Developments in ducted water current turbines

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Brian Kirke
Sustainable Energy Centre, University of South Australia, Mawson Lakes, SA 5095, Australia

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Abstract

Unlike conventional hydro and tidal barrage installations, water current turbines in open flow can generate power from flowing water with almost zero environmental impact, over a much wider range of sites than those available for conventional tidal power generation. Recent developments in current turbine design are reviewed and some potential advantages of ducted or "diffuser-augmented" current turbines are explored. These include improved safety, protection from weed growth, increased power output and reduced turbine and gearbox size for a given power output. Ducted turbines are not subject to the so-called Betz limit, which defines an upper limit of 59.3% of the incident kinetic energy that can be converted to shaft power by a single actuator disk turbine in open flow. For ducted turbines the theoretical limit depends on (i) the pressure difference that can be created between duct inlet and outlet, and (ii) the volumetric flow through the duct. These factors in turn depend on the shape of the duct and the ratio of duct area to turbine area. Previous investigations by others have found a theoretical limit for a diffuser-augmented wind turbine of about 3.3 times the Betz limit, and a model diffuser- augmented wind turbine has extracted 4.25 times the power extracted by the same turbine without a diffuser. In the present study, similar principles applied to a water turbine have so far achieved an augmentation factor of **3** at an early stage of the investigation.

Keywords: Water-current turbines, ducted, diffuser-augmented

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1. Introduction: static head and current flow tidal power

There are basically two methods of extracting energy from tidal flows. The conventional method is to place a barrage across an estuary with a large tidal range to create a static head or pressure difference, and operate a low head hydro-electric power plant with intermittent, reversing flow. The best known example of this approach, which has been treated in detail in Baker [1], is the 240 MW installation in the Rance River Estuary in France, completed in 1966. An interesting variant has been proposed for Derby in Western Australia, where two adjacent tidal basins exist [2]. The proposal is to allow flow from the ocean into one estuary at high tide and out of the other at low tide, thereby creating a permanent difference in level between the two basins. A steady one-way flow could then be maintained through turbines in conduits connecting the estuaries. More efficient turbines can be used for one-way flow, and a steady flow overcomes one of the major drawbacks of most ambient energy sources, i.e. intermittent availability. Pumped storage also becomes a possibility, whereby water is pumped back into the higher basin at off-peak periods for use during peak periods. However this scheme, like other proposals for large schemes based on static head, suffers from the drawbacks of expensive civil works, disruption to shipping and environmental concerns.

The less well-known method of extracting energy from tidal and other flows is to convert the kinetic energy of moving water directly to mechanical shaft power without otherwise interrupting the natural flow, in a manner analogous to a wind turbine. This concept is not entirely new, having been investigated by Reading University in the UK in 1979 [3], by Davis in Canada [4] and by Hilton in Australia at about the same time [5]. It was in use in Africa on a small scale in the early 1980s to extract energy from river currents [3].

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*Corresponding author: Tel: +618 83023026; fax: +618 83023380.
E-mail address: Brian.Kirke@unisa.edu.au

But the idea of using current flow on a large scale is new. Even as recently as 1991 a complete book on tidal power made no mention of the concept [1]. It is only now that this concept is being explored for larger scale use [4, 6, 7, 8, 9, 10, 11].

Direct conversion of kinetic energy by a turbine in open flow harnesses less of the total available energy in a tidal flow in an estuary than could be extracted by damming the whole estuary. However direct conversion has several advantages:

1. The capital cost of civil works is eliminated.
2. Disruption to ecosystems and boating is minimised.
3. Ocean currents, wind-induced currents and river flows as well as tidal flows can be used. There is no need for a large tidal rise and fall – for example the Messina strait between Sicily and the Italian mainland has 2.4 m/s currents with negligible rise and fall [11]. Hence a wider range of sites can be exploited, including rivers, straits between islands, sites off headlands and any other sites where there is frequent or constant strong flow.

There are also some potential problems with tidal or marine current turbines. These include

1. Very large downstream drag forces, several times larger than those acting on a wind turbine of similar power output, requiring strong anchorage.
2. Weed growth on blades, which could reduce their efficiency.
3. Corrosion.
4. Storm damage.
5. Possible danger to shipping and to swimmers in some areas.

However these problems should not be insurmountable, given the knowledge gained from some two centuries experience with ship propellers and several decades of experience with offshore oil platforms**. … reports that a 300 kW tidal stream turbine has operated successfully off the Devon coast in the UK (ref)**

2. Recent developments in current flow turbine design

Unlike wind turbine design, which is now a mature technology in which the axial flow propeller type turbine has emerged as the preferred design, water current turbine design is at an early stage of development. Incremental improvements to wind turbine technology since the early 1980s has reduced the cost of grid-connected wind energy by a factor of about 5, to the point where it is now economically competitive with conventional fossil fuels in some areas. This process has not yet happened with water current energy conversion, and subsidies will be needed for research for some time to come.

The potential contribution of this form of energy is huge: it has been estimated that the UK could obtain 20% of its electricity from tidal currents [12]. Several forms of turbine are being investigated around the world and none has yet emerged as a clear winner. Some of the various forms currently being evaluated are reviewed below.

2.1 Axial flow turbines

Marine Current Turbines Ltd in Britain are pioneering the use of axial flow turbines. In 1994 they demonstrated a 10 kW axial flow turbine in Loch Linnhe in Scotland, and they are currently developing a 300 kW turbine for the Severn Estuary off Devon, England [7, 8, 9, 10]. This turbine is expected to resemble one or two conventional wind turbines, mounted on a cantilever tower fixed to the ocean floor (Fig.1). Other small pontoon-mounted axial flow turbines have been built, for example by Teamwork Technology in the Netherlands [13] and by Swenson at the Northern Territory University in Darwin, Australia [14].

2.2 Cross flow turbines

Turbines in which the direction of flow is across the axis of rotation are commonly referred to as “vertical axis” turbines, since their axis is usually vertical. However they are more accurately described as “cross flow” since their distinguishing feature is the fact that the direction of flow is across the axis of rotation, which may be horizontal. Davis conducted laboratory tests on a cross-flow water turbine in 1981-2 and constructed a prototype which produced 20 kW electrical power and an estimated 45 kW shaft power in 1983 [4]. More recently a 6 m diameter vertical axis turbine (Fig.2) has been installed in the Strait of Messina, between Sicily and the Italian mainland. It is expected to produce about 50 kW electrical in a 2.4 m/s current [11]. Gorlov and co-workers in the United States have tested models of a cross-flow turbine with helical blades and claim that its performance is superior to a conventional Darrieus cross flow turbine [15]. Gorlov has proposed large helical blade turbines to convert energy from the Gulf Stream. Salter [16] has proposed a large cross-flow turbine with 10 blades supported by rings top and bottom, driving ring-cam hydraulic pumps to deliver 10 MW in a 4 m/s current.

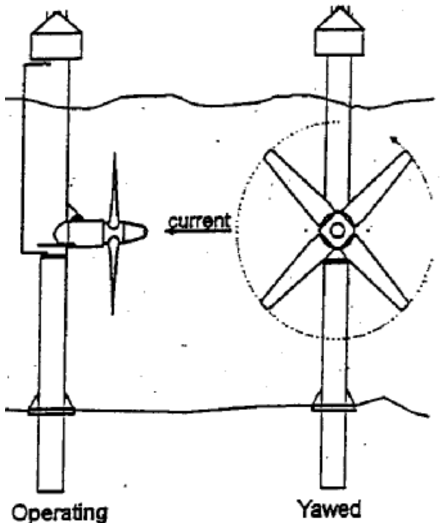

Fig.1. Open axial flow turbine concept [7].

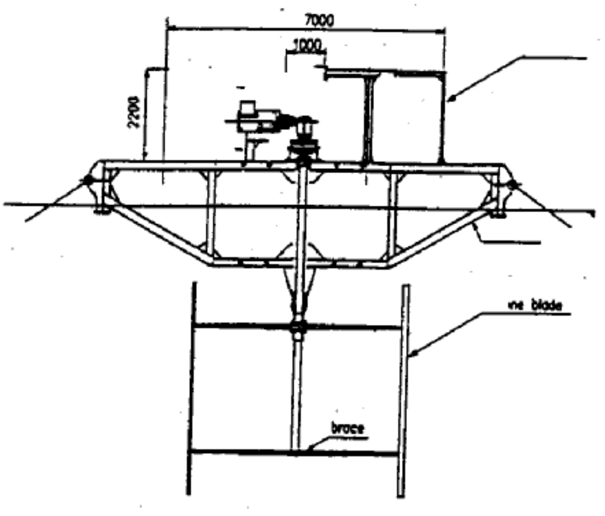

Fig.2. Italian cross flow turbine [11].

3. Open and ducted turbines

Like conventional hydropower turbines, installations such as the Rance River in France utilise the pressure difference created by a static head, i.e. the potential energy inherent in a difference in water surface elevation. In contrast, wind turbines and open water current turbines such as those shown in Figs. 1 and 2 utilise the kinetic energy of a moving fluid directly. Between these extremes, Darrieus [17] proposed placing turbines in ducts to augment the power extracted from a given sized turbine.

Blue Energy Canada has proposed two variants on this theme: a single turbine can be placed in a duct in open flow without obstructing the free flow of water around the installation, or alternatively their proposed “tidal fence” (Fig.3) forces all of the flow to pass through the turbines. They have proposed an ambitious scheme to build a tidal fence across a strait and use a large number of vertical axis turbines to produce up to 2200 MW [4, 12]. Recently other organizations have also been investigating this concept. Ponta and Dutt [18] have tested various profiles for a channelling device or duct to increase the available pressure drop and flow velocity through a cross-flow turbine. Teamwork Technology’s Tocardo turbine [19], Fig.4 is an example of a ducted axial flow turbine.

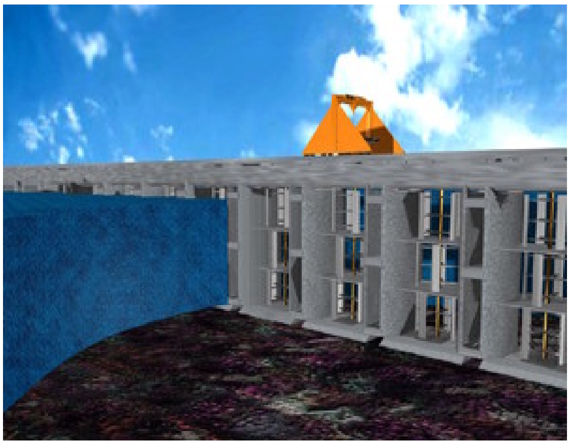

Fig.3. Tidal fence concept [4].

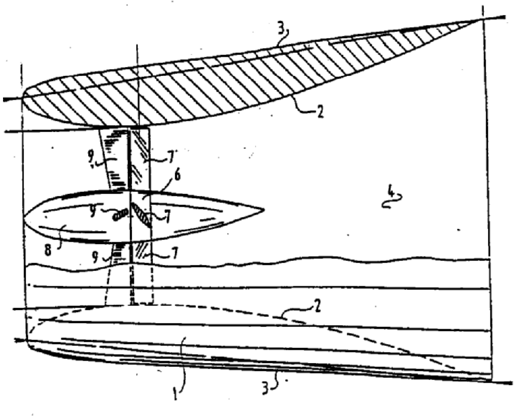

Fig.4. Ducted axial flow turbine [19].

4. Advantages of ducted turbines

There are several practical advantages in placing the turbine in a duct.

1. In areas where there is a danger of divers and/or floating debris being drawn into the turbine, a grid could be placed on the upstream opening, thus reducing danger to life and danger of damaging or clogging the turbine.
2. The duct shades the turbine itself from direct sunlight, and weed growth will thereby be reduced. Along with floating debris, this was one of the major problems experienced by Swenson in his work on tidal turbines in tropical waters near Darwin (Swenson, 1999).
3. A large duct made of low cost materials can be designed so the downstream side acts as a diffuser and reduces the downstream pressure, thereby increasing the available pressure drop, drawing in more flow and increasing the power output of a given sized turbine. Put another way, large flow area containing a large amount of energy is concentrated into a smaller area so that a smaller, lower cost turbine can be used for a given power output. Because a smaller turbine in a faster flow spins faster, the torque for a given power output is less and a smaller, lower cost gearbox can be used. This is a highly significant factor since flow velocities and hence turbine speeds are low and very large torque is required to produce useful amounts of power.
4. The duct eliminates tip losses on axial flow turbine blades, improving efficiency
5. A rotating rim could be provided flush with the static duct, joining the blade tips of an axial flow turbine, with a belt or geared drive on its outside, thereby eliminating torque on the main turbine shaft.
6. This idea has been taken a step further in the Tocardo turbine, with magnets incorporated in the blades and stator windings in the duct so that the turbine rotor also functions as the rotor of a permanent magnet generator, thereby eliminating gearing as well as torque on the main turbine shaft [20].

5. Principles of operation of ducted turbines

Open turbines extract energy from the fluid by reducing the flow velocity with little or no pressure reduction as the fluid passes through the turbine rotor. The streamlines must therefore expand to maintain continuity (Fig.5) and they cannot expand indefinitely: hence there is a theoretical limit to the percentage of kinetic energy that can be extracted from the fluid. This limit has been shown by Betz [21] to be 16/27 or 59.3% for a single actuator disk (i.e. surface across which energy is extracted as the flow passes through it). Newman [22] showed that the corresponding limit is 16/25 or 64% for a double actuator disk such as a cross flow turbine.

But if a duct is provided around the turbine as in Fig.4, the flow boundaries are defined and streamline expansion is limited by the duct geometry. Energy is extracted primarily by a pressure drop, and in this way the turbine behaves more like an ultra-low head hydro turbine than like a conventional wind turbine. The maximum power available is the product of flow times available pressure drop. Radial flow along the blades of an axial flow turbine is prevented by a duct, and high conversion efficiencies up to about 90%, similar to those achieved by hydro turbines, should be achievable.

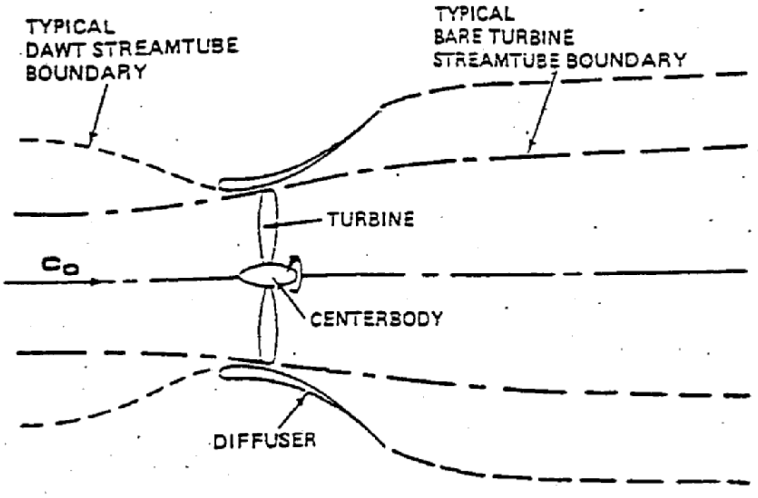

Fig.5. Streamlines through turbine in open flow and DAWT [23].

The pressure drop available to a ducted turbine depends on the shape of the duct and the flow through and around it. If the duct is designed as a diffuser it will draw more fluid through it and will also increase the available pressure drop across the turbine by recovering some of the velocity head downstream as pressure head. The turbine then becomes “diffuser- augmented.” Considerable work has been done on diffuser-augmented wind turbine design, but the concept has not so far been systematically applied to water turbines, with the possible exception of Blue Energy. Their web page [4] refer to tests in a laboratory flume in Ottawa in 1981-2 from which they estimated that an augmentation factor up to about 5 could be achieved in a ducted cross-flow water turbine. However they have not discussed the diffuser concept nor published any experimental data in the literature.

Riegler [23] showed that the theoretical maximum power coefficient for a diffuser-augmented turbine based on turbine area is 1.96, i.e. 3.3 times higher than the Betz limit. This is possible because flow is drawn in from a greater area upstream than that intercepted by the same sized turbine in open flow.

After much experimentation with wind tunnel models, Gilbert and Foreman [24] reported a power augmentation factor of 4.25 for a turbine with a diffuser, i.e. it produced 4.25 times as much power as the same turbine in open flow. They used slots (Fig.6) to draw in high energy flow from outside the diffuser for boundary layer control and were able to achieve this result with a short, wide angle diffuser, a much more economical arrangement than the long diffusers studied by a number of other investigators.

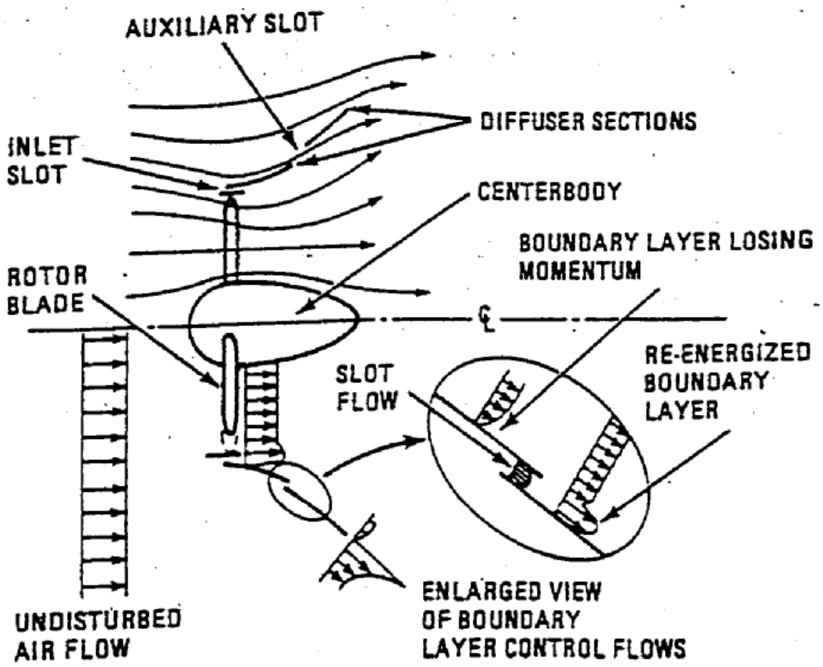

Fig.6. Short, wide angle diffuser with slots for boundary layer control [24].

Their measured augmentation factor of 4.25 is not inconsistent with Riegler's theoretical finding because the turbine they used had untwisted blades of low aspect ratio and its performance in open flow would have been well below the Betz limit.

It has been strongly argued by Dörner [25], with some justification, that the additional cost of a diffuser on a wind turbine will far outweigh the advantages. Wind turbines must be designed to survive wind forces many times higher than those at which they develop their rated power output. They normally do this by feathering either the complete turbine rotor or the blades to reduce the area presented to the wind. This cannot be done with a diffuser, which presents a large area to the wind whatever its orientation. Further, an axial flow wind turbine must normally be made to yaw to follow rapid changes in wind direction, so that the diffuser must be made not only very strong, but also light to minimise its inertia. Even so, Vortec in New Zealand raised enough capital to construct a 7 m diameter turbine based on the findings of Foreman and Gilbert before going into liquidation.

In contrast to wind turbines, the maximum loads on a marine current turbine can be accurately predicted and are in the same order as normal operating loads. Further, a marine current turbine duct can be made neutrally buoyant so that its weight need not be supported by a tower. It can be used to support the turbine and can be moored so that it orients itself into the current like a boat at anchor. It can therefore be argued that Dörner's criticisms are not applicable to marine current turbines.

6. Experimental work

Experimental work is being undertaken in conjunction with Tidal Energy Pty Ltd of Palm Beach, Queensland, in several stages:

1. model performance testing in a flume
2. flow visualisation on a flow table
3. model performance testing in a tow tank
4. prototype testing under a motor-driven pontoon in still water
5. prototype testing under a moored pontoon in a current.

1. In 1999 a 0.2 x 0.4 m cross flow turbine was tested in two ducts of parabolic profile in a flume at the Queensland Government Hydraulics Laboratories at Deagon in Brisbane. Because very small Darrieus turbines do not generally self-start [26], a Savonius rotor was used. The aim was to assess the augmentation factor rather than to demonstrate maximum overall efficiency, and the characteristics of Savonius rotors are well known. Although these tests indicated some augmentation it was difficult to quantify the effect as the turbine was not tested without a duct and bearing friction was significant.

2. Flow table tests were subsequently conducted on various two-dimensional duct profiles to visualise qualitatively the effect of the profile on the flow pattern. In particular we were interested in the possibility of enhancing the boundary layer control effect demonstrated by Foreman and Gilbert [24], by using flaps or slats of aerofoil profile. These tests showed clearly how the duct draws in the upstream flow (Fig.7).

Fig.7. Flow table dye traces showing flow drawn in upstream (on left).

However the Reynolds numbers were low and flow was laminar. It is well-known that aerofoils perform poorly in laminar flow, and the diffuser effect of the downstream part of the duct is similar to the action of a wing section in that it must deflect the flow. Consequently these tests did not conclusively demonstrate diffuser action. In fact two diffuser profiles based on those shown in Foreman and Gilbert’s patent specification [27] completely failed to demonstrate diffuser action.

3. Tow tests were then conducted on a 280 mm diameter high solidity axial flow turbine to compare the power and efficiency of the bare turbine with that of the same turbine in various types of duct. This type of turbine was used as it was readily available, self-starting and more efficient than any type of cross flow turbine in very small sizes. Since the aim of this phase of the work was to compare the performance of the bare turbine with that of the same turbine in a duct, the exact dimensions of the turbine were not important. The impeller of a desk fan was used as a turbine. A slatted duct of rectangular section was used as it is easier to construct than one of circular section, and a sheetmetal transition of the type used in air-conditioning ducts was used between the circular shroud around the turbine and the rectangular diffuser portion. Results plotted in Fig.8 show approximately 70% increase in output with a slotted diffuser. The trend curve for the ducted turbine suggests higher efficiencies at less than 50 RPM. However it was not possible to obtain data points at lower speeds by increasing the load torque as this stalled the turbine. The result was encouraging in that it demonstrated the augmentation effect of the diffuser, but the somewhat clumsy duct arrangement was never intended as a pattern on which full-scale prototype could be based.

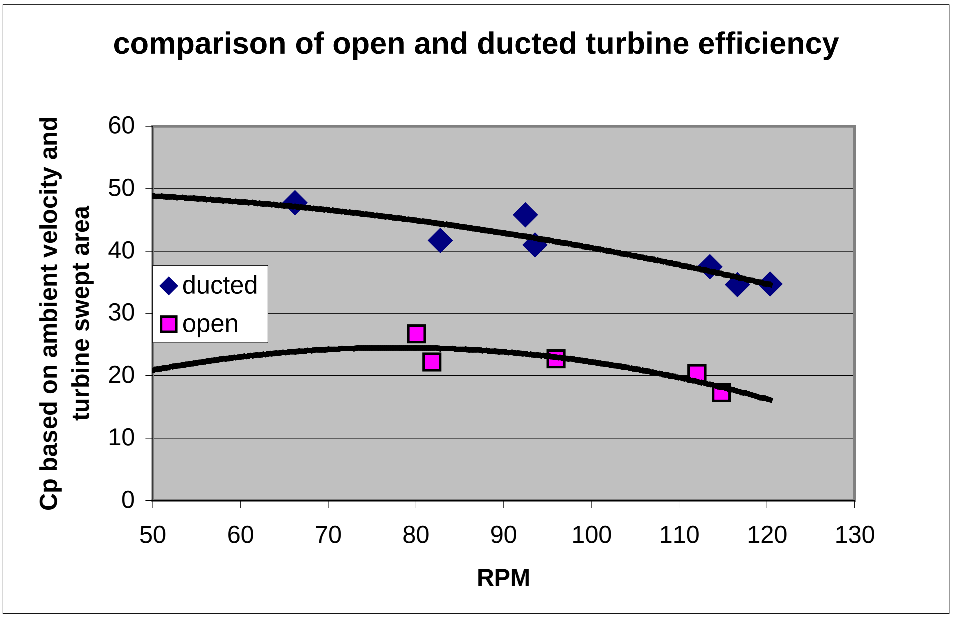

Fig. 8. Performance of model axial flow turbine with and without diffuser.

4. The next step was to build a turbine in a form which could be scaled up. A cross-flow turbine was selected for three reasons:
   (i) It can fit in a rectangular duct, which is much easier to fabricate than a duct of circular section, especially when it is made up of aerofoil section slats.
   (ii) It is easier to measure the power on a vertical shaft which protrudes above the water
   (iii) The author has some experience in the design of cross flow wind turbines

However an axial flow turbine may yet prove superior in larger installations.

A 1.2 m diameter Darrieus turbine was constructed with 3 straight, 1.2 m long fibreglass blades of 100 mm chord length, giving a solidity nc/r = 0.5 where n is the number of blades, c is the chord length and r is the turbine radius. The blades were mounted between two discs rather than on radial arms as is normal with straight blade Darrieus turbines, so the discs could form part of the duct when the turbine was operating in a duct. A cambered blade section was used in preference to a symmetrical section because cambered sections tend to perform much better than symmetrical sections at low Re and positive incidence, more than compensating for their inferior performance at negative incidence. Modelling reported in [26] predicts superior performance of small Darrieus turbines with cambered blades compared to those with symmetrical blades. The FX 63-137 section was selected from a large range of sections designed for low Reynolds number operation as it appears to give the best combination of structural strength and high lift to drag ratio over a wide range of incidence, according to data published in [28]. With relative velocities of only a few m/s, cavitation is not expected to present a problem with this profile. At higher relative velocities different blade profiles can be used to avoid cavitation [11].

The 100 mm chord length was expected to give blade chord Reynolds numbers ranging from 10^5 to 3×10^5, assuming a tipspeed ratio of 2 in an ambient flow of 1 m/s. A compromise was necessary, since larger chord length gives greater mechanical strength and higher Reynolds numbers with correspondingly better individual blade performance, but higher turbine solidity which generally leads to poorer overall performance. A discussion of these conflicting requirements for small Darrieus turbines is given in [26]. The number of blades was subsequently increased to 4 and blades were allowed to pitch, initially through ± 5° and then through ± 10°, to give more even torque as the turbine rotates. Water turbines rotate much more slowly than wind turbines of similar size, and it was found that the inertia of the rotor was not enough to even out torque fluctuations with azimuth angle.

The turbine was tested by mounting it in front of a motorised barge (Fig.9) and driving it at a steady speed, as far as possible, in still water. This is equivalent to mounting the turbine under a fixed pontoon in moving water, but it has the advantage that the relative velocity between the water and the turbine can be controlled.

Fig.9. Ducted turbine mounted on motorised barge, tilted partly out of the water to show construction.

The velocity was measured using a Swoffer propeller type current velocity meter mounted on a pole well out to the side of the turbine. The available power in the water was then calculated from

$$P_w = \frac{1}{2} \rho A V^3$$

Where ρ is the fluid density = 1000 kg/m^3 for water, A is the turbine swept area and V is the ambient water velocity. Turbine angular velocity ω was measured by counting the time for 5 revolutions. Torque T was measured by noting the tensions at the two ends of a rope wrapped around a 400 mm diameter pulley mounted on the turbine shaft and the shaft power output was calculated from

$$P_T = T\omega$$

The performance coefficient C_p is given by

$$C_p = P_T/P_w$$

For comparison purposes the same definition was used for C_p for the ducted turbine, although the velocity through the turbine in this case is actually greater than ambient so an apparent $C_p > 1$ is theoretically possible. The turbine was tested by driving it at speeds ranging from 0.5 to 0.9 m/s, initially without a duct, with the blades allowed to pivot freely up to ± 5°. The pitch amplitude limits were then increased to ± 10° and the bare turbine was tested again. A duct was then added, as shown in Fig.9. The duct is flat on the top and bottom faces, incorporating the discs on which the blades are mounted, and the sides are made up of aerofoil section slats.

7. Results and discussion

As shown in Fig.10, overall performance of the bare turbine was low. This is to be expected, considering that blade chord Reynolds numbers were significantly lower than anticipated, ranging from 115000 to 241000 on blades moving upstream, down to 0 to 67000 on blades moving downstream. This was partly due to the limitation on speed imposed by the 10 HP outboard motor used to drive the pontoon and partly to the lower than expected tipspeed ratio range. But the significant finding was that the performance increased by a factor of about 3 when the duct was added, as shown in Fig.10. This is consistent with the findings of [23] and [24]. The scatter in the data points appears to be mainly due to the difficulty in maintaining a steady speed, which was not anticipated. It was difficult to hold the speed within a range of ± 5%, which corresponds to ± 15.7% in available power.

A 2.4x2.4 m turbine and a larger barge were subsequently constructed and the turbine tested in 2005 in the same manner, at similar speeds (i.e. up to about 0.7 m/s). As expected, with higher blade chord Reynolds numbers the maximum C_p was considerably higher, just under 60%. The 2.4x2.4 m turbine was not tested without the diffuser due to practical difficulties, so it is not possible to determine the augmentation factor, but since it is geometrically similar to the 1.2x1.2 m turbine it is reasonable to assume that it was similar. The intention is that assembly will be motored to a suitable site and moored in moving water where the current velocity will not be controllable but should be steady over the duration of a test. It is reasonable to expect that with further optimisation of the geometry, still higher efficiencies could be achieved.

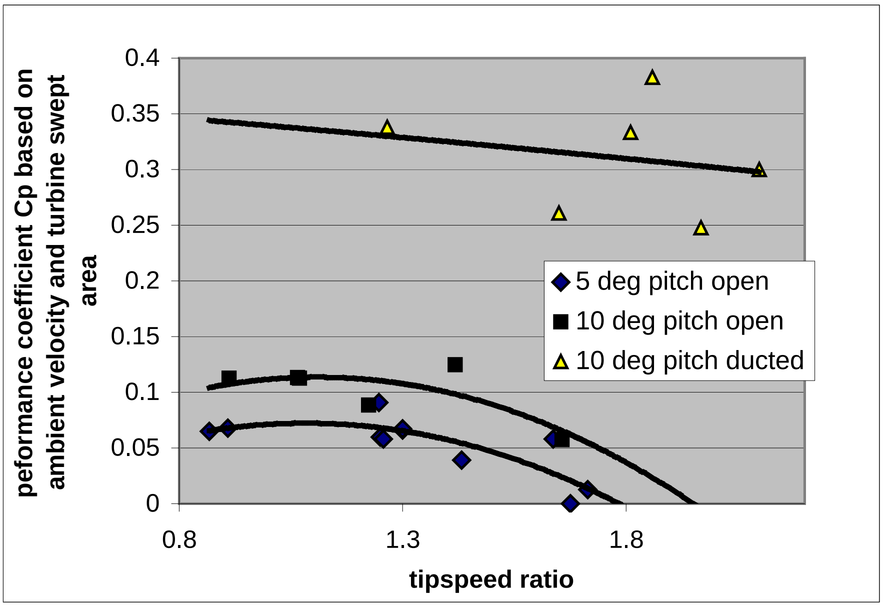

Fig.10. Performance of a small straight blade Darrieus turbine at low Re with and without a duct.

Conclusions

Water current turbines, which operate in a manner analogous to a wind turbine, are a relatively new technology which can generate power from flowing water with very little environmental impact. A duct placed around the turbine has several potential advantages. The maximum efficiency of energy conversion by ducted turbines is not subject to the Betz limit of 59.3% of the energy incident on the swept area of an open turbine, since a suitably shaped duct can draw in flow from a larger area and increase the available pressure drop across the turbine, generating about three times more power than an open turbine of similar swept area. Besides these theoretical advantages, a duct has several major practical advantages, including improved safety, protection from weed growth, increased speed and reduced turbine and gearbox size for a given power output. Unlike diffuser augmented wind turbines, ducted turbines in water do not need to be supported by a tower with a yawing mechanism. The duct can be constructed of low cost, heavy material such as structural steel, and can be moored under a pontoon, which forms part of the duct, so that it swings to face the current. It is concluded that the ducted tidal current turbine is an attractive option for further development.

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