ADVANTAGES OF THE DIFFUSER-AUGMENTED WIND TURBINE

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The fact that substantial performance advantages can be realized by the use of a shroud and diffuser on a wind turbine was recognized in the 1950's. The work of Lilley and Rainbird (ref. 1) indicates that diffuser-augmented turbines can produce up to twice the power of unshrouded turbines of the same diameter, and our independent analysis indicates the same range of performance improvement. Even more attractive is the potential for operational flexibility afforded by the diffuser, enabling useful power generation at lower and higher wind velocities, and simpler control features.

Figure 1 shows an artist's conception of a diffuser-augmented wind turbine. The basic function of the diffuser is to convert the kinetic energy of the flow downstream of the rotor into a pressure rise. This lowers the pressure level behind the rotor, and makes it possible for the rotor to capture airflow from a free stream tube area that is greater than that of the rotor itself. The inlet area need not be large, as the stream tubes will converge naturally to the inlet if the diffuser is sufficiently effective. The optimum conditions for such a system are very significantly different from the familiar ideal optimum for an unshrouded rotor (cf. Glauert, ref. 2). The flow velocity through the rotor is typically 20 to 60 percent greater than the free wind velocity as opposed to 67 percent less than the free wind for the unshrouded case. In addition to offering more output per unit rotor area, this fundamental change in stream tube configuration enables practical rotor designs to operate even at very low wind speeds. The presence of the diffuser also offers the opportunity to accommodate to very high wind speeds without the need for variable pitch in the rotor blades. These large performance and operational advantages may be sufficient to overcome the cost of the large diffuser, especially in applications for which storage is a significant cost factor.

Our one-dimensional analysis differs from that of Lilley and Rainbird in that the drag of the shroud does not enter explicitly into the performance prediction. Figure 2 shows that stations used in the analysis, and indicates schematically that the upstream capture area is greater than that of the rotor, but smaller than that of the rotor stream tube far downstream of the diffuser exit. We define the ideal power coefficient $C_{P_i} \equiv \Delta p_{23} V_2 / (1/2) \rho V_0^3$, which through Bernoulli's equation, continuity, and a statement of losses in inlet and diffuser can be expressed as

$$C_{P_i} = \Big[1 - K_i - C_{p_4}\, \varepsilon - (1 - \eta_D)\varepsilon^3 - \eta_D \varepsilon^3 \lambda^2$$

where $\varepsilon = V_2/V_o$, K_i is the inlet loss coefficient, η_D is diffuser efficiency, $C_{p,4} = (p_4 - p_o)/(1/2)\rho V_o^2$, and $\lambda = A_3/A_4$.

The optimum velocity ratio and the corresponding ideal power coefficients are shown in figures 3 and 4, while the off-optimum performance is shown in figure 5, all for $K_i = -C_{p,4}$. Because of the very low exit velocity, viscous entrainment downstream of the exit should make it possible to operate with slightly negative $C_{p,4}$, increasing ideal performance beyond that indicated. It is to be understood that no real turbine could achieve these ideal figures, but the relationship between shrouded and unshrouded systems should be at least as favorable to the diffuser-augmented type as that shown. The effect of the shroud in reducing tip losses is not accounted for in this analysis, nor is the reduced swirl loss due to radial expansion in the diffuser and the reduced optimum disk loading of the diffuser system ($\Delta p_{23}/(1/2)\rho V_o^2 =$ 2/3 versus 8/9 for the unshrouded optimum).

The relative advantages of a diffuser-augmented wind turbine will be sensitive to the type of application; that is, the size of unit, the economic value of a broader operating range, and the local wind spectrum. Technical issues that need better definition are the relationships between diffuser efficiency and diffuser geometry with a turbine exhaust as input flow, the range of $C_{p,4}$ that can be achieved with a practical external contour as a function of V_4, diffuser and support construction costs, optimization of λ for given applications, and trade-offs for rotor design factors such as pitch control and disk loading as affected by the diffuser.

REFERENCES

1. Lilley, G. M.; and Rainbird, W. J.: A Preliminary Report on the Design and Performance of Ducted Windmills. Technical Rep. C/T119, The British Electrical and Allied Industries Research Association, Great Britain, 1957.

2. Glauert, H.: The Elements of Aerofoil and Airscrew Theory. Second ed., Cambridge University Press, 1948.

DISCUSSION

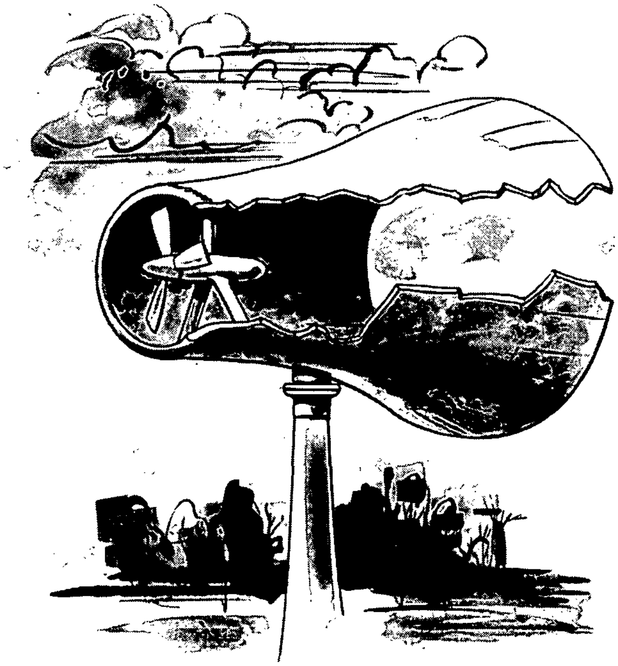
COMMENT: Our calculations show very similar results. One point, though, which I am sure the speaker is aware of is that a ducted rotor is never better than a free rotor that has an area equal to the area of the duct exit.

A: Right. The equivalent rotor would be between the two. It can be better in that it can have a very much lower wind velocity cut-in speed.

That could be more important than the power per unit size.

Q: Did the speaker ever consider actually making the duct rotate with the rotors? What might the losses be in a system like that?
A: On what axis?

Q: Just fasten the rotor tips to the duct itself, so that you removed all your clearance and mechanical problems, and have the duct go round.
A: I think the bearing problem would bother us more than the tip losses at the wall would.



DIFFUSER-AUGMENTED TURBINE

Figure 1

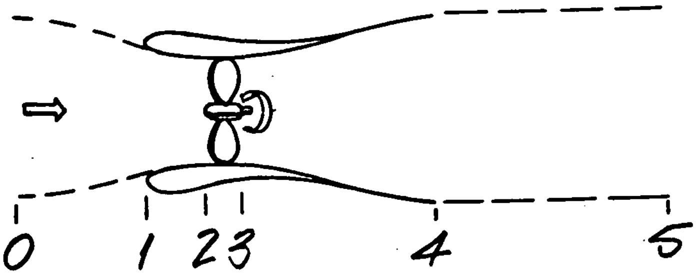


Figure 2

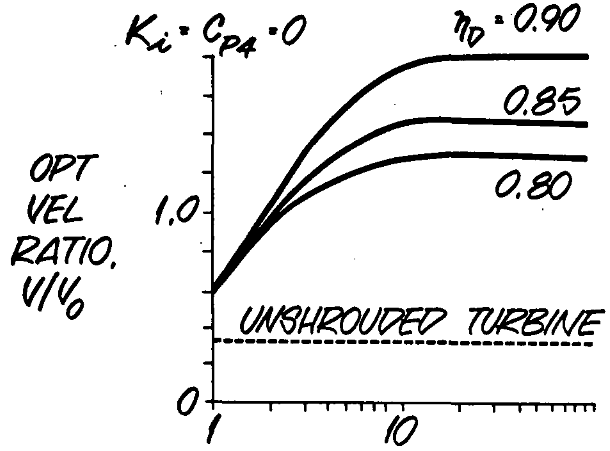


Figure 3

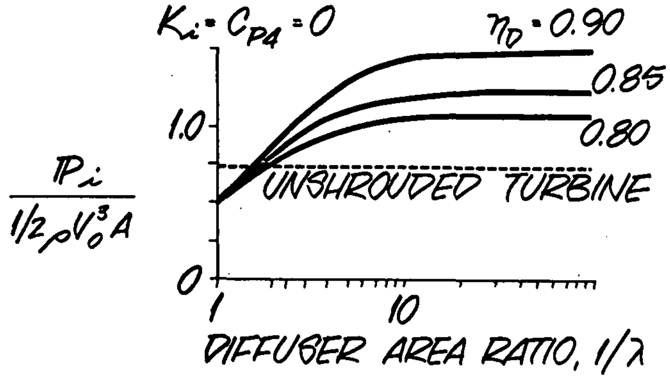


Figure 4

OFF-DESIGN PERFORMANCE

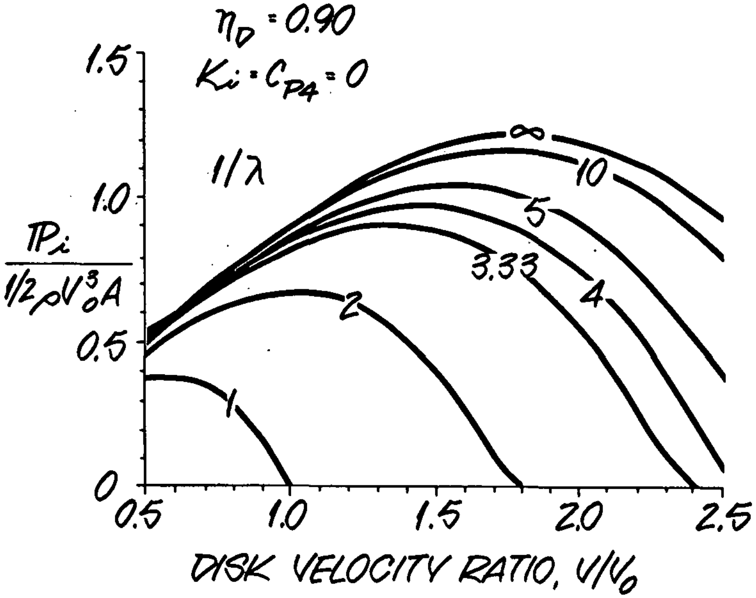


Figure 5