Diffuser Augmented Wind Turbine (DAWT) Technologies: A Review

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Abstract- Diffuser Augmented Wind Turbines (DAWT) are an optimised class of wind turbines that use a Diffuser to accelerate and direct air flow onto a wind turbine rotor to drive it for higher rpm and power output than without the Diffuser. This power output is typically rated in terms of the power augmentation. Diffuser design and theory was pioneered in the 1970's with a recent re-emergence in a range of new technological approaches that are designed for laminar wind profiles, low exit pressures, improved pressure recovery, improved torque generation and adaptability to wind directional and speed changes. Computational Fluid Dynamics (CFD) theory and software has been crucial in the advancement of design and performance of DAWT's. Power augmentations have been achieved within the range of 2-3 for small-medium scale turbines, though this is largely in theory than in practice. In this review, ground-based Diffuser technologies have been presented according to rotor type, i.e. horizontal- and vertical-axis. Large-scale on-shore and off-shore concepts have been presented along with airborne technologies. Building-integrated DAWT's are then presented with a description of some of the influential economic and technical factors that currently affect the development of the DAWT industry. The current DAWT industry is mostly research-based with very little commercialisation as the majority of technologies presented here are in their early developmental stages. Innovations in issues associated with the increased weight of a Diffuser, the effects of loading, turbine stability, vibrational effects during operation and yaw angle effects are necessary in the advancement of DAWT's.

Keywords Augmentation factor, DAWT, Diffuser, Energy, Wind Turbine

Nomenclature

A	Cross-sectional Area
C_p	Power Coefficient
C_D	Turbine Disk Loading Factor
C_{pr}	Pressure Recovery Coefficient
C_{pe}	Exit Pressure Coefficient
C_t	Thrust Coefficient
D	Diffuser Inlet Diameter
k	Turbulent Kinetic Energy
L	Diffuser Length
$\dot{m}$	Mass Flow Rate
$\boldsymbol{P}$	Power
P	Pressure
Q	Air Flow Rate

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r	Augmentation Factor
$\boldsymbol{T}$	Thrust
V	Velocity
Subscripts	
t	Diffuser Throat
e	Diffuser Exit
∞	Far Upstream/Downstream
Greek/Latin Script	
α	Angle of Attack
β	Area Ratio
ε	Turbulent Dissipation
γ	Back Pressure Velocity Ratio
Φ,θ	Diffuser Inlet Angle
ρ	Density
η	Diffuser Efficiency
Γ	Circulation
ν	Viscosity

1. Introduction

Global energy demands for electrical power and energy are continuously increasing. With depleting fossil fuel supplies, focus has notably shifted to renewable power generation to make anthropogenic energy use and demand more sustainable. There are a few factors propelling this development. Aside from the increasing need to replace existing conventional power generation technologies, an unprecedented increase in the effects of climate change and global warming is encouraging a faster response. In December 2015, an international pledge in Paris, France, was made to fund projects worth $100 billion to reduce carbon emissions, slow the global temperature rise and strengthen the shift toward renewable energy generation [1]. As such, wind power generation is a promising avenue. Albeit unable to completely replace conventional power systems in the short term, wind driven technologies[2] provide incredible potential and versatility in application.

Power generation by wind energy increased at a rate of 17.2% in 2015 up from 16.4% the previous year. Current worldwide installed capacity is at its highest at 63.7GW [2]. The growing global agenda to shift to renewables depends heavily on the invention of new technologies as well as the improvement of existing technologies. A multitude of research produced in recent years has addressed improvements in overall performance, efficiencies and the life-span of wind driven technologies.

From the early windmill to present day innovations such as the bladeless Saphonian turbine, wind power technologies have progressed significantly. There is a real desire to design turbines with larger power outputs for a given rotor swept area. Augmenting power with the action of a Diffuser is not a new concept. Diffuser Augmented Wind Turbines (DAWT) were introduced in the 1970's amid the oil crisis. Diffusers, also known as Shrouds[3], are aerodynamic structures commonly found in turbomachinery for aircraft engines and so they translate well to applications in wind technology. They are intended to increase wind turbine power outputs and optimise performance by accelerating air mass flow through their funnel-shaped structure. The Diffuser therefor contributes to increasing the capacity of a typical turbine by increasing the rpm of the rotor and decreasing its starting torque. The Diffuser also provides the turbine and its blades some protection from adverse climatic conditions and atmospheric exposure whilst also extracting power for stable operation in a wider range of wind velocities starting at low wind speeds and in turbulent conditions. This is beneficial towards a reduction in blade-tip losses and even encouraging a reduction in the rate of bird strike as airborne wildlife can perceive the Diffuser as a singular, stationary object compared to the blur of moving blades [3].

It has always been assumed that up-scaling a wind turbine rotor in terms of its rotor swept area was the main way to increase power output and capacity. The use of DAWT's however can be considered a lateral approach to optimising wind turbine performance without following the economies-of-scale approach. A Diffuser can, in theory, be applied to any conventional wind turbine. Indeed, the geometry of the Diffuser is such that it presents additional requirements for manufacture, installation and maintenance. The foundation and tower would also need to be strengthened [3].

It was during the *Innovative Wind Systems Conference* in the US (1979) that DAWT's were introduced and gained recognition as valid potentials for augmented power of conventional wind power systems. Unfavourable capital and O&M costs at the time however quickly slowed down DAWT popularity and focus shifted to the development of Horizontal Axis Wind Turbine (HAWT)

[2] Wind driven technologies also commonly known as Wind Energy Conversion Systems (WECS)

[3] Shrouds are often an assembly of one or more aerodynamic structures including a Diffuser

technology [4]. Due to the improvements in analysis tools for fluid dynamics, a re-emergence in interest for DAWT's have led to a range of studies into Diffuser aerodynamic design and analysis.

1.1 The Evolution of Diffuser Design

One of the earliest recorded assessments of the use of a Diffuser was in 1956 by Lilley and Rainbird [5]. Existing 1D theories on the performance of 'unshrouded windmills' compared to 'ducted windmills' were compared. Based on the 1D theory Lilley and Rainbird [5] had calculated that a 65% increase in maximum power could be achieved using a duct with a 3.5 area ratio and 15% pressure loss compared to a conventional system. The analysis was however based on rough geometries.

Pioneering research into DAWT's was notably conducted by Ozer Igra of the Ben Gurion University of the Negev in the 1970's. Igra investigated techniques in reducing the requirement of a large length-diameter ratio of a Diffuser without affecting performance. One such example was to blow or draw in air into the latter part of the Diffuser. Igra [6] conducted wind tunnel experiments for three different Diffuser designs with the same inlet section and different area ratios. In the experiment, a straight wall Diffuser with a series of drilled-in ports was used with an aerofoil cross-section and flat-plate ring around the exit (8mm gap between ring-flap leading edge and Diffuser trailing edge). Bleeding and the use of a ring-flap were investigated and compared. It was found that bleeding air (in or out) through all ports didn't improve flow separation but introduced more turbulence into the system than drawing air in. While blowing through some ports in the higher pressure region of the Diffuser was able to increase output power by 20%, using aerofoil ring-flaps increased power outputs up to 65%.

The importance of the aerofoil in Diffuser design is significant. The lift achieved when using an aerofoil increases the air mass flow through a Diffuser for a given length-diameter ratio compared to a straight-wall Diffuser. The latter does however have its own advantages in terms of reduced material weight, cost and reparability. Aranake *et al.* [7] conducted a 3D CFD analysis to compare Diffuser geometries with aerofoil cross sections. Four were computed; the Eppler E423, Selig S1223, NACA0006 (baseline design) and the FX 74-CL5-140. From a 2D analysis of the flow fields it was found that the Selig S1223 exhibited the best performance. The NACA0006 allowed an augmentation factor (for definition, see section *1.2*) of 1.92 and for the Selig S1223 it was 3.39 at a free stream velocity of 5m/s.

Fundamental to the development of Diffusers is the use of computational analysis. The two main methods involve Blade Element Momentum (BEM) theory and Computational Fluid Dynamics (CFD). The former, more commonly used, is a simple theoretical method developed for blade optimisation and rotor design. In CFD, Navier-Stokes equations are solved with a choice of turbulence models each approximating wind turbulence. Apart from experimental testing, computational analysis has proved a crucial tool that has allowed an accurate understanding of flow characteristics through the Diffuser. These include velocity and pressure profiles, the effect of turbulent and steady state flow, boundary layer effects, flow separation, wake rotation etc. all of which are fundamental to Diffuser design and performance. Different approaches in assessing augmentation have been applied in a variety of CFD studies. Most studies do not consider all influences of augmentation parameters in any one study as usually only a few are prioritised based on design.

Jafari and Kosasih [8] modelled a simple Diffuser for a small turbine, AMPAIR 300, in a virtual wind tunnel for a range of rotor rpm's at a constant wind speed to obtain tip speed ratios. Kosasih and Hudin [9] investigated the effect of different turbulence intensities on a DAWT and an equivalent bare wind turbine (NACA 63-210, 190mm diameter) so as to measure their relative performance in terms of coefficient of performance and tip speed ratio. Mansour and Maskinkhoda [10] used the Spalart-Allmaras and $k-\varepsilon$ RNG (Re-Normalisation Group Theory) turbulence models to study the flow fields around flanged Diffusers using equal dimension flanged DAWT's one with an inlet and the other without and the third with just a Diffuser. Bontempo and Manna [11] performed a 2D CFD actuator disk method analysis in ANSYS Fluent on a bare wind turbine and a DAWT (NACA5415) comparing the results with the non-linear actuator-disk model. Hansen *et al.* [12] used the 1D actuator disk model to show that an increased mass flow rate through a DAWT results in an increased augmentation factor and then Vaz *et al.* [13] used the extended Blade Element Momentum (BEM) method to compare their results against the actuator disk model previously studied. Hjort and Larsen [14] presented a comparative 2D CFD study of different Diffuser designs using the RANS solver in Comsol MultiPhysics using the $k-\varepsilon$ turbulence model and Shives and Crawford [15] performed an analysis on several Diffusers with different geometries where the baseline aerofoil cross section is NACA 0015.

While there exists issues with computational limitations and accuracy, a better understanding of air flow characteristics through DAWT's has been achieved with forecastable improvements in design and performance. Most studies have used an independent, case-based methodology in Diffuser design and usually justify a combination of different Diffuser parameters as measures of performance dependent on initial design. Results are however uniformly published in terms of a ratio or percentage of power increased compared to a bare wind turbine rotor with an equivalent swept area. In CFD analysis the main parameters influencing DAWT performance are the area ratio, length-diameter ratio, and pressure across the rotor. The pressure recovery computed at the diffuser exit, tip speed ratio, disk loading and thrust coefficient also contribute to Diffuser design and performance analysis.

The aim of this paper is to provide a review of the various DAWT technologies that exist either through research, as working technologies or as innovative concepts. This is in order to provide an understanding of the current developmental stages of DAWT's and a view on their continuous growth.

1.2 Technical Background and Assessment Methods

The 1D Actuator Disk Theory (also known as 1D Momentum Theory) analyses the energy balance in the Diffuser using Bernoulli's equation and calculates a momentum balance. This semi-empirical approach was constructed from established wind turbine theory with the same applied assumptions. It does not take into consideration wake rotation/swirl, the definite number of rotor blades, aerodynamic drag and associated tip losses. In an advanced analysis, external forces acting along the Diffuser would need to be considered for a detailed understanding of how energy is extracted from the air currents across the rotor [16]. In this section, the development in understanding of DAWT parametric analysis is presented and discussed.

The Diffuser can be split into four regions, see Fig. 1: 0 – Inlet, free-stream; 1 – front of rotor; 2 – behind rotor and 3 – outlet/exit, far wake region [17]. $V_\infty = V_0$ due to the inlet free stream condition. Since momentum is conserved, and there is steady-state flow, thrust is equal to the change in momentum with mass flow conserved; $\dot{m} = (\rho A V)_0 = (\rho A V)_3$ and can be expressed in terms of the pressure difference between stations 2 and 1 and the rotor disk area based on the implication that it is positive; $V_3 < V_0$. Assuming frictionless air flow and conserved energy, Bernoulli's equation is applied to either side of the rotor. With velocity across the rotor being constant: $V_1 = V_2$ and using mass flow rate at the rotor, $\dot{m} = \rho A_2 V_2$ it is found that velocity in front of the rotor is an average of the upstream and downstream wind speeds. The axial induction factor, $= \frac{V_1 - V_2}{V_1}$, quantifies the drop in velocity from upstream to the rotor, where, $a = \frac{1}{3}$.

$$\boldsymbol{P} = TV_t \tag{1}$$
$$\boldsymbol{P} = \frac{1}{2}\rho A_t V_0^3 4a(1-a)^2 \tag{2}$$

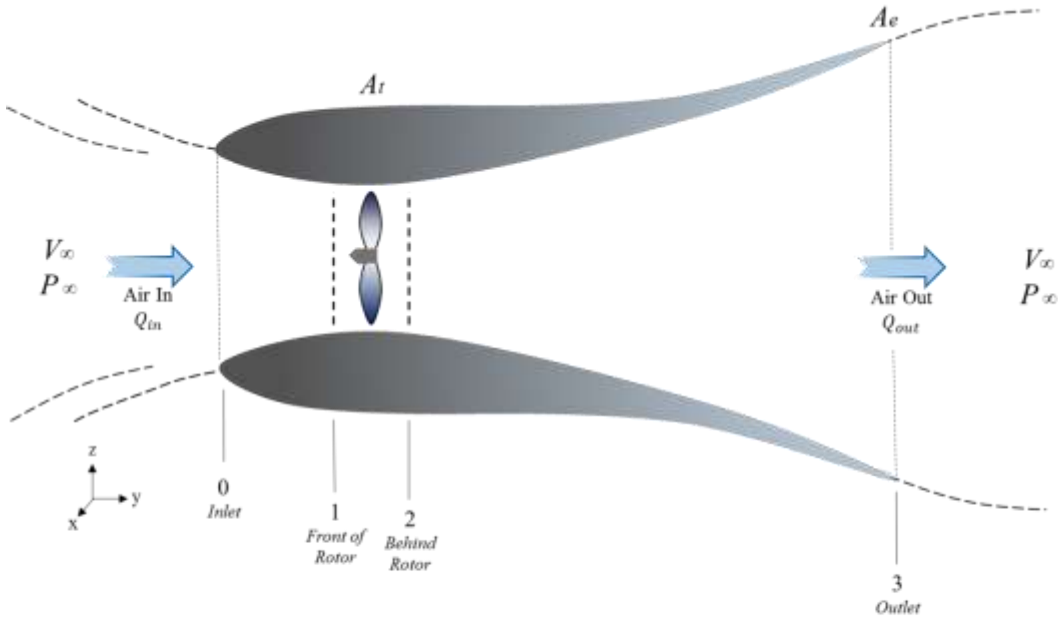


Fig. 1. Schematic for a typical Diffuser. The rotor is usually placed at the smallest diameter; for a flat wall Diffuser it would be at the inlet. The blue arrows indicate the direction of air flow. The subscripts '*t*' and '*e*' refer to the '*throat*' and '*exit*' respectively.

The semi-empirical nature of this analysis arises due to dependence on physical data for the induction factor. A large reduction in wind speeds increases the induction factor leading to a greater power output. The power coefficient which defines the extracted power from available power by the rotor is then:

$$C_p = \frac{\boldsymbol{P}}{\frac{1}{2}\rho A_t V_0^3} \tag{3}$$
$$C_p = 4a(1-a)^2 \tag{4}$$

The main limitations with this standard theory involve the lack in accounting for frictional losses and the effect of wake rotation (i.e. vortex theory) [5]. Air Flow characteristics in a Diffuser are therefore crucial to understanding its real performance more accurately. In order to advance this analysis, thrust is also considered.

1.3 Pressure and Velocity Profiles for a Diffuser

The velocity and pressure profiles through a Diffuser are dependent on its geometry and the change in cross-sectional area. V_o and P_o are the ambient velocity and pressure respectively found far upstream and in the wake of the Diffuser. V_e is the exit velocity and the relationship between velocities at the nozzle and exit are proportional to the Diffuser area ratio, β [4]: $V_1 = \beta V_3$. An under pressure occurs at the nozzle when the area ratio is greater than 1. In other words, the exit area must be larger than the nozzle area with no flow separation. The back pressure velocity ratio defined as: $\gamma = \frac{V_3}{V_o}$. A negative back pressure can exist at the exit, because air flow is forced radially through the Kutta condition [4]. This implies that the exit velocity will be different from the inlet velocity. Velocity is calculated at different locations along the Diffuser in accordance with the continuity equation as long as the local area to exit area ratio is known using the assumption of uniform velocity distribution. Velocity changes are dependent on Diffuser geometry within limitation. The inlet geometry of the Diffuser should therefore be designed to allow for smooth inflow and prevent flow separation. Turbine presence will cause an overall reduction in pressure computed at the exit which is why the best location for the rotor should be at the smallest cross-sectional area to allow for the smallest rotor diameter where it is the inlet for a straight-walled Diffuser. This was further validated by [18]. Resultant pressure change or drop is independent of Diffuser area ratio, back pressure ratio and the turbine's placement in the Diffuser. The amount of air passing across the rotor increases by $\beta\gamma$ compared to a bare wind turbine with equivalent rotor swept area.

1.4 Assessing Performance of the Diffuser

The 1D Actuator Disk theory considers a flow field at atmospheric pressure. The DAWT is able to sustain sub-atmospheric pressures at the rotor [19]. The augmentation factor is the basis for assessing and comparing the performance of all DAWTs. The turbine load factor, also known as the disk loading coefficient C_D, is sometimes independently set based on the choice of turbine rotor. The effective-Diffuser pressure recovery coefficient C_{pr} and Diffuser exit pressure coefficient C_{pe} are also crucial in quantitatively describing Diffuser performance.

The augmentation factor is defined as a ratio of output powers from a rotor of fixed swept area when applied with a Diffuser and without a Diffuser. Using the augmentation factor is a way of measuring Diffuser effectiveness against benchmark existing wind turbines. Power out from a DAWT can be expressed in terms of the turbine load factor. For a zero C_D, there would be no power output; $C_D \propto \boldsymbol{P}$. As C_D increases, A_∞ will decrease and as $C_D \rightarrow \infty$ air flow rate will equal zero thereby resulting in no power output. Augmentation factor can be made dependent on C_{pr} and C_{pe}. The maximum augmentation factor, r_{max}, is dependent on $C_{D,max}$ as it is most often defined in the DAWT design stage. C_{pe} and C_{pr} can be found empirically assuming C_D is independent, it can be differentiated with respect to the augmentation factor and set to zero. The maximum augmentation factor is:

$$r_{max} = 0.649\sqrt{\frac{\left(1 - C_{pe}\right)^3}{1 - C_{pr}}} \tag{5}$$

For a larger augmentation factor, the Diffuser efficiency and area ratio (with small expansion angle to encourage streamline flow) should be as large as possible as stated by [19]. The latter aspect means the Diffuser would need to have a large length-diameter ratio, a costly limitation. Additionally, the exit pressure would need to be as small as possible for increased augmentation. To achieve this, the Diffuser should ideally be designed with an annular wing profile which (according to aerofoil theory) that will allow for sub-atmospheric exit pressures. Other theoretical models also exist that consider a refinement of the 1D Actutor dik model to account for turbulence, shear forces, thrust loadings and velocity profiles as investigated by [12, 13, 14, 20, 21].

1.5 Characterising DAWT's

Wind Turbines are traditionally classified according to rotor size, scale, axis of rotation, on-shore, off-shore, number of blades etc. Since DAWT's are based on the conventional wind turbine with the addition of the Diffuser, they fall into similar categories. However, among the DAWT community of technologies there are clear distinctions between the different types of Diffusers and the application of the DAWT. Figure 2 shows a breakdown of the various DAWT classifications and their co-dependencies, if any, based on current technologies.

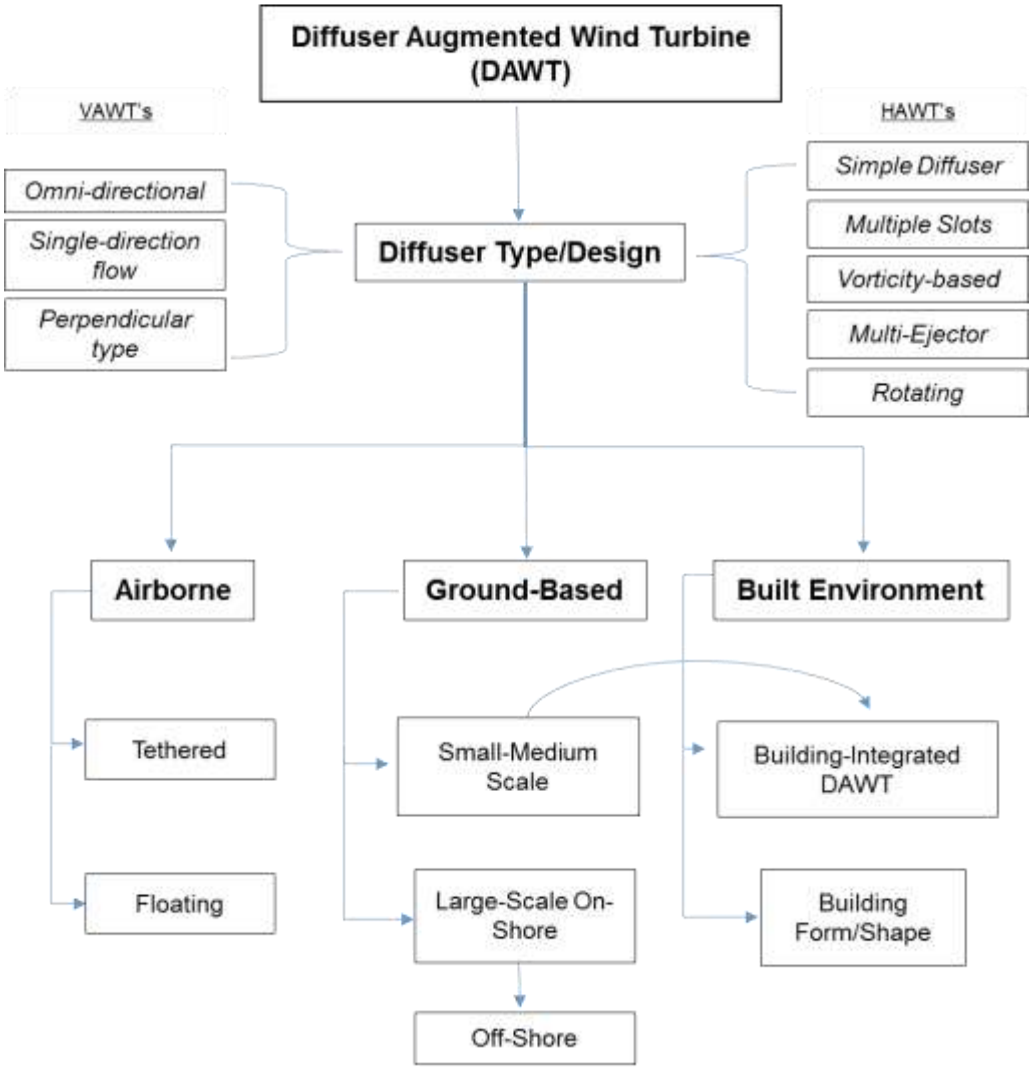
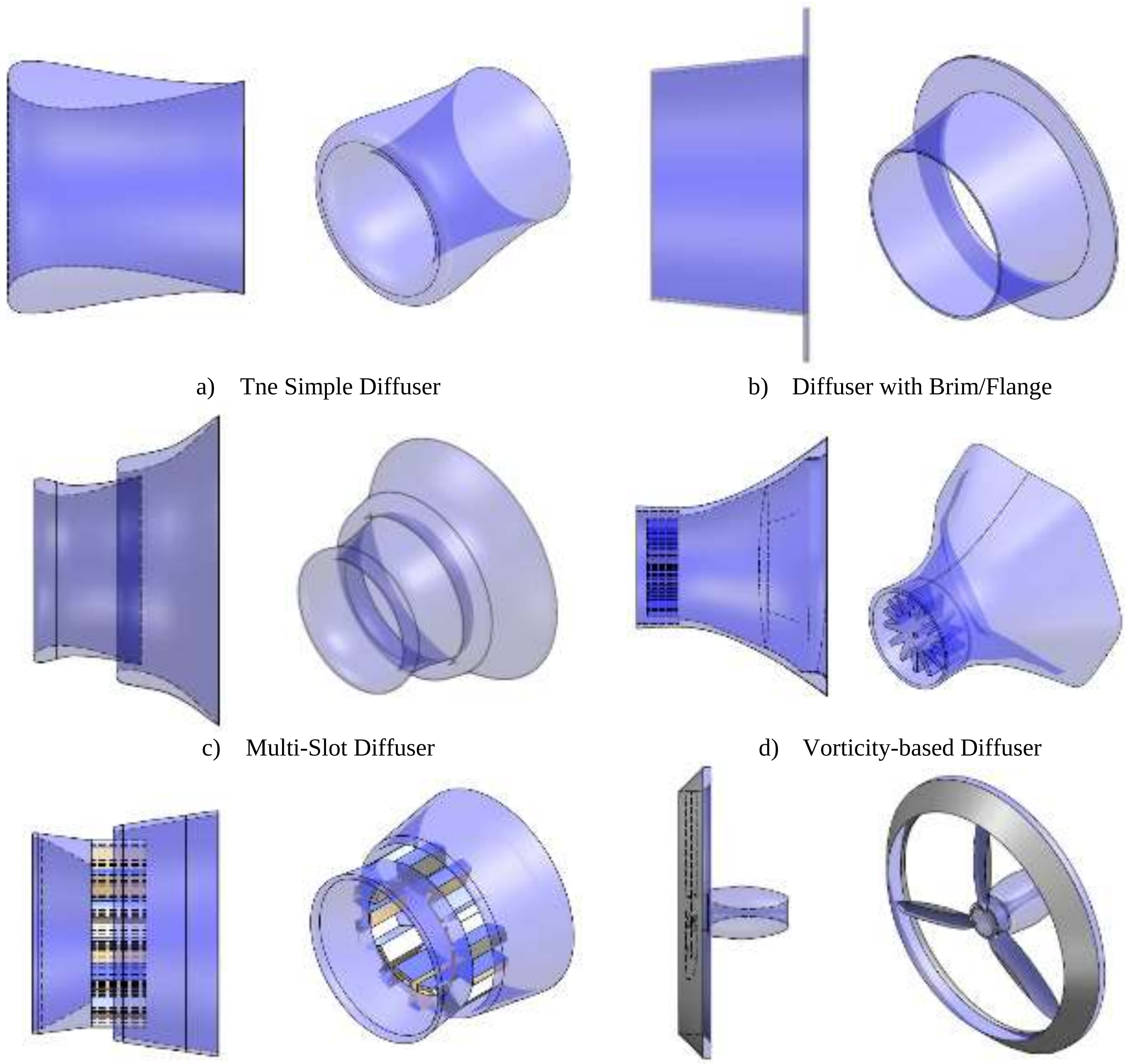


Fig. 2. DAWT Classifications based on established concepts and designs.

2. Ground-based DAWT Technologies using HAWT's

Small wind turbines installed at low altitudes are often susceptible to local wind interferences and intermittencies that are hard to predict or ignore. Some Diffuser technologies have been advanced to allow for better fluid dynamic performance, synchronised rotation to wind directional changes, operation at higher rpm's, rotor protection from wear and tear and flexibility in number of blades. Diffuser designs are commonly available for small-medium size rotors for small-scale applications in specific locations, such as road-side, roof-mounted, small fields/gardens etc. Although large-scale turbines require additional structural and mechanical considerations, each Diffuser presented in this section can be applied in theory to most turbines. DAWT's are typically designed to exploit low wind speeds in areas that were otherwise close to urban development. This does not however restrict their potential to high wind speeds. *OrganoWorld* [22] proposed a non-circular 1.8MW convergent-divergent shroud claimed to surpass the performance of the traditional three-bladed DAWT and contribute to the development of smart grids. The 'Winga-E-Generator' was designed for low wind speeds operating between 4 and 7m/s. The shroud was made up of a large divergent duct with a 'Borger' optimized convergent duct involving a Venturi structure to align and accelerate air flow onto three high-solidity, multi-bladed annular rotors. Each rotor, 8m in diameter, is connected to its own independent generator thereby allowing larger torque generation at an estimated optimum 300rpm. In Figure 3, the Diffusers **a)-c)** allow a variability in the selection of rotor given a consideration of a blade-tip clearance of at least 2%. For **d)** and **e)**, the rotors shown are specific to the Diffuser design, while for f) there is flexibility for the blade number to increase.



a) Tne Simple Diffuser   b) Diffuser with Brim/Flange

c) Multi-Slot Diffuser   d) Vorticity-based Diffuser

e) Mixer-Ejector Diffusers   f) Rotating Diffusers

Fig. 3. The main types of Diffusers.

2.1 The Simple Diffuser

Diffuser types vary according to the cross-sectional profile (aerofoil versus constant thickness etc.), adjustments in the area ratio, length-diameter ratio and actual Diffuser diameter. The simple Diffuser, Fig. 3a), involves a converging inlet that expands to a diverging outlet with the rotor positioned at the smallest diameter.

2.2 Brim and Flange Technology

Ohya and Karasudani [23] from the Kyushu University, Japan, developed the ‘Wind-lens Technology’. The original idea was to improve on problems such as/ large wind loads and structural weights, of a 500W DAWT by proposing an upwind 5kW “compact acceleration structure (compact brimmed Diffuser)”. Tests were conducted to identify the best ‘compact’ geometry and the Ciii type was chosen as it was tested with the best power augmentation results; 2.6 times the power out from an equivalent bare turbine. The Wind-lens technology aims at brim-based yaw control allowing the turbine autonomous control over wind directional changes. With the compacted design, this technology has seen recognisable success. Decreased loading on the overall structure has allowed for the rotors rotational ability. Power augmentations were typically in the range of 2-3.

This new class of flanged Diffusers were then studied by Abe *et al.* [24] and Ohya *et al.* [25]. The former studied the flow fields behind a small flanged (so called because a brim is installed at the exit of the Diffuser) wind turbine, Fig. 3b). It was found that for a small wind turbine flow patterns were similar for both the equivalent bare- and flanged-Diffuser wind turbines. In the downstream region at exit, vortex structures rapidly deteriorated for the flanged-Diffuser system but this was observed further downstream in the bare wind turbine.

2.3 Multiple Slotted Diffusers

The purpose behind this technique is to reintroduce external air flow into the wake of the turbine thereby reenergising the boundary layer along the inner surface of the Diffuser using high lift aerofoil Diffuser rings. This should create local velocity and pressure fields which will mean a lower pressure distribution through the Diffuser inducing greater mass flow of air [16, 28].

Wood [27] patented a DAWT in 2014 that employed one or more Diffuser rings to form a turbine cowling. This created an effective outlet area greater than the Diffuser cross sectional area. Additionally, with the use of one or more slots connected to the vent, air can bleed from the system creating a suction effect. Figure 3c) shows the DAWT geometry and how the slots are created using the first and second Diffuser rings. The pre-rotation vanes are so called because of their location, they are stationary and attached to the rotor to channel air flow. Note that using the method of multiple slots, the length to diameter ratio of Diffusers can be significantly reduced, which means potentially less material and weight for the DAWT.

2.3.1 The First Generation Shroud

Igra designed the first generation shroud in 1980 [19] that had a straight-wall bell-shape inlet attachment fixed onto a straight-wall Diffuser with an apex angle of 8.5° with length to diameter ratio 7:1. Although this ratio is economically unfavourable, the maximum augmentation factor was 3 at a yaw angle of 30°. Following the work carried out by Oman *et al.* [29], Foreman *et al.* [16] compared an aerofoil ring Diffuser with a boundary layer Diffuser. The former achieved an average augmentation factor of 1.6 at a disk loading coefficient of 1.1. The ratio for boundary layer control was defined in terms of the fractional pressure difference between the inlet and behind the rotor. It was 1.31 for the boundary layer Diffuser and 0.9 for the aerofoil ring Diffuser. In both cases this surpassed the design equivalent bare wind turbine which was 0.44. These studies however lacked a comprehensive approach to understanding flow fields around Diffusers. A second shroud, 'model A' was the same as the first but with a shorter Diffuser (area ratio of 2, compared previously with 3.5 and $L:D = 3.64:1$) but with the addition of three aerofoil ring-flaps. It was found that with successive addition of the flaps, the pressure recovery coefficient improved, which increased Diffuser efficiency by 86% and augmentations up to 3 (with 3 ring-flaps and $C_D \sim 0.22$). From this study a third shroud, 'model B' was proposed. It was found that a Diffuser with an aerofoil cross section should in theory be able to produce high lift significantly increasing performance. The new design used a NACA 4412 Diffuser and a single aerofoil ring-flap with $L:D = 3.07:1$ but no bell-shape intake. In terms of effect of using ring-flaps, comparing the models A and B at $C_D = 0.5$ it can be seen that the increase in augmentation was 20% and 52% respectively. When model B was tested at different area ratios, the largest ratio produced the largest augmentation increase of 70%. Igra [19] concluded that a maximum augmentation factor of 3 is achievable compared to an ideal bare wind turbine of the same geometry and flow conditions.

2.4 Vorticity Based Turbines

Vorticity is a physical fluid phenomenon that describes the curling of velocity profiles and is used to measure local fluid rotation. This concept is applied in DAWT technology to reduce air pressure in the wake of the Diffuser thereby increasing the pressure differential across it. This encourages a 'pull' on air into the Diffuser. Although achieving a laminar flow profile though the Diffuser is the ideal case, this is very hard to achieve in reality due to the unpredictability of natural wind inflow conditions.

Early experimental investigations on the effects of swirl rotation were studied by Okhio *et al.* [30] on introducing a circumferential velocity component to overcome flow separation in a wide-angle Diffuser with an open angle of 16^0 and an area ratio of 4.4. With the use of probes to measure static pressure, a visual profile flow was developed. Different inlet swirl strengths were tested with the best resulted yielding a 60% reduction in total Diffuser losses. It was found that above this threshold the creation of a re-circulating zone lead to further dissipative losses. A more recent study by Mariotti *et al*. [31] investigated multiple local recirculations in increasing Diffuser efficiency. Three Diffusers with an area ratio of 2 and different divergence half-angles of 2^0, 3.5^0 and 5^0 were subjected to induced local re-circulations along the Diffuser walls. At smaller half-angles, flow remained attached to the Diffuser walls and with increasing half-angle asymmetric zones of separated flows developed. Introducing optimal cavities aided in improving pressure recovery and preventing flow separation due to a decrease in momentum losses in the re-circulation regions. In all cases an increase in power coefficients for the optimised cases was measured around 25%.

2.4.1 WindTamer

Brook [32] patented a vorticity reducing cowling DAWT design in 2009, see Fig. 3d). The cowling involved uses a plurality of spacers that operate to couple the Diffuser to the shroud in a spaced apart manner thereby defining a bypass passage between the outer and inner surface of Diffuser. The cowling is mounted to the shroud upstream of rotor and operates to compress the fluid flowing onto and past the blades, while reducing the vorticity of the fluid flowing onto and past the blades. The WindTamer 8.0 by Arista Power, was designed to operate in wind speeds ranging from 5-12m/s for small-medium scale usage in an open-field or roof-mounted with a tower height upto 12m.

2.5 Mixer Ejector Wind Turbines

Figure 3e) shows mixer ejector technology that involves the use of single- and multiple-stage ejector technology that was aimed at exceeding the Betz limit. Presz Jr. *et al* [33] designed a shroud that was contoured with an inlet, a ring of stator vanes, a ring of rotating blades and a mixer/ejector pump to increase the flow volume through the turbine while mixing the low energy turbine exit flow with high energy wind flow that enters through the second stage slot. Power augmentations of 3-4 compared to an equivalent bare turbine are predicted. This claim is used to encourage the increase in productivity of wind farms by a factor of 2 or more and will be ideal for populated areas because it is safer and quieter. To produce streamwise vortices, lobed mixers and vortex generators can be used.

2.5.1 FloDesign

'FloDesign' now owned by the *Ogin Technology Company* [34] was designed to create vorticities in the wake of the turbine to reduce the pressure through the outlet as much as possible. This design was intended to accelerate airflow though the inlet and mixer, then direct and control turbulent flow by introducing external air through the ejector. The ejector has a larger diameter than the mixer to 'spread out' airflow in the wake also contributing to a reduced turbulence FloDesign has been designed for deployment in wind and water and even for applications in the aircraft industry. Claims by the manufacturer include a reduced infra-red signature as the mixer-ejector shroud doubles as a passive cooling system for the turbine, increased propeller efficiency and reduced noise.

2.6 Rotating Diffusers

Anakata Wind Power Resources [35] in the UK recently patented augmented wind turbine technology using rotating Diffusers. Also referred to as dynamic Diffusers because they can rotate around the horizontal axis of the turbine, the Diffuser ring is fixed to the turbine to form a rotor cowling. The Diffuser therefor moves with the rotation of the rotor. The Diffuser may have more dynamic or aero-elastic devices attached to the trailing edge of the Diffuser can include slot gaps to allow for external flow into the turbine. The DAWT typically includes a vortex generator and guide vanes may be employed to prevent airflow twist. These guide vanes may comprise of pre-rotation vanes located upstream of the turbine or post-rotation guide vanes located downstream of the turbine. Figure 3f) shows a schematic design. The 0.85m diameter A007 rated at 370W at 12.5m/s. The rotor is the downwind type and made of Acrylic coated ABS, a strong, wear-resistant material that is easy to replace and maintain as well as allowing a weight and load reduction. With this technology, the blades being attached to the Diffuser, the blades are less susceptible to vibrations. However, it is not clear the effects of the rotating Diffuser on the aerodynamic drag of the turbine and whether this reduces the rotor rpm.

3. Ground-based DAWT Technologies using VAWT's

Using a Diffuser is an optimising technique for achieving greater power outputs for a given rotor swept area. In more recent years, this technique has extended its reach to VAWT's. With the advantages of operation in low wind speeds, robustness and design simplicity (leading to low material demands, O&M costs and recyclability) VAWT's present a valid and very realistic potential success in the DAWT sector. However, the well-established disadvantages to this type of DAWT arise from low self-starting torques and poor efficiencies of bare VAWT rotors. The two main types of VAWT's are the lift-type (e.g. H-rotor and Darriues) and the drag-type (e.g. Savonius). For VAWT's, Diffusers are usually referred to as 'Shrouds' due to their thin-sheet wrap-around designs that have a constant thickness and cross-sectional area. An in-depth review on power augmented VAWT's using Shrouds was conducted by Wong *et al*. [36]. DAWT's based on vertical axis rotors have not yet advanced as far as their horizontal axis counterparts due mostly to the lower power coefficients and augmentations, lower power ratings and lower performance stability.

3.1 Single-direction Flow

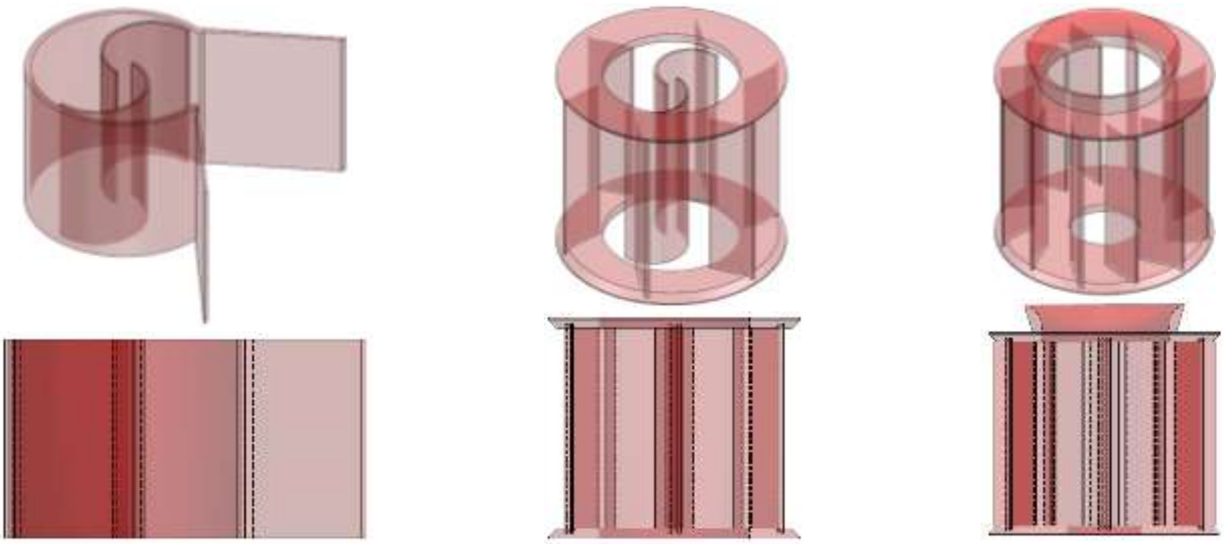
VAWT's are often subject to both positive and negative torque, i.e. based on variable inflow wind conditions, the axis of rotation can be clockwise and anti-clockwise. Although this may appear beneficial because in theory a VAWT can capture wind and produce power in all wind directions, the inherent problems of difficult starting torques removes the possibility of reliable power outputs. To address this, the single-direction shroud aims at channelling wind onto the rotor for a continuous positive torque, similar to the operation of centrifugal pumps and the Tesla turbine. The drag-type single-direction DAWT as seen in Fig. 4a) uses a wrap-around structure and can be applied to lift-type turbines [37]. Although it has been reported that the lift-type single-direction DAWT may use a deflector instead of a wrap-around structure and is placed upstream of incoming wind flow [38]. The advantage of using a deflector instead of a wrap-around structure is to prevent areas of re-circulation that may develop between the blades and the shroud that reduces torque-generating capabilities. There have been significant improvements in power coefficients and augmentations, but these are still lower than for DAWT's based on HAWT's.

3.2 Omni-directional Flow

The reported power coefficients and augmentations for this type of DAWT are significantly higher than for the single-type DAWT. However there are higher capital costs due to the care in design of the guide vanes involved in the Shroud. In the lift-type omni-directional DAWT guide vanes are placed at specific angles to accelerate oncoming wind to an optimum angle of attack. This is aimed at controlling and reducing negative torque and turbulence, thereby also removing the need for a yaw mechanism [39]. At lower tip-speed ratios, the use of guide vanes in this way can increase torque output. This design feature also applies to the drag-type omni-directional DAWT. The Zephyr VAWT was specifically designed to have a high solidity at low tip speed ratios to define the upper limits of optimum performance [40]. Power coefficients are still quite low for this technology. In another design, a Vortical Stator Assembly (VSA) uses two ring shaped discs that contain the guide vanes, similar to the one shown in Fig. 4b). The aim here was to create 'vortical' flow that would pull in and accelerate oncoming wind to the rotor and reduce its negative torque. The power coefficients and augmentations were more promising for this DAWT [41].

3.3 Perpendicular Flow

In a new approach to controlling and channelling wind flow onto a rotor, these types of turbines direct inlet air to drive torque and then leave the turbine in the direction of the axis of rotation either above or below the rotor. There are two main types of perpendicular flow turbines, the single-direction and omni-directional inlet as seen in Fig. 4c). In the single-direction flow, the cowling is at the centre of this turbine and is made of two parts. Air is directed into the vent tube using guide vanes and recirculates. A pressure differential is then induced along the chimney to the atmosphere where air is then drawn out of the turbine. Efficiencies are low with this type of turbine but improve with fewer blade numbers. The omni-directional perpendicular flow turbine is based on the same principles as the single-direction where air is drawn in through the inlet and recirculates. In this case, air is then directed through an accelerating column where it is driven through a turbine in a tunnel perpendicular to the incoming wind. This type of turbine does not typically have high efficiencies and directing air flow through a complex pathway depends heavily on its aerodynamic design and availability of high wind speeds. The energy dissipative effects would need to be considered.



a) Single-direction Flow b) Omni-directional Flow c) Perpendicular Flow

Fig. 4. Examples of the different types of DAWT's based on VAWT's. a) and b) are the drag-type examples with the Savonius rotor. The lift-type and perpendicular flow turbines are subject to changes in the rotor used and the geometry and number of guide vanes and cowling employed.

4. Large-scale On-Shore DAWT's

There are examples of utility-scaled DAWT's that aimed at capturing and accelerating high wind speeds for smaller starting torques than traditional medium-large scale bare wind turbines. The main advantages are the higher levels of augmented power and the suitability to wind farm application. Most of the research in this particular field has been experimental with the aim of observing performance and efficiency changes when the DAWT is up-scaled. Questions of increased noise levels, increased climatic exposure, strains on yaw control and pressure recovery effectiveness still need to be addressed for large-scaled DAWT's. In the latter case, if recovery is poor, a strong suction effect may be created which could potentially damage the rotor and overcome torque generation. Additional obvious considerations of increased weight, load and material erosion may defined the ultimate success of large-scale DAWT's. It is expected that future tower support structures will be constructed using steel and/or concrete in modular units [42].

4.1 Igra's Turbine

Following his own work on Multi-slot Shrouds, one of the earliest DAWT's was built by [19]. The throat was 3m in diameter with outer diameter 6m and length 8m. The Diffuser cross section was a NACA 4412 positioned at a 5° angle of attack. The prototype pilot plant was positioned 3.5m above the ground, down from 9.5m as originally planned**.** Figure 5 shows the test rig for the pilot plant that was set up in the backyard of the *Israel Aircraft Industry* campus where it was manufactured. The tested free stream velocity was 5m/s and the design power was 0.8kW. The actual power output achieved was 0.66kW with an efficiency of 82.5% and an augmentation factor of 2. This was calculated based on the theoretical maximum power output of 0.33kW. The tested prototype fell short of the intended design due to a limited budget, it was not aerodynamically accurate. Nonetheless, the DAWT survived stormy conditions and showed strength in durability. Igra and previously, Foreman, discussed the importance of cost and size reduction of Diffuser design.

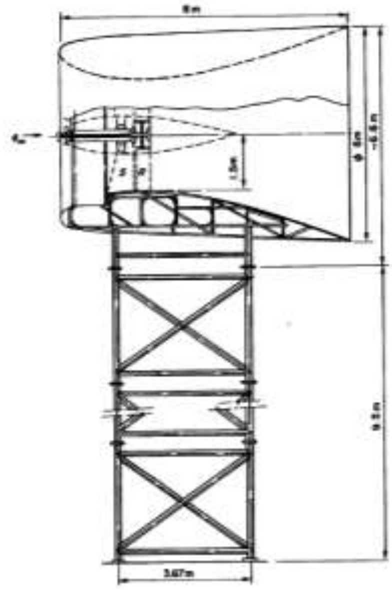


Fig. 5. The Pilot Plant for Igra's Turbine. 'q' refers to volumetric air flow rate (m^3/s) [19].

4.2 DonQi Urban Windmill

The 'DonQi Urban Windmill' developed by *TU Delft University*, was developed to work as a large-scale DAWT that is compact and quiet and can be installed in urban environments on large and small buildings [43]. Part of a class of 'Urban Windmills', the DonQi has a three-bladed rotor with a diameter of 1.5m. The Diffusers' cross section is an aerofoil with an area ratio of 1.73 and has a Gurney Flap attached to the outlet of width 40mm. The DonQi is able to catch wind speeds from 2.5m/s to 12.5m/s.

4.3 Catching Wind Power

Raymond Green [44] created a working prototype of a 'bladeless' DAWT in California in 2007 that was aimed at being wildlife friendly and conducive to deployment in wind farms with power augmentations claimed upto 2. The 'Compressed Air Enclosed Wind Turbine' weighs 20 kg, while the turbine assembly itself measures 30 cm in diameter and the vorticity-based Diffuser which surrounds it has a diameter 78 cm at its widest point. The 'Inner Compression Cone Technology' aims to draw in wind through its inlet, pushing air through the smallest diameter of the shroud where the rotor is positioned. Due to this technology, the rotor blades can be kept shorter for a given power output compared to a bare turbine, thereby running for a quieter operation. The aim was to install multiple DAWT's on a single tower to capture wind at similar altitudes.

5. Large-scale Off-Shore DAWT's

For the deployment of DAWT's in off-shore applications, changing marine environments and much harsher climatic conditions need to be carefully understood. There already exist example of off-shore wind farms and even underwater turbines. Nonetheless, access to maintenance and water pollution due to damage present very realistic limitations. The increased weight of a DAWT accentuated by its increased rotors size will require substantial platforms and foundations in the sea bed. Two approaches have arisen to address this. One method looks closely at the design of a robust tower structure that may in some cases serve to accommodate more than one rotor at a time or a floating platform that will allow for improved access to shallow waters as well as deep and adaptability to wind directional changes.

5.1 Wind-Lens Wind Farm and the Honeycomb Concept

In a desert area of North West China, six 5kW downwind units of the 'Wind-Lens Turbines' were successfully installed on irrigation land. The units were each set-up as part of a micro-grid power distribution network feeding in to a central pumping system. The power from the turbines were stored in battery technology at the station. At a seashore park in Fukuoka City, Japan three 5kW downwind turbines were installed with a hub height of 15m. The exact location these turbines were determined from an examination of the wind profiles in the area at 15m. They have been placed near the entrance of the major river at Hakata Bay where it was found that air accelerated across the waters on to land but decelerated over high-rise buildings.

Following this, an innovative design in off-shore wind farms was then proposed. At the Renewable Energy International Exhibition in 2010, the Wind-Lens Technology was re-introduced for application in a wind farm as the 'Honeycomb', see Fig. 6. It would be a hexagonal array of connected floating platforms. The entire platform would be mobile and rotate to capture wind flow as well as match wind-induced wave flow. Intended initially for shallow waters, the hexagonal array was chosen to reduce the potential overall weight of the platform and provide a strong structural support. Each lens is approximately 112m in diameter and as estimated to be able to power an average household. The concept endeavoured to re-invent off-shore wind farming as efficient, re4liable, aesthetically pleasing and easy to access. Building an array platform also has the advantage of holding the capacity for combined collection and monitoring of electrical output and output losses can be reduced instead of feeding electricity from a single unit. The project is still in its early stages of implementation. [22].

5.2 Vortec 7 Wind Farm Concept

The *Vortec Energy World Power Company* in New Zealand expanded their operations to offshore wind power. The 'Maxi Vortec' and the 'Mini Vortec' were intended designs but didn't reach manufacturing success due to a lack of interested investors. 'Vortec 7' was then developed further for off-shore applications. A 5 MW upwind turbine with a V66 blade was designed with a single large diameter, 'thick' tower structure fixed to the ocean floor aimed at withstanding rough deep sea conditions [45]. If successful, this concept would have a mega-watt capacity potential per unit DAWT albeit at high capital costs. Unless prioritised, the safety and access risks would also be very high.

5.3 Innowind

'Innowind' [46], a Norwegian company produced DAWT technology for use off-shore and potentially in an off-shore wind farm based on Diffuser mixer-ejector theory. The approach was to increase the surface area of the turbines without building excess structural weight which is why the off-shore turbines are triple headed. Innowind's on-shore equivalent has a large diameter in the range of 20-30m for power outputs of 1.5-3MW.

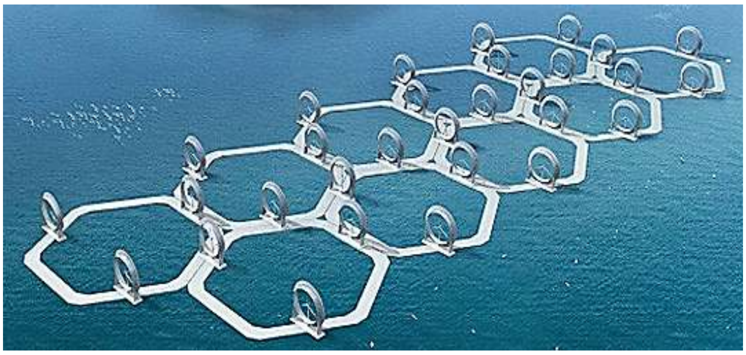


Fig. 6. The Honeycomb Concept [22]

6. Airborne DAWT Technologies

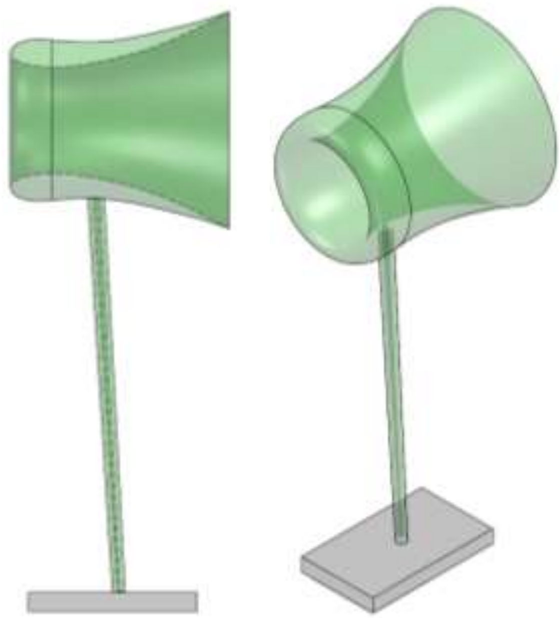
There are two main approaches to suspending DAWT's in different altitudes. The first approach requires a dedicated design to an anchor-transmission system that is robust and can distribute and stabilise the weight of the DAWT system as it will move in many degrees of motion. Although not a typical fixed-ground-station system, this DAWT will usually have a rigid tether containing the transmission line for electricity and may be restricted to some degrees of motion [48]. Working like a wind vane, this type of 'tethered' DAWT, see Fig. 7a), will be able to align its inlet to oncoming wind. Yaw control, stability in lack of wind conditions and blade loading due to multi-directional and atmospheric changes could result in poor efficiencies. In the second approach, the Diffuser can be treated as a balloon-like structure that can be filled with a gas such as helium to encourage buoyancy which will lighten the turbines load. While the latter approach may allow better atmospheric mobility for the turbine, achieving a precise aerodynamic profile for a gas-filled structure may be very difficult even with the use of lightweight, aero-elastic material. However, managing yaw control with unpredictable directional changes may be a challenge. The idea of the floating turbine was proposed by *TU Delft University* as seen in Fig. 7. The aim and advantage of this system is to access a wider range of wind speeds, especially at higher altitudes where wind speeds are more predictable in terms of direction and magnitude, while using a smaller rotor but allowing for a greater power extraction threshold compared to a bare wind turbine.

6.1 *Polifemus*

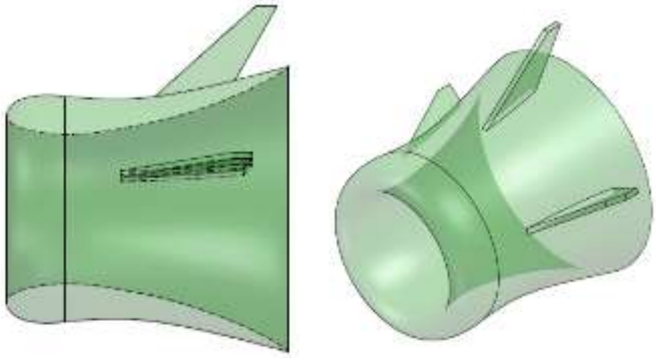
Ponta *et al* [47] carried out a study on floating water-current turbines. The concept was then applied to wind turbines. Inspired by the floating DAWT concept by *TU Delft University*, the 'Polifemus Project' was introduced. This turbine uses double-flow channelling, co-axial vortex generator and modular assembly. The so-called channelling device is made of an internal Diffuser with aerofoil cross section and external deflectors that encourage the 'suction effect', i.e. the pull of a greater mass of air. The co-axial generator was included to add a tornado-eye effect to the suction in the wake at low pressure. The generator and double-flow techniques effectively increase the power extraction capacity of the turbine which implies an intercepted area greater than the equivalent physical area of the rotor. This characteristic is very similar to the hydro-Straflo turbine because the size of the turbine bulb can be reduced. Inflow air can be used via the multiple inlet slots in the tubular case to provide cooling through the polar pieces of the generator.

6.2 *Altaeros*

The 'Altaeros', developed in 2010 is an innovative concept in power augmentation from a given rotor at variable altitudes, Fig. 7b). The Altaeros can reach 600 meters in altitude where wind speeds have between five to eight times greater power density. It is expected that the Altaeros can produce power augmentations up to 2. With an automated control system and a helium-inflatable shell channels the Altaeros is a large but lightweight structure. The shell with dimensions 15m by 15m is able to stabilise itself whilst floating at high altitudes and producing aerodynamic lift and buoyancy [48].



a) Tetherered



b) Floating

Fig. 7. The main types of airborne DAWT's.

7. Summary of DAWT Technologies

In Table 1, the main advantages and disadvantages based on technical features have been summarised. For Diffusers in their conceptual phases, the augmentation factors are still missing as research is required in these areas to either validate or invalidate these concepts. The lack of augmentation data does not however remove any recognition from the concept itself. Due to limitations in weight and efficiencies, DAWT technology has so far been restricted to small-medium scale. These limitations are subject to further study and innovation. Relative to each other, the more successful DAWT technologies usually employ horizontal-axis wind turbine rotors due to better visualisation and manipulation of wind flow profiles.

Table 1 Summary of main DAWT technologies presented in this paper. 'S', 'M' and 'L' refer to small- (<5m), medium- (5-20m) and large-scale (≥20m) rotors respectively.

Tech. Name	Rotor *Type*	*Scale*	Power Rating	Augmentation Factor	Main Advantage(s)	Main Disadvantage(s)

Simple Diffuser	HAWT	S,M	Up to MW	2-3	Design flexibility Increases air mass flow rate onto rotor Favourable pressure distribution through Diffuser	Bulk weight Need for large length-diameter ratio
Mixer-ejector	HAWT	S,M	kW	N/A	Increasing air acceleration	Increased turbulence
Multiple slots	HAWT	S,M	kW	2-3	Re-energised boundary layer	Dissipative losses in wake regions
Rotating	HAWT	S,M	kW	N/A	Removal of tip-blade losses	Increased rotational strain on supporting nose cone, nacelle and tower
Vorticity-based	HAWT	S,M,L	kW	N/A	Re-circulation of air for lower exit pressures	Prone to inducement of turbulence
Brim/Flange	HAWT	S,M	kW	2-3	Reduces requirement of larger L/D ratio	Limited design flexibility
Single-direction	VAWT	S	<kW	<1	Encourages continuity in positive torque production	Doesn't encourage laminar accelerated flow
Omni-directional	VAWT	S	<kW	<1	Greater potential for positive torque generation	Low efficiencies
Perpendicular	VAWT/ HAWT	S,M	<kW	N/A	Production of re-circulation zones	Low efficiencies
Tethered	HAWT	S,M	kW	N/A	Availability to greater variety of wind speeds and directions	Long term structural risks
Floating	HAWT	S,M,L	kW	<2		Transmission and collection of electricity

8. Business Opportunities

Proof-of-concept exists for DAWT technologies but there has not been any significant market penetration yet due to lack in popularity, awareness, capital cost, maintenance and lack of an established industry presence. Masukume *et al* [49] conducted a study on a ducted wind turbine installation in South Africa. The Levelled Unit Cost of Energy (LUCE) based on the capital costs and recovery factors for the generator, battery bank, inverter and controller were computed along with the annual electrical energy of the system (in this case, 1900 hours of operation at a mean annual speed of 5m/s) to give US 0.26/kWh which was found to be lower than the equivalent bare wind turbine. Wind power generation can potentially reduce water and carbon dioxide levels unlike conventional power plants due to lower consumptions. Current engineering cost models however, do not take these factors into account due to a focus on the direct relationship between capital costs and electrical outputs.

Foreman *et al* [50] conducted one of the first economic analysis of the DAWT system. The DAWT can provide an operational advantage because it can reduce the minimum cut-in wind speed and raise the high-speed and cut-out wind speeds compared to a conventional system. Also providing stability to turbine blades DAWT's are less likely to be damaged by cyclic operation. It was claimed, that turbulence and intermittent wind speeds can be moderated allowing the DAWT access to a wide range of applications and wind capture at yaw angles $\pm 30°$. Costs were compared between DAWT' and WECS based on equal rotor diameters and equal power output's. For example, at an augmentation factor of 1.89 and a 40m DAWT turbine, the equivalent WECS in terms of power output would need to have a 55m turbine. However, it was found that the specific power costs associated with DAWT's were only lower than WECS's when the rotor diameter was either very small ($< 20m$) or very large ($> 50m$).

9. Other Considerations

Other than the emphasis on the design of Diffusers, there are other influences that affect the developments of DAWT technologies. The considerations highlighted below have been identified as crucial to DAWT's. Following these considerations, a consequential study of factors such as advances in yaw control techniques, electricity transmission and storage and improvements in tower supports and structural strength and integrity will be necessary.

9.1 Increasing the Number of Turbine Blades

Wang and Chen [51] studied the effect of the number of rotor blades on a DAWT's performance. The investigation used NACA4412, NACA4420 and NACA4416 aerofoil cross sections for the Diffuser. Using the ANSYS CFX package the RANS solver was used and the $k - \varepsilon$ turbulent model. For an air incident angle of 7° the different Diffusers were tested for 2, 4, 6, and 8 rotor blades with two different rotor of blades. It was found that increasing the number of blades increases the starting torque and reduces the cut-in speed. But, increasing the number of blades also leads to greater blockage effects and a gradually reduced entrance velocity. The number of blades should be chosen in alignment with generator choice. Generally, the tip-speed ratios for both the simulated blades were in the range 4-6 and above this the power coefficient reduced [52, 53]. Further to this, optimising blade design for bare wind turbine rotors (e.g. HAWT's) for improvements in both turbine efficiency and rotations in low wind speeds should also be carefully considered [54, 55, 56].

9.2 Material Considerations

It is expected that developments in the field of carbon-based materials and 3D printing will be able to transform the wind turbine industry for faster and frequent manufacture, durability and reduced weight. Additionally, developments in high strength fabrics enable specific lightweight aerodynamic structures to be strong and weather resistant. Wang *et al* [57] conducted wind tunnel experiments to assess the effect of a flanged (with a soft brim) Diffuser (namely the Wind-Lens) on the blades of a 3kW turbine placed inside it. The tested blades were made of carbon-reinforced plastic (CRFP) with a solid foam core. The tests were carried out at wind velocities from 6.9m/s to 11.6m/s and across yaw angles from $0 - 30°$. Results showed that the blade rotational speed was higher with the flanged Diffuser than without, but centrifugal forces acting on the blades also increased though not as much as for when conventional materials were used in the blade manufacture. The soft foam structure prevented a large increase in centrifugal forces in small wind turbines. There were larger dynamic strains observed in the blade root and higher tensile strains in the rest of the blade for the flange Diffuser system than the bare wind turbine. In conclusion, it was found that large yawing angles can reduce strains on the blades. The results were extrapolated to a higher wind velocity, to a maximum of 30m/s. At this speed it was found that there would be maximum tensile force on the blades under a no loading condition and 0° yaw angle, but with the flanged Diffuser this force would be less that the ultimate strength of the blades.

9.3 Air Inflow Angles

The numerical study of multi-directional flow onto the rotor of a DAWT has not yet been studied. Existing technology has tried to address this issue by using a combination of a rotating base/tower with wind guide vanes that enable the rotor to catch multi-directional flow. These cases are mostly for smaller rotors that easily rotate to match wind direction without compromising their structural integrity. There exists no research or technology addressing the effects on performance and power augmentation for a DAWT that can allow rotation of its Diffuser and/or rotor to match wind directional changes. Yaw changes and effects on performance thus need to be considered carefully.

10. Conclusion

A review of DAWT technologies has been presented in this paper. A compilation of several fundamental Diffuser design concepts was compared for their relative effectiveness in augmenting power. A description of the success of these technologies, their technical advantages and disadvantages and current developmental limitations have been described. Power outputs from small-scale wind turbines can be increased with the employment of a Diffuser, with augmentations achievable between 2 and 3. Currently, an understanding of DAWT technology depends mostly on the design of Diffusers. There is no set methodology for the design of a Diffuser, a wind turbine rotor is typically chosen and a Diffuser is designed to allow the turbine to accomplish a greater output. There are measurable design parameters, such as the area ratio, length-diameter ratio, turbine disk loading etc. that have been outlined in this paper and can be used as key outcomes of performance in terms of power output and efficiency. In theory, the Diffusers presented can be adapted to any given wind turbine rotor, accounting for blade-tip clearances.

The established flat-walled and simple Diffusers for horizontal-axis turbines are still the most recommended designs due to a clear understanding of the improvements in laminar wind profiles and adaptability to a wider range of bare wind turbine rotors, albeit small-scale. The technologies presented are valid concepts but have not yet reached commercial success due mostly to high capital costs, low popularity and additional loading due to Diffuser weight. The most pressing needs for the development of DAWT technologies include the relative contributions to performance of each Diffuser perhaps by employing a single continuous rotor and the practical issues involving bulkiness, installation and operation. A further consideration should be given to the visual impacts of the DAWT system and its levels of acceptance and perceptions among mainstream renewable technologies.

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