nozzle exit plane. Boundary layer controlled diffuser models were constructed of stainless steel and aluminum sheet metal. Ring wing models were machined from aluminum bar stock. Over 150 configurations have been investigated in this program.

The instrumentation employed a variable reluctance differential pressure transducer. The measurements were derived from the combined use of a single static pressure probe and a single total pressure probe, each of which can pass right through the screens used. For the axial and radial pressure measurements, the probes were mounted on a motor-driven traversing mechanism. This device produces an electrical output proportional to its position so that pressure versus spatial position could be recorded.

Since a family of wind turbines is impractical to build for an exploratory investigation of small scale diffuser models, we simulated the turbine energy extraction by screens that dissipate the energy at the turbine station. The turbine performance is simulated by the screen loading. The power extracted per unit area is the product of the total pressure drop and local velocity.

From measurements of disk loading and ratio of local to free stream velocity, the augmentation ratio, r, can be found. Repeated axial surveys at different radial positions indicate that r increases with radial distance from the axis. The weighted average over the entire cross section of the turbine simulator gives the total diffuser augmentation ratio, $\bar{r}$.

MODEL TEST RESULTS

The augmentation ratio was measured by performing hundreds of pressure surveys on a large number of model diffusers in a range of turbine disk loadings between 0.3 and 1.10. A peak $\bar{r}$ value of almost 1.9 can be achieved with a 30° diffuser half angle at an optimum disk loading coefficient of about 0.63, using boundary layer control (see Fig. 4). The ring wing diffuser exhibits an increasing $\bar{r}$ value with disk loading. Although an optimum disk loading has not been encountered for the flapped NACA 4412 contour diffuser tested, an $\bar{r} = 1.6$ is indicated for the maximum disk loading coefficient tested, 1.10.

The ratio of local-to-free stream velocity for the boundary layer control (BLC) diffuser at peak $\bar{r}$ is 1.27. The value of this ratio is 0.9 for the ring wing design at $\bar{r} = 1.6$. Both diffusers produce considerably greater inflow velocity to the turbine than the theoretically best velocity ratio value (0.67) for conventional unshrouded turbines, at an optimum disk loading coefficient of 2.0. For the BLC diffuser, where such a comparison is possible, the optimum performance from one dimensional theory should occur at a local disk loading of 0.65. This is computed from a measured reduction of exit plane pressure equal to 0.57 of the wind dynamic pressure and a measured induced velocity ratio of 1.27.

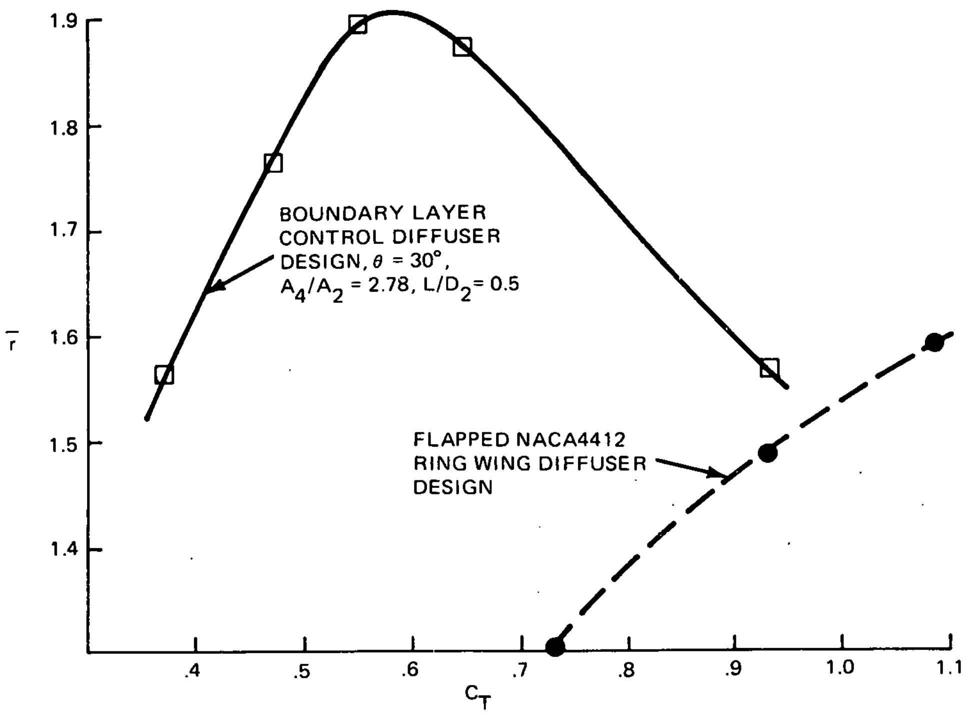


Figure 4 Representative Model Test Results of Two Short Diffuser Designs

EXIT PLANE PRESSURE REDUCTION

The low exit plane pressures that are always measured in our DAWT experiments were first noted by Igra. They are so large and so significant to DAWT performance, that their origin must be explained. Originally, the phenomenon was attributed to the strong shear layer peripheral to the wake, but recent analysis based on thin airfoil theory has indicated that the phenomenon is explainable completely by inviscid processes. This fact promotes confidence that low base pressures will remain when diffusers are scaled up to full size and high Reynolds numbers.

ECONOMIC ANALYSIS

Economic assessment of the DAWT relative to a conventional WECS requires that the most competitive versions of each concept be identified and priced according to realistic and consistent costing rules. We established an analysis objective of comparing the capital cost per unit power of DAWT with that of the optimum conventional wind turbine. This involves the cost trend of production quantity ($\sim$ 100/year) wind turbines with size as well as the cost trend of a short diffuser of demonstrable augmentation capabilities. The rotor cost information has been generated by two different contractors under NASA-Lewis Research Center sponsored contracts. The diffuser cost estimates were made by Grumman on the basis of a finite element structural analysis for a full scale BLC baseline diffuser design (2.78 area ratio, length/turbine diameter = 0.5, $\theta = 30°$, $\bar{r} = 1.89$). The total cost of only the diffuser and rotor elements has been normalized by the cross sectional area of the turbine to facilitate comparison of the two systems. Two characteristics of these input data are clear:

- A 100 percent uncertainty exists in state of the art turbine cost estimates, especially in the low to intermediate size range, depending on the estimating organization
- The typical U-shaped average cost curve shows the initial economics of scale to about 25 meters diameter, and sharply rising costs as larger rotor diameters require more elaborate construction and advanced materials to overcome escalating aeroelastic stresses

At this time, operationally reliable rotor diameters greater than about 65 meters are highly speculative. The most straightforward advantage of the DAWT is that is offers an alternative to replication of conventional turbines when desired unit output is greater than that of a larger-than-optimum WECS. With a DAWT, significantly greater power can be generated without the cost and time delay of additional land acquisition, legal hearings, grid terminals, maintainence and operating staff, or other costs of replication of size-limited wind power plant designs. Other secondary benefits from using DAWT are tower cost reduction, elimination of tower wake and reduction of wind shear and direction problems, and greater annual on-line factor. The operational usefulness of the annual wind energy spectrum is broadened because the DAWT inlet acceleration lowers the minimum wind speed for cut-in of turbine power for fixed size and rpm rotor. Further, the duct can easily raise the high speed cut-out, end of the wind spectrum because of the inherent capability of the diffuser to modulate flow by introducing spoilers or movable stators.

It is possible to compare the DAWT with conventional WECS in different ways, depending on the application. To illustrate the differences, we have chosen two specific comparisons:

- Equal rotor diameters used in both systems
- Equal rated power output in both systems

For the latter condition, the rotor diameter of the WECS is increased by the square root of the DAWT augmentation ratio, $\bar{r}$. Of course, it is not currently realistic if the WECS turbine must be increased much beyond 65 meters.

The two cost comparisons are shown in Figs. 5 and 6 on the basis of the turbine and diffuser elements of the system only. That is, differences in the costs of the electrical generator, tower, foundation, control system, and mechanical shaft linkage or transmission system components have not been considered in these cost comparison, nor have any other system economics of scale. In the case of equal rotor size in both systems (see Fig. 5) it is

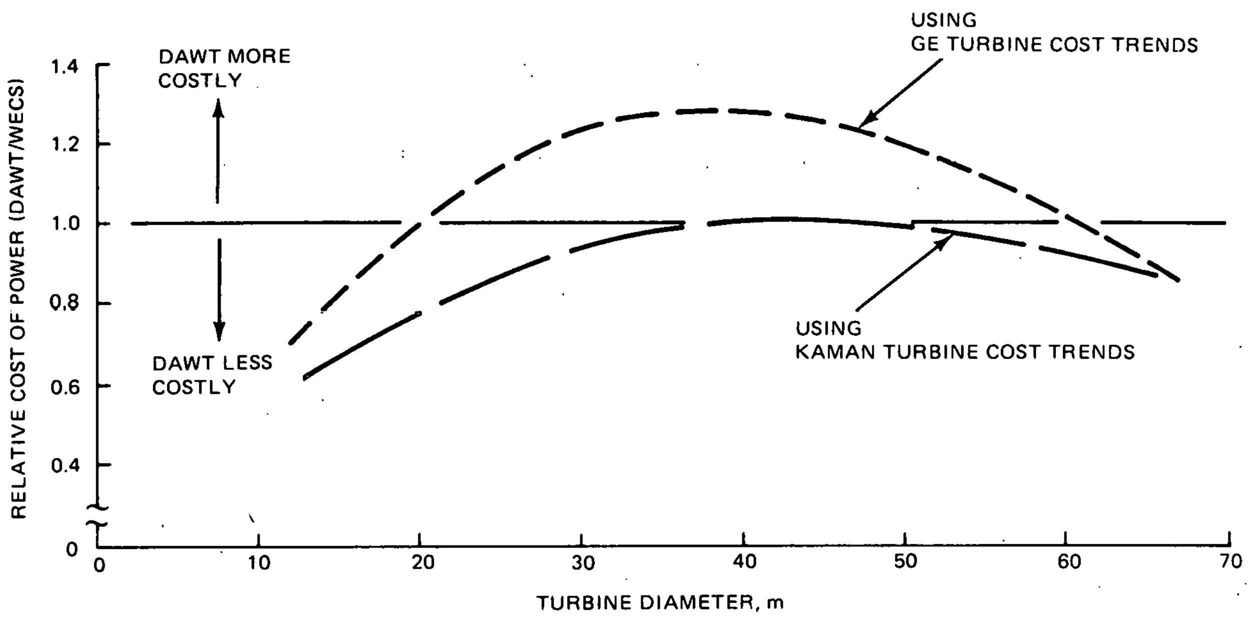


Figure 5 Cost Comparison of DAWT and Conventional WECS for Equal Rotor Size

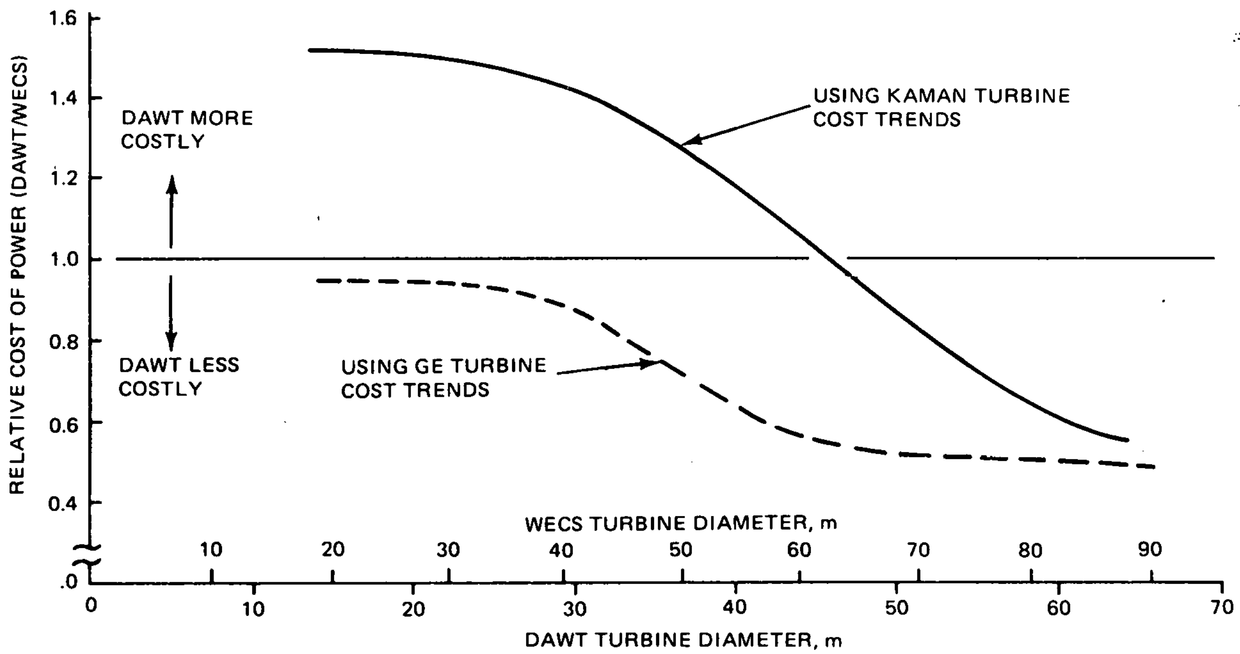


Figure 6 Cost Comparison of DAWT and Conventional WECS for Equal Rated Power

clear that DAWTs have an economic advantage for small rotors and very large turbine diameters. The economics in the intermediate size range are clouded by the diversity of authoritative cost estimates; the DAWT can be marginally less (i.e., 0 to 10 percent) or up to 25 percent more costly.

For equal rated power output, shown by Fig. 6, the DAWT can be significantly cheaper ($\sim$ 50 percent) than a WECS for turbine diameters greater than about 35 meters. For smaller turbine sizes, the DAWT can be anywhere from marginally cheaper to significantly more expensive depending on which cost trend one actually experiences.

A usable annual wind pattern factor has not been included in the graphic results. Because of the inherent wind speed-up features of the diffuser inlet section, there can result a 5 to 50 percent greater annual power conversion for the DAWT compared to the WECS. Therefore, there is a probable real economic advantage for the DAWT, regardless of which turbine cost estimate is appropriate.

STATORS

One of the goals of our investigation was to determine if the struts that will support the turbine within the shroud could be used to advantage as a variable stator. The objective was to provide varying preswirl to a constant speed, constant pitch, rotor so that it could operate efficiently throughout the wind range. A computer code was written to investigate this concept in the context of a DAWT, and several such designs were formulated and evaluated. They appear in most respects to be satisfactory in performance, although repeated attempts to broaden the region of high power coefficient suggested that the wind range over which the stator control could be effective was narrow. This suggested a comparison of matched rotor installations with and without stator preswirl. Off design performance increased substantially without the stator, both above and below the design wind speed. This surprising result is because the rotor airfoils gain less by remaining at an ideal angle of attack than the rotor, as a whole, loses. These losses are due to adverse change in relative velocity when the stator attempts to hold rotor angle of attack constant with fixed pitch and speed. We therefore have reached the following conclusions:

1. Controllable stators are useful only as a possible means of inexpensive protection against overload at high wind speeds

2. A constant speed, fixed pitch rotor is practical without a controllable stator if the rotor dynamic design can withstand the oscillations of rotor blades operating fully stalled at high wind speeds

3. Because struts are needed anyway, there may be some value in introducing a constant preswirl to produce better performance at low wind speed with less rotor blade area, sacrificing performance at high wind speeds when the power available is greater than that which can be used by a controlled generating system

We intend to do a very limited exploration of the possibilities for fixed stator preswirl in the second year's work. The main use for the computer programs in subsequent work will be design of small fixed rotors for wind tunnel experiments.

KEY ISSUES FOR FUTURE WORK

Cost/Performance

The most important single factor in development of the DAWT is to increase further the performance while minimizing cost of the diffuser. Among the means to this end, the most important is probably a better understanding of the slot flow as it enters the high adverse pressure gradient of a 30° half angle diffuser. This will allow more confident scaling to higher Reynolds number (i.e., larger sizes), and hopefully the maximum augmentation for each diffuser size. Another possibility is reducing structural cost by improved design features, and innovative concepts to relieve the high cost of meeting storm load survival criteria. The possibility exists also that some improvement may result from axial contouring of diffusers.

Demonstration

The small scale results of the diffuser must be demonstrated at significantly greater scale, and in such a fashion that further scaling-up can be justified. The screen simulations of turbine output must be shown to be realizable (and improved upon) by a real turbine. Drag loads must be measured. The origin of the exit plane pressure reduction should be better explained.

Design

The relatively crude baseline designs we have generated must be improved, both as the basis of construction of prototypes and as the basis for better cost estimates and comparisons.

RECAPITULATION

Our investigation of cost-effective diffuser augmentation of wind turbines has revealed at least two effective types of diffusers; that is, boundary layer controlled diffusers and flapped ring wings. Model tests have already demonstrated significant power augmentation capabilities for DAWT, approaching a factor of 2 in a very compact configuration. Diffuser exit plane pressure substantially below atmospheric ($\sim 0.6\, q_o$) has been verified. Because of this low exit pressure and the diffuser pressure recovery it is possible to induce much larger amounts of air through a DAWT than passes through a conventional WECS; thus it can convert more power than a WECS of the same size.

Economic studies using and comparing the most recent turbine component cost trends, and Grumman-generated diffuser cost estimates and performance measurements show that DAWT should have lower specific power costs than WECS for very large and small turbine diameter sizes. The possible direct benefits of DAWT in the intermediate size range are somewhat obscured by the significant uncertainties of current turbine cost estimates. The indirect benefits of DAWTs, including a potentially greater factor for usable annual wind energy patterns, probably mean that DAWTs have the possibility of becoming more economical than conventional WECS, regardless of size or turbine costing.

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