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DIFFUSER AUGMENTATION OF WIND TURBINES

by

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ABSTRACT

The major deterrent to widespread use of windpower is economic. One of the more promising advanced concepts for reducing significantly the cost per output KW-hr is the Diffuser-Augmented Wind Turbine (DAWT). The diffuser controls the expansion of turbine exhaust flow, producing a highly sub-atmospheric pressure at the turbine exit. The low static pressure induces greater mass flow through the turbine ~~vs.~~ a conventional turbine design of the same diameter. Thus the output power and disk loading of the DAWT is much larger than for an unshrouded turbine. The freely expanding exhaust air downstream of the diffuser is re-energized by mixing with the external wind flow.

Our wind tunnel investigation of models of two diffuser design concepts is directed toward unconventional, very short, cost-effective configurations. One approach uses the energetic external wind to prevent separation of the diffuser's internal boundary layer. Another method used high lift airfoil contours for the diffuser wall shape.

Diffuser model tests have indicated almost a doubling of wind power extraction capability for DAWTs compared to conventional turbines. Economic studies of DAWTs have used these test data and recent (1975) cost projections of wind turbines with diameter. The specific power costs (\$/kW) for a realistic DAWT configuration are found to be lower than conventional wind turbines for very large size rotors, above 50 meters diameter, and for rotor diameters less than about 20 meters. The cost-to-benefit assessment for intermediate size rotors is affected by the uncertainty band of cost for these rotor sizes.

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INTRODUCTION

It is the consensus of experts (Ref. 1) that the major unresolved technical problem in the design of conventional wind turbines 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 the above capital and performance restrictions of conventional wind turbine systems can be reduced or eliminated by enclosing the wind turbine in a suitably shaped duct. The non-rotating duct structure provides a diffuser section behind the rotor that produces a power augmentation of considerable magnitude (typically 1.5 to 2 fold) for a given size rotor, as well as dampening gusts and raising the level of axial velocity significantly.

Ducted windmills have been suggested periodically for over half a century. Unfortunately, one prestigious early investigator (Betz, Ref 2) concluded that diffusers were not economical for then-current applications. This result, although based on correct theory, followed from restrictive conditions that the diffuser exit plane static pressure would be equal to ambient atmospheric pressure, that only small ratios of exit to throat area were allowable and that disk velocity ratio would be lower than was being projected by erroneous analyses at that time. Thus progress in applying ducted wind turbines was effectively squelched until the late 1940's to mid-1950's. Renewed interest in Japan and Great Britain took the form of more general analyses and limited experiments of ducted windmills. The test results even with crude ducting showed enhanced power output over free rotors (Ref. 3). Parametric analyses indicated that, for example, with a 3.5 diffuser expansion ratio and a 15% diffuser pressure loss, the power output of the ducted windmill would be 65% greater than conventional systems. Further, the disk loading of the rotor would be only 1/4 of the free turbine and thus be cheaper to make. Despite these clear indications of aerodynamic superiority, to our knowledge continued work toward definitive experiments was not pursued in England. Early in 1960, an Israeli group repeated much of the earlier analytical development and proceeded to some experiments concerning performance of two dimensional diffusers (Ref. 4), duct inlet contour effects on axial misalignment of the incoming flow (Ref. 5), and performance of short axisymmetric diffusers with exit plane ejectors

Later studies by Igra (Ref. 6) showed that the exit plane of a Diffuser-Augmented Wind Turbine (DAWT) has, in fact, the greatly depressed pressure level caused by downstream interaction that was hoped

for in order to enhance the augmentation effect. Indications are that base pressure reductions on the order of $\frac{1}{2}q_\infty$ result from downstream interaction and this kind of base pressure reduction will raise the diffuser augmentation above the four-fold range. The diffusers in this application have the unique advantage that a plentiful supply of high energy air exists just outside the diffuser wall. Our initial investigation in 1972 (Ref. 7), discovery of the Igra results, and further exploration on our part has led to an extremely promising prognosis for the concept, especially in the context of large systems. The benefits of DAWTS 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. We call such short diffusers cost-competitive designs because they will reduce the capital expense of electrical energy generation by wind energy conversion.

THEORY OF DIFFUSER AUGMENTATION

The results of one-dimensional momentum theory applied to a diffuser-augmented wind turbine were presented by Oman and Foreman (Ref. 7). Referring to Fig. 1 the ideal power coefficient, C_{P_i} can be written:

$$C_{P_i} = \Delta P_{23} V_2 / \frac{1}{2} \rho V_0^3 A_2 \quad (1)$$

and

$$C_{P_i} = \left[1 - K_i - C_{P_4} \right] \epsilon - \left[1 - \eta_D (1 - \lambda)^2 \right] \epsilon^3 \quad (2)$$

where

$$\begin{aligned} \Delta P_{23} &= \text{pressure drop across turbine stage(s)} \\ V_2 &= \text{axial velocity at turbine} \\ \rho &= \text{air density} \\ V_0 &= \text{free wind velocity} \\ \epsilon &= V_2 / V_0 \\ K_i &= \text{inlet total pressure loss} / \frac{1}{2} \rho V_0^2 \\ C_{P_4} &= (p_4 - p_0) / \frac{1}{2} \rho V_0^2 \\ \eta_D &= (p_4 - p_3) / \frac{1}{2} \rho (V_3^2 - V_4^2) \\ \lambda &= A_2 / A_4 = A_3 / A_4 \end{aligned}$$

The main significance of Eq. (2) is that the power available to a perfect ducted turbine can be made to increase significantly by a small rotor/exit area ratio, a high diffuser efficiency (η_D), an optimum disk velocity ratio (ϵ), and a strongly negative base pressure coefficient

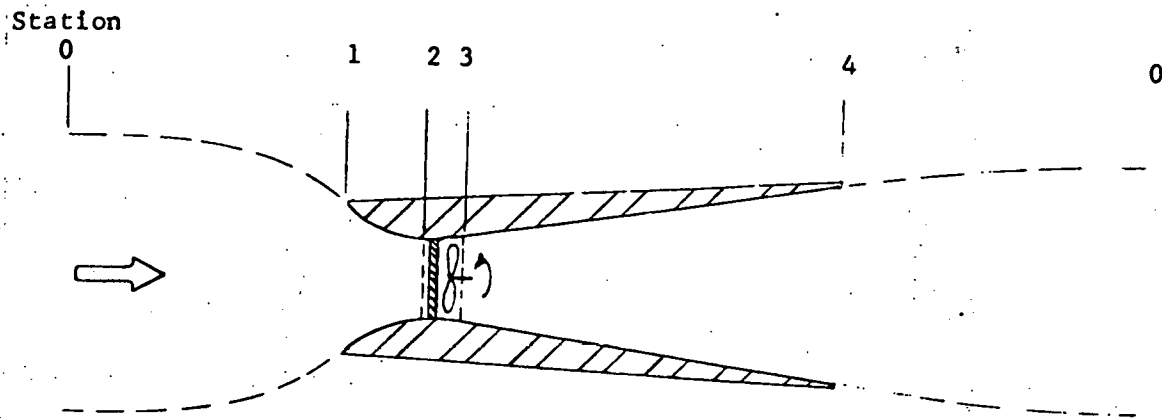


Fig. 1 Ducted Wind Turbine Showing Reference Stations

(C_{P4}). The velocity ratio will be determined by the disk loading ($\Delta p_{23}/\frac{1}{2}\rho V_0^2$) of the turbine that is installed in the duct, which is where the detailed design of the turbine begins.

Since the maximum ideal power coefficient of an unducted (free) turbine equals $16/27$, the relative power coefficient, r , of a shrouded to the best unshrouded wind turbine is

$$r = 27 C_{P_i} / 16 = 1.686 C_{P_i} \quad (3)$$

Based on equal turbine rotor diameters and free wind speeds, r can also be expressed by

$$r = \frac{27}{16} C_T \left(\frac{1 - C_{P4}}{1 - C_{P_R} + C_T} \right)^{3/2} \quad (4)$$

where

$$C_T = (p_2 - p_3) / \frac{1}{2}\rho V_2^2$$

and

$$C_{P_R} = (p_4 - p_3) / \frac{1}{2}\rho V_3^2 = \eta_D \left[1 - \left(\frac{A_3}{A_4} \right)^2 \right]$$

The inlet duct losses are combined into the overall duct pressure recovery coefficient, C_{P4} , in Eq. (4). Since the turbine load factor C_T is practically unrelated to C_{P4} (Ref. 4), the maximum relative power coefficient is:

$$r_{\max} = \frac{9}{8} (1 - C_{P_4}) \sqrt{\frac{(1 - C_{P_4})}{3(1 - C_{P_R})}} \quad (5)$$

which coincides at the optimum load factor (Ref. 4):

$$(C_T)_{\text{opt}} = 2(1 - C_{P_R}) \quad (6)$$

Thus, the greatest power augmentation over conventional wind power generators is obtained for:

- The largest possible negative value for exit-plane pressure coefficient (i.e., diffuser exit pressure is reduced below atmospheric pressure by downstream entrainment)
- The largest possible diffuser pressure recovery coefficient
- A unique relation of turbine disk loading to diffuser pressure recovery in which high recovery favors low power loading by inducing greater volume flow through the disk

DIFFUSER DEVELOPMENT

There are several different types of diffuser concepts that have been suggested for a diffuser-augmented wind turbine. The design criteria of an appreciable subatmospheric pressure at the exit plane and a large pressure recovery within a diffuser having the smallest possible structural cost immediately imply the need for functional diffusers with equivalent half angles much greater than the conventional 3° to 6° . Nevertheless they 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 the injection of the 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 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 distribution along the internal ring surface induces more flow through the turbine. By the use of high lift wing contours for the rings or by flaps, appreciable augmentation should be obtainable.

EXPERIMENTAL APPARATUS

The experiments have been conducted in a low speed, low turbulence level, free jet tunnel facility (see Fig. 2). The core region of a free

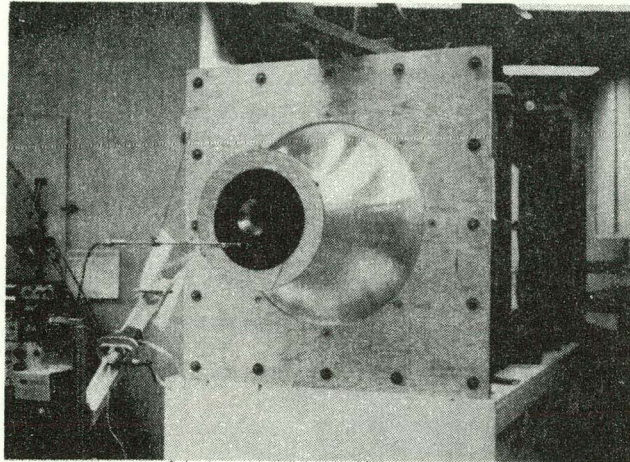


Fig. 2 Photograph of Jet Tunnel with DAWT Model Installed

jet flow is used as the test section in which uniform wind conditions are simulated. The 29.2 cm circular jet issues from a 91.4 x 91.4 cm settling chamber. The jet is formed by flowing through a standard ASME long-radius nozzle. The mean flow is quite uniform across the exit. The maximum velocity of the facility is 17.7 m/sec (58 fps), however, a velocity of 14.7 m/sec (48 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. Uniform screens were used to simulate the turbine. Over 150 models and test conditions have been investigated in this current program.

The instrumentation employed a transconductance differential pressure transducer. The most successful measurements were derived from the combined use of a single static pressure probe and a single total pressure probe. These are constructed from very slender stainless steel tubing which can pass through the screens used. Complete axial pressure traces are taken from an upstream to a downstream position passing right through the screen. For the axial and radial pressure measurements, the probes were mounted on a tri-directional, motor-driven traversing mechanism. This device gives an electrical output proportional to its position so that pressure vs. spatial position could be directly traced on an x-y recorder.

TURBINE SIMULATION

Since a family of wind turbines is impractical to build for an exploratory investigation of small scale diffuser models, we have simulated the turbine energy extraction by screens that dissipate the energy

at the turbine station. We represent the turbine performance by the local disk loading coefficient,

$$C_T = (p_2 - p_3) / \frac{1}{2} \rho U_2^2 \quad (7)$$

The power extracted per unit area is the product of the total pressure drop and the local velocity. From knowledge of the disk loading and the measured ratio of local to free stream velocity, V_2/V_0 , the augmentation ratio can be found:

$$r = \frac{C_T}{.593} \left(\frac{V_2}{V_0} \right) = \frac{C_T}{.593} (q_2/q_0)^{3/2}. \quad (8)$$

In Fig. 3, we show a typical axial static pressure traverse along the centerline of a diffuser employing boundary layer control to inhibit separation. The local flow approaching the screen (turbine simulator) is accelerating because of the subatmospheric pressure condition (C_{p4}) existing at the diffuser exit plane. Therefore, the q_2/q_0 value is significantly greater than 1.0 at a disk loading coefficient of 0.47 and

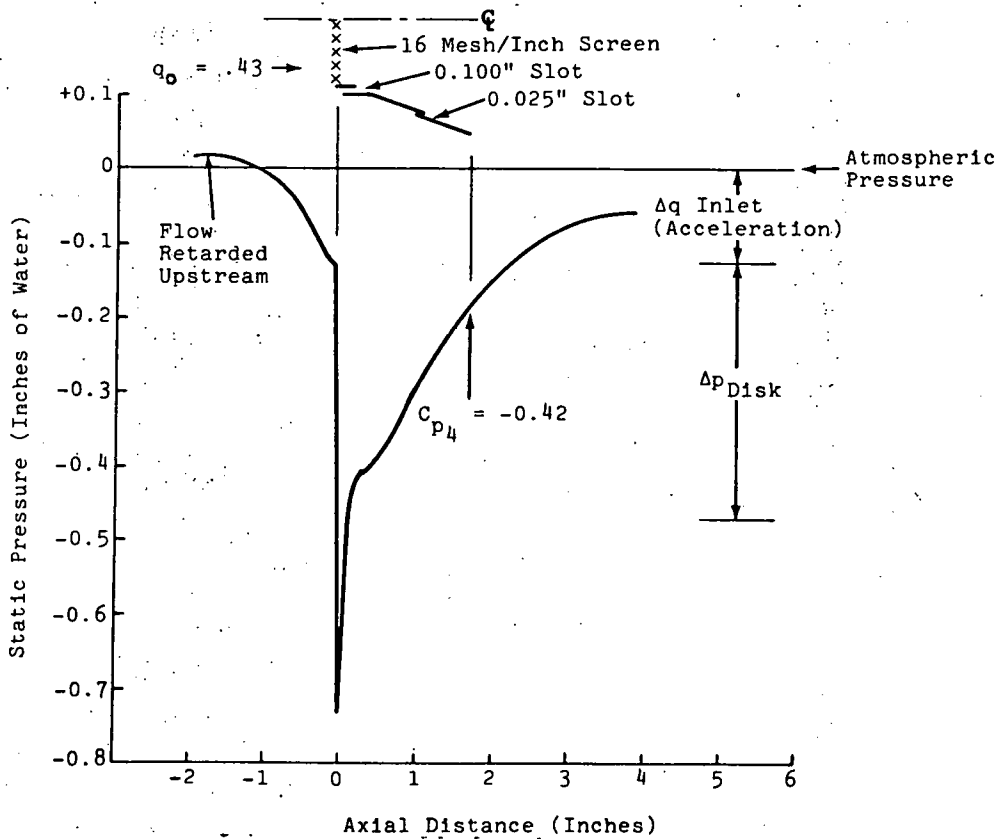


Fig. 3 Centerline Static Pressure Survey in a 20° Half-Angle Diffuser

the augmentation ratio at the axis is 1.25. From repeated axial surveys at different radial positions it is found that the q_2/q_0 ratio and \bar{r} increases with radial distance from the axis. The weighted average, \bar{r} , augmentation ratio for the entire cross section of the turbine simulator is 1.66 for the diffuser design of Fig. 3.

MODEL TEST RESULTS

The model test results of measured augmentation ratio for a range of turbine disk loadings between 0.3 and 1.10 is shown by Fig. 4. Examples of both types of short diffuser concepts, the boundary layer control and ring wing designs, are presented. It is apparent that a peak \bar{r} value of almost 1.9 can be achieved with a 30° diffuser half-angle at an optimum disk loading of about 0.6, using boundary layer control. The ring wing diffuser exhibits an increasing \bar{r} value with C_T . Although a peak value of \bar{r} was not yet encountered for the flapped NACA 4412 contour diffuser tested, an $\bar{r} = 1.6$ is indicated for $C_T \approx 1.10$.

The ratio of (q_2/q_0) for the boundary layer control diffuser at peak \bar{r} is 1.31. The value of this ratio is 0.9 for the ring wing design at a $C_T = 1.1$. Both diffusers produce considerably greater inflow

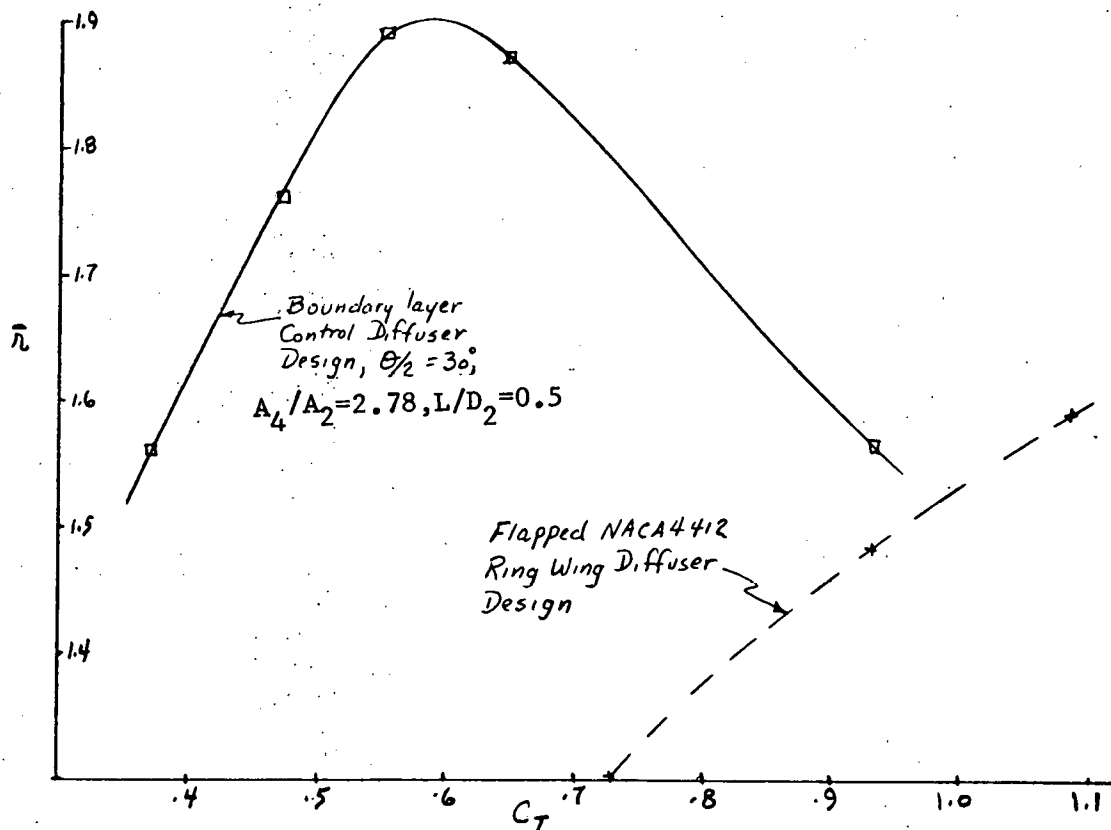


Fig. 4 Representative Model Test Results of Two Short Diffuser Designs

velocity to the turbine than the theoretically best q_2/q_0 of 0.44 for conventional unshrouded turbines, at an optimum C_T of 2.0 .

ECONOMIC ANALYSIS

Economic assessment of the diffuser-augmented wind turbine (DAWT) relative to a conventional wind energy conversion system (WECS) requires that the most competitive versions of each concept be identified, and priced according to realistic and consistent costing rules. Identifying the cost-optimized DAWT is more complicated than for conventional WECS, because there are more parameters affecting the economics, and there is a paucity of good performance and costing laws for compact diffusers.

To avoid the complicated calculation of utility cost of electrical power (i.e., mills per watt-hour), we set an analysis objective to compare the capital cost per unit power of good DAWTS with the best conventional wind turbine machine. This involves the cost trend of production quantity ($\sim 100/\text{yr}$) wind turbines with size as well as the cost trend of a short length diffuser of demonstrable augmentation ratio, r , capabilities. The rotor cost information has been generated under NASA-Lewis Research Center sponsored contracts (Ref. 8 and 9). The diffuser cost estimates were made by Grumman on the basis of a finite element structural analysis for a full scale optimum boundary layer control diffuser design (2.78 area ratio, length/turbine diameter = 0.5, $\theta/2 = 30^\circ$, $\bar{r} = 1.89$) indicated by data of Fig. 4. The total cost of the diffuser and the rotor has been normalized by the cross sectional area of the turbine to facilitate comparison of the two systems. Two characteristics are clear for the normalized rotor cost trends depicted by Fig. 5:

- A 100% uncertainty in 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 economies 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 60 meters are highly speculative. Alternatives to specifying the rated output at an installation site beyond the capability of a 60 meter diameter rotor, are:

- Replication of conventional turbines on supplementary superstructure to create a multi-unit system
- Using a DAWT

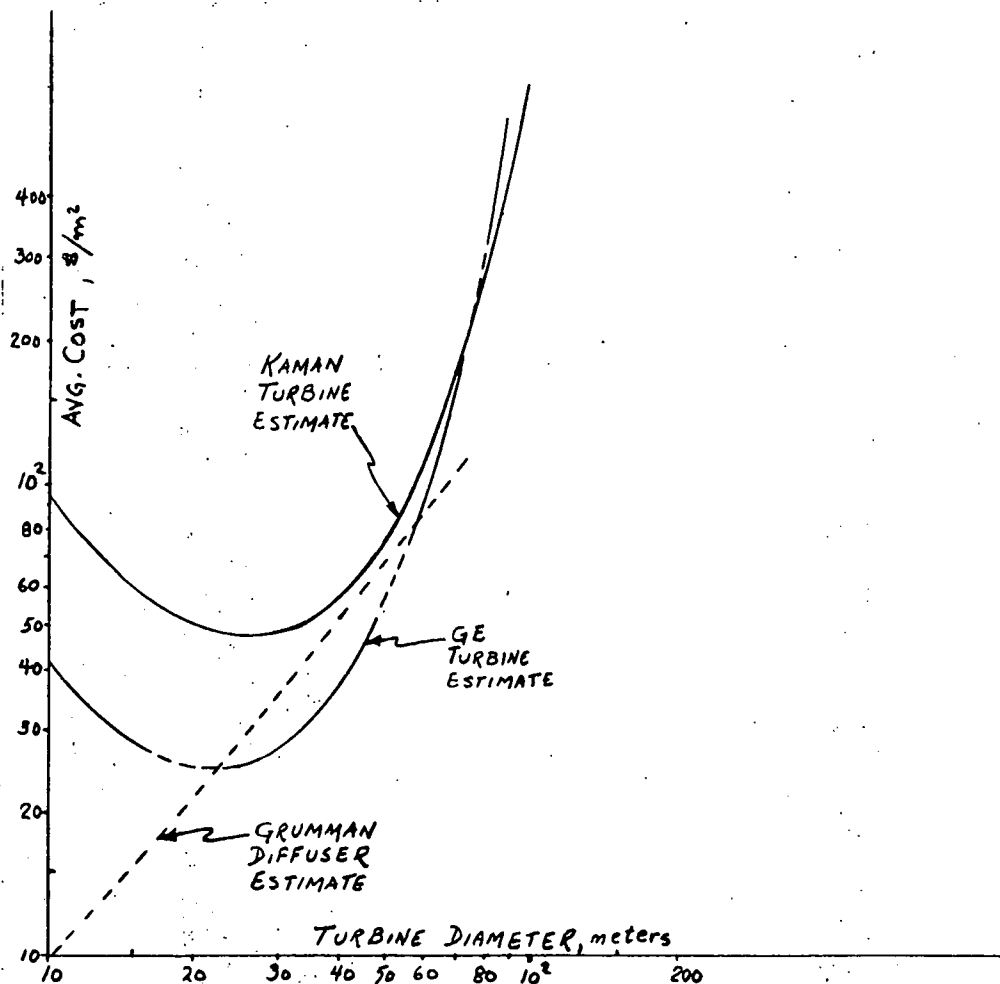


Fig. 5 Average Cost Estimates of Wind Turbines and a Diffuser Design

With a DAWT, significantly greater power can be generated without the cost and time delay of additional land acquisition, legal hearings, or replication of size-limited wind power plant designs. Secondary benefits from using DAWT rather than replication of conventional WECS are reduced maintenance and security manpower requirements, and greater annual on-line factor. The operational usefulness of the annual wind energy spectrum is broadened because the DAWT's inlet acceleration lowers the minimum wind speed for cut-in of turbine power, and it can 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 moveable stators. DAWTs also preclude the exposure of turbine blades to cyclic operation in tower wake, and the diffuser moderates natural wind turbulence and short term directional fluctuations:

Based on the average costs of Fig. 5 it is possible to compare DAWT with conventional wind energy conversion systems (WECS) on the basis of:

- 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} . Thus a 40 m turbine in a DAWT with a $\bar{r} = 1.89$ requires that the turbine diameter of a conventional WECS be 55 m in order to yield equal power ratings. Of course, if the WECS turbine must be increased much beyond 60 m, it is not currently realistic to consider such measures.

The two cost comparisons are presented by Figs. 6 and 7. In the case of equal rotor size in both systems (see Fig. 6) it is 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%) or up to 25% more costly.

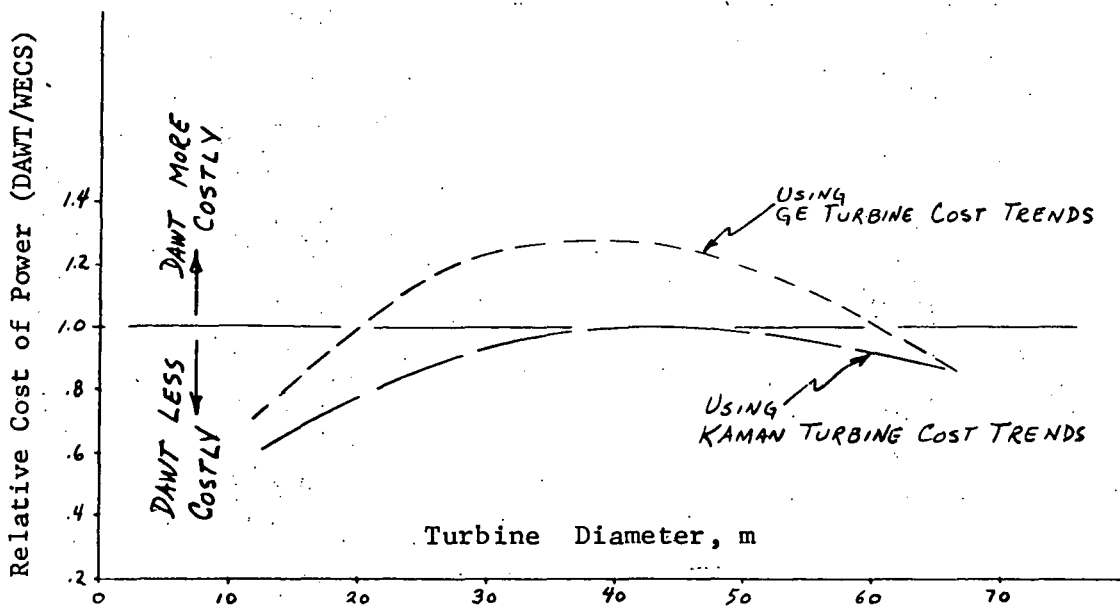


Fig. 6 Power Cost Comparison of DAWT and WECS for Equal Turbine Size

For equal rated power output, shown by Fig. 7, the DAWT can be significantly cheaper (~50%) than a WECS for turbine diameters greater than about 40 meters. For smaller turbine sizes, the DAWT can be marginally cheaper to significantly more expensive depending on which cost trend one actually experiences.

It should be noted that in both comparisons graphically depicted we have not attempted to include a quantified usable wind pattern

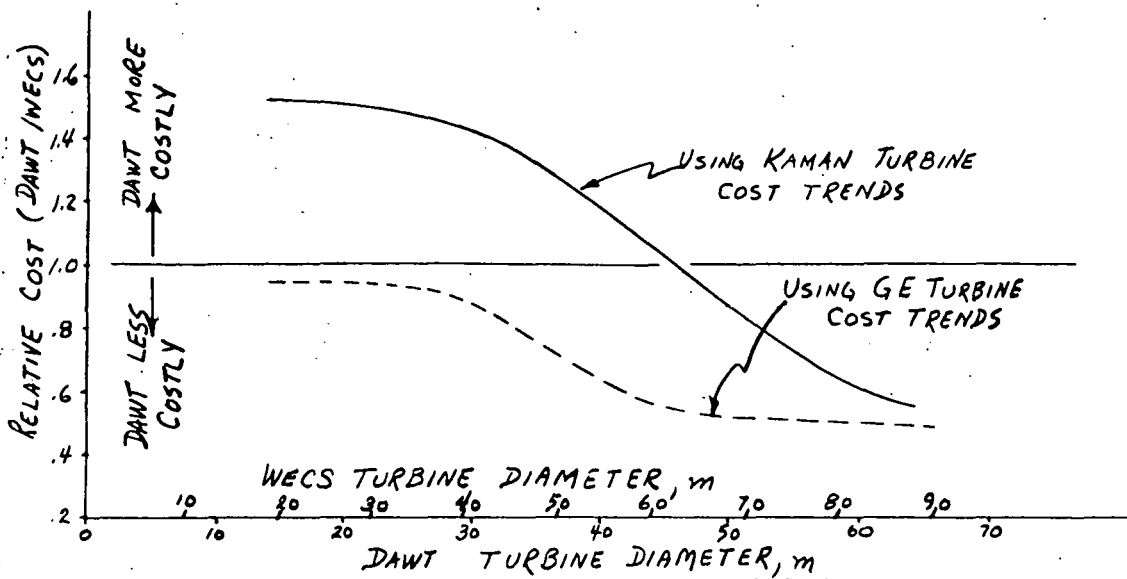


Fig. 7 Cost Comparison of DAWT and WECS for Equal Rated Power Output

factor. Because of the inherent wind speed-up features of the diffuser inlet section, this can result in 10% to 20% greater annual power conversion for the DAWT compared to the WECS, leading to a greater real economic advantage for the DAWT during each year of operation.

CONCLUSIONS

Our investigation of cost-effective diffuser augmentation of wind turbines has revealed at least two effective types of diffusers:

- Boundary layer controlled diffusion
- Flapped ring wings

Model tests have demonstrated significant power augmentation capabilities for DAWT, approaching a factor of 2. Diffuser exit plane pressure substantially below atmospheric ($\sim 0.6 q_0$) has been verified. Because of this low pressure it is possible to pump much larger amounts of air through a DAWT's wind turbine than a conventional WECS, and thus convert more power.

Economic studies using the most recent turbine cost trends and Grumman-generated diffuser cost estimates show that DAWT have lower specific power costs than WECS for very large and for small turbine diameter sizes. The relative direct benefits of DAWT in the intermediate size range are somewhat obscured by the significant uncertainty of realistic turbine cost estimates; DAWT can be marginally cheaper to much more expensive depending on whose authoritative judgement is used. The indirect benefits of DAWT, including a potentially greater

factor for usable annual wind energy pattern, probably means that DAWTS generally become more economical than conventional WECS, regardless of size or turbine costing, the longer they are in operation.

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