Aerodynamic analysis of clustered, diffuser-augmented turbines

Uli GOELTENBOTT*, Yuji OHYA**, Takashi KARASUDANI**, Shigeo YOSHIDA** and Peter JAMIESON***
*Department of Aeronautics and Astronautics, Kyushu University
744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan
E-mail: uli@riam.kyushu-u.ac.jp
**Research Institute for Applied Mechanics, Kyushu University
6-1 Kasuga-koen, Kasuga 816-8580, Japan
*** Wind Energy DCT, University of Strathclyde,
Royal Collage R336, Glasgow, G1 1XW, Scotland

Abstract
The wind turbine industry has seen innovations leading to growing size of turbines of currently over 160 m in diameter. However, as pointed out by some recent studies, up-scaling of blades has its limitations and therefore advantages of multi-rotor system concepts have been suggested by Jamieson et al. The so-called wind lens turbine, which was developed by Kyushu University, shows increased power output using a brimmed diffuser to augment the approaching wind flow. In the presented research we are investigating the aerodynamics of wind lens turbines spaced closely together comprising a multi-rotor system. We placed up to three of these turbines closely in an array perpendicular to the flow and measured power output. The total power output of multiple turbines was then compared to the power of the stand-alone setup. Several different wind lens configurations have been used, mainly varying the brim height. We observed that the performance of the turbines is influenced by the width of the gap between the brims and the brim height of the wind lens configuration. The best performance was at a gap of 0.15 D with 10% brim height which leads to a power increase of more than 9% in a three turbine side-by-side arrangement. Further it was observed that the individual power output doesn’t follow the trend of the cumulative power output. These phenomena can be explained with flow patterns observed in gap flow analysis of bluff bodies. Further research is necessary to fully understand which mechanisms in three dimensional gap flow cause the effect on the performance of the turbines.

Key words: multi rotor, clustered turbines, wind lens, diffuser augmented

1. Introduction
The cost of energy is the main driver for innovation in the renewable energy industry including wind power. Trends in wind turbine development show that the size and hence the blade length has continuously increased. At present, the standard diameter of a 5 MW wind turbine is slightly over 125 m. In the EU funded “UpWind” programme 10 – 20 MW turbines with blade lengths beyond 80 m are subject to feasibility studies (Upwind Project 2014). Japan faces challenges for installing wind turbines because promising locations are in remote and mountainous regions or offshore with quickly dropping sea beds. Therefore, blade length is of interest, since it is a driver for cost and transportability. A promising solution to overcome the challenge of increased blade length is to use more than one rotor in a single structure, so-called multi-rotor systems. By applying the most recent blade production technology on shorter blades there is a significant weight and cost saving potential as described in the book “Innovation in wind turbine design” by Jamieson (2011). Further cost reduction effects are possible through volume production reaching levels of the automotive industry. Cost reduction possibilities have been presented in detail in Jamieson and Branney (2014).

A shrouded wind turbine with brimmed diffuser (hereafter called “wind lens turbine” (WLT)) developed by Kyushu
University, shows increased power output compared to a conventional wind turbine (Ohya and Karasudani 2010). The mechanism is based on the establishment of a low pressure field behind the turbine which draws more wind through the rotor plain. This low pressure field is created by vortex shedding at a brimmed diffuser. The first multi rotor system that uses wind lens turbines was installed in December 2014 at Kyushu University in Fukuoka, Japan. It comprises three 1 kW wind lens turbines in a triangle arrangement as shown in Figure 1.

There has been research on a side-by-side arrangement of two conventional turbines by Smulders et al. (1984) concluding that an increase in power output of a few percent is possible. More recently Ransom et al. (2010) added results from a simulation also suggesting small increase in power output.

In the presented research we investigate the application of wind lens turbines in a multi rotor arrangement. An experimental evaluation of turbine spacing and its effect on cumulative and individual turbine output power are subject of investigation.

2. Experimental setup

Wind lens turbines are placed in the wind tunnel test section, which has a cross section of 3.6 m by 2 m and a length of 15 m. An outline of the wind tunnel can be seen in Figure 2. The test section consists of 6 elements, the side walls and ceiling plates have been removed for the elements 3 – 5. With the removal of the side walls and ceiling plates the wind tunnel becomes semi-open which helps to avoid blockage effects.

Fig. 1 Multi-rotor wind lens turbine using three 1 kW wind lens turbines at Kyushu University

Fig. 2 Wind tunnel specification with test section. Side walls and ceiling plates were removed for elements number 3, 4 and 5.
Previous wind tunnel experiments in the semi-open test section proved to suppress blockage effects by showing good agreement with field data, therefore we neglected blockage effects in the presented study. The rotor plane of the turbines was 1 m downstream from the first opened side walls (Element number 3). Arrangements of two turbines and three turbines placed side-by-side normal to smooth flow are analyzed. The setup for the three turbines can be seen in Figure 3. Vertically, the rotor shafts of the turbines are located 0.65 m above the floor which leaves a distance between brim and floor of around 0.31 m when using the CiB10 wind lens type (Wind lens types are shown in Figure 4). Horizontally, the middle turbine is located in the center of the wind tunnel (at 1.8 m).

To adjust the gap, the turbines are moved horizontally on a rail. Further downstream, a torque meter is connected to the rotor shaft on one end. On the other end a speed-controlled motor is connected. Optimum tip speed ratio is determined by setting the appropriate rotational speed of the rotor. For the time of measurement the motor speed is held constant by the motor controller. The two turbines setup with description of the major dimensions is illustrated in Figure 5.

3. Power output of turbines

Wind lens turbines are placed in the wind tunnel in an array perpendicular to the flow direction. The power coefficient \( C_{PW} \) of a stand-alone turbine is calculated with:

\[
C_{PW} = \frac{P_{Turbine}}{P_{Wind}} = \frac{\tau \cdot \omega}{\frac{1}{2} \rho A U^3}
\]

Fig. 3 Wind tunnel setup with view in flow direction showing three wind lens turbines

Fig. 4 Wind lens types normalized to throat diameter \( D_{th} \)

Fig. 5 Schematics of two wind lens turbines placed side-by-side. \( D = \) biggest diameter of one turbine (rotor diameter for bare turbine and brim diameter for wind lens turbines), \( s = \) gap between the brims of neighboring turbines, \( L_t = \) length of the lens structure and \( H = \) projected width of the wind lens.
The power in the wind is calculated with the density $\rho$, the wind speed cubed $U^3$ and the area swept by the rotor $A$. The rotor swept area is used as a reference for both the bare turbine and the wind lens turbine. The power $P_{\text{Turbine}}$ from the turbines is calculated from torque $\tau$ multiplied with angular velocity $\omega$. Sampling interval of 60 seconds and sampling rate of 100 Hz are used to calculate power output. Maximum power output was estimated for each turbine at a given spacing at optimum tip speed ratio. For capturing the maximum power output of a stand-alone turbine, the other turbines were removed respectively.

The average power coefficient of multiple turbines is calculated for $n$ being the number of turbines:

$$c_p = \frac{c_{p1} + \cdots + c_{pn}}{n}$$

(2)

And the percent variation we defined as:

$$\% - \text{var.} = \frac{c_p - c_{p0}}{c_{p0}} \cdot 100$$

(3)

The power coefficient $C_{p0}$ is the power coefficient of a turbine in multi-rotor arrangement. The power coefficient of a stand-alone turbine is denoted as $C_{p0}$.

The gap of turbines for each setting was between 0 and 0.5 brim diameters ($D$). At a wind speed of 7 m s$^{-1}$ the Reynolds numbers ($Re$) are shown in Table 1 using the biggest diameter of the turbine as characteristic length $L$. For the bare turbine $D$ is equal to the rotor diameter, for the WLT $D$ is equal to the brim diameter. The formula for the Reynolds number is:

$$Re = \frac{U \cdot L}{\nu}$$

(4)

with $U =$ wind speed, $L =$ characteristic length and $\nu =$ kinematic viscosity. The rotation direction of the rotors is clockwise for all turbines seen in flow direction.

<table>
<thead>
<tr>
<th>$L$ [m]</th>
<th>Bare</th>
<th>CiB03</th>
<th>CiB05</th>
<th>CiB07</th>
<th>CiB10</th>
<th>Blade (chord length)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Re \times 10^5$</td>
<td>0.512</td>
<td>0.595</td>
<td>0.615</td>
<td>0.636</td>
<td>0.667</td>
<td>0.06</td>
</tr>
</tbody>
</table>

As a reference value for the power of multi rotor setup, the power of stand-alone wind lens turbines is measured in the wind tunnel. Figure 6 shows the power curves of a bare turbine and wind lens turbines using Ci-diffuser with brim height from 3 to 20%. We can clearly see that the performance of the wind lens turbine is significantly above the bare turbine. Within the wind lens turbines the best performance is achieved with brim heights between 5% and 10%, then decreasing for the 15% and 20% brim heights. The brim heights are referenced to the throat diameter $D_{th}$ as seen in Figure 3.

![Power curves of a stand-alone bare turbine and stand-alone wind lens turbines using Ci-diffuser with brim height ranging from 3% (CiB03) to 20% (CiB20)](image-url)
4. Performance of multiple turbines

To measure the performance of multiple turbines in an array we started by placing two and later three turbines side-by-side and measured the power output in the wind tunnel. The operational tip speed ratio in a multi rotor setup didn’t change from the stand-alone setup of $\lambda$ around 4.

4.1 Two turbines in side-by-side arrangement

First, two turbines were placed side-by-side and power output was measured and compared to each stand-alone value. Measurement error is estimated to be around $\pm$ 0.5 %. The smallest gap for the two bare turbines was chosen to be 2.5 % of the rotor diameter as a safety gap to avoid collision of the rotor blades. The bare turbines show a power increase of around 1 % for all the gaps from 0.025 to 0.5 D as seen in Figure 7. The wind lens turbines generally show a little increase in power at 0 D gap, where the brims of neighboring turbines are in direct contact. When further increasing the gap the power increases to a maximum of 3 % for the CiB03 and 5 % for the CiB10 lens configuration, as seen in Figure 7.

![Variation of power coefficient vs spacing of two WLTs side-by-side](image)

**Fig. 7** Power variation over gap width of two turbines side-by-side (left). Setup of two wind lens turbines, CiB05 with gap of 0.15 D in the wind tunnel (right)

4.2 Three turbines in side-by-side arrangement

In the three turbine side-by-side arrangement we can observe a similar tendency in power increase compared to the two side-by-side case.

![Variation of power coefficient vs spacing of three WLTs side-by-side](image)

**Fig. 8** Power variation over gap width of three turbines side-by-side (left). Setup of three wind lens turbines, CiB07 with gap of 0.15 D in the wind tunnel (right)
From the graph in Figure 8 we can see that the bare turbine’s increase in total power output is around 4.5 % at the closest spacing and also at a gap of 0.1 D. Increasing the gap to 0.3 D there is some variation between 3 and 5 %. For the wind lens turbines we also observed a stronger power increase at 0 D gap starting from 2% for the CiB05 wind lens to almost 5% for the CiB10 wind lens. The peak of power increase was reached at a gap of 0.15 D for most cases. We didn’t increase the gap to 0.5 D like shown previously in the two turbine case, in order to keep the turbines within a distance of 1 D from the sides of the test section. Maximum power increase reached 4.5 % for the bare turbines and 9.1 % for the wind lens turbine using the CiB10 configuration.

4.3 Individual turbine performance in multi-rotor arrangements

When looking at individual power output of the turbines there are cases where each of them is not equally contributing to the trend of the cumulative power of all three turbines, especially between 0 and 0.2 D gap width, but still visible until gaps of 0.5 D. In Figure 9 we can see the increase in power output of the three wind lens turbines with CiB05 in side-by-side arrangement. The power increase for turbines on the left, middle and right side is shown with the total power increase in percent. We can observe that the turbine on the left side shows very similar power increase as the total power increase. The turbine in the middle shows higher increase and the turbine on the right side shows lower increase than the total.

![Graph showing individual turbine power variation with three turbines in side-by-side arrangement.](image)

We expected the middle turbine to have a higher increase than the turbines on the sides because the middle turbine is affected by two turbines on each side. However, we didn’t expect the turbines on the left and right side to have such a difference in power increase.

To analyze the effect of the floor we conducted an experiment moving the three WLTs from Figure 10 (right side) towards the vertical center of the wind tunnel, the rotor shafts being at 0.99 m above the floor.

![Graph showing power increase in per cent of three WLTs in side-by-side arrangement at different heights above the floor.](image)
The wind lens configuration CiB05 was used with a gap of 0.15 D between the brims. The total power output reached 5.9% increase, the left WLT 3.9%, center WLT 8.4% and right WLT 5.2% increase compared to each stand-alone power output. From Figure 10 we can see that the power increase of the center turbine doesn’t change and also the total power increase is the same as when the WLTs are at 0.65 m above the floor. The only difference is the power increase of the WLTs on the sides. It seems like the power has shifted from the WLT on the right to the WLT on the left. We assume that this power shift is not related the effects from the ground but rather from a biased gap flow between the brims of neighboring WLTs.

Ohya et al. (1986) described the flow around multiple flat plates. It is shown that there are different bi-stable flow patterns possible at gaps of s/D < 2. In the case of biased gap flow the drag coefficients of two flat plates next to each other vary greatly. Figure 11 shows flow patterns for two flat plates and Figure 12 shows flow patterns for three flat plates placed normal to the flow. The drag coefficient of flat plate on biased side increases when the drag coefficient of the flat plate on the other side decreases. We are assuming that a biased gap flow between the turbines has a similar effect causing one turbine to increase performance while the performance of the other turbine decreases.

![Fig. 11 Two normal flat plates, drag and base pressure coefficient over T/D from Ohya et al. (1986)](image1)

![Fig. 12 Three flat plates, drag and base pressure coefficient over T/D from Ohya et al. (1986)](image2)
4.4 Gap flow analysis

From another experiment with three wind lens turbines in triangle arrangement we measured the flow velocity $U_{HW}$ between the brims of two turbines using a hot wire. In this case the third turbine is above two side-by-side turbines. The measurement was taken between to lower two turbines. We observed the flow 0.2 D downstream from the blades on a horizontal line between the two rotor shafts of wind lens turbines. The hot wire signal is measured at 100 Hz for a duration of 10 seconds. The two different diffusers used in this experiment are CiB05 and CiB10. In Figure 13 we can clearly see the asymmetric flow velocity distribution in the gap at the center of the graph. The start of the brim is clearly visible by the sharp drop in velocity to around $0.15 - 0.3 \ U$, the reference flow velocity which is the wind speed in the wind tunnel. This is followed by a small local peak which is caused by the tip clearance between blade tip and diffuser throat. The wind speed in the wind tunnel is measured with an ultrasonic anemometer 2.2 m upstream of the rotor planes, 0.75 m above the floor and 0.5 m from the side wall.

The power output of the same two turbines is measured during each hot wire measurement. The average of all power output measurements in reference to their stand-alone values is shown in Figure 14. The left turbine shows increased power output where the turbine on the right shows no change or even a power decrease. The difference in power output of the turbines from Figure 14 could be linked to the asymmetry in the flow velocity distribution in the gap from Figure 13.

The results presented in Figure 13 and 14 are the first approach to analyze the gap flow with only little data available so far. Therefore, further analysis of the gap flow velocity distribution is planned for future experiments.

5. Discussion

For both the two and three turbines in side-by-side arrangement there is a clearly visible power increase. For the conventional, bare turbines the power increase is around 1 % (two turbines) and around 4 % (three turbines). Using wind lens turbines the power increase depends on brim height and gap width. At 0 D gap, the power increase is small, reaching its maximum at around 0.15 D. Three turbines show higher increase than two turbines. With three wind lens turbines the highest power increase was between 4 % (with CiB03) and 9 % (with CiB10).

Wind lens turbines use the formation of vortices around the brim to create a low pressure field that draws more air through the rotor plane. When wind lens turbines are placed close together the formation of vortices is partially inhibited. However, there seems to be a phenomenon that leads to an increase in power. Nakamura and Ohya (1986)
described vortex shedding from square prisms in smooth flow. It was observed that the vortices shed in one of two fixed planes which are parallel to the sides of the prism. The wake plane switched irregularly between the two sides.

Ohya (2014) showed that the vortex shedding around the brim of a wind lens turbine is random and not uniform around the circumferential direction. To establish a uniform flow separation in a stable segment around the brim so-called vortex control plates were introduced. The vortex control plates were able to strengthen the vortex shedding and further increased the power output of the wind lens turbine.

In the three turbines arrangement a similar effect as described by Nakamura and Ohya (1986) could be present. Due to the vicinity of neighboring turbines vortices shedding predominantly occur at the top and the bottom of turbines, hence the shedding becomes more uniform in a 2-dimensional plane compared to a stand-alone turbine. With stronger vortices, the pressure drop becomes larger and as a result the performance of the turbines increases.

When measuring the flow speed in the gap between turbines we were able to observe an asymmetric flow speed distribution. This is a sign for a biased gap flow which was studied in detail for two dimensional bodies by Ohya et al. (1986). The drag coefficient of a flat plate on the biased side increases, which means for a turbine that the power output increases. Therefore, we can observe differences in individual power output of turbines when they are spaced closely together. The wind lens turbines are concentrating and accelerating the incoming flow through the rotor plane. The wind that passes through the rotor is collected from a wider source area compared to a bare turbine. If the turbines are spaced closely together, there might be an overlapping of source area. This could also result in differences of power output of individual turbines.

6. Conclusion

Wind lens turbines have been spaced closely side-by-side and maximum power output has been captured at various gap widths between 0 and 0.5 D. Conventional turbines and wind lens turbines showed an increase in power output. Wind lens turbines show higher power increase than conventional turbines reaching its maximum at around 0.15 D gap between neighboring brims. The power increase is further dependent in the brim height of the wind lens configuration. The highest power increase was observed with 10 % brim height (CiB10).

We conclude that wind lens turbines with suitable spacing have high potential to increase the efficiency of wind turbines. Further research we will focus on experimental analysis to understand the phenomena of gap flow between brimmed diffusers, the wake interference and their relationship to the power output of the turbines. Additionally we plan to compare the experimental data with CFD simulations.

7. Acknowledgement

Acknowledgements go to Mr. Kimihioko Watanabe and Mr. Keiji Matsushima for supporting the wind tunnel experiments. Further, the Ministry of Education, Culture, Sports and Science (MEXT), Japan is acknowledged for scholarship support.

References

Nomenclature

\( A \) rotor area (m²)
\( c_p \) power coefficient (dimensionless)
\( C_{p0} \) power coefficient of a single turbine (dimensionless)
\( C_{pn} \) power coefficient of a turbine in multi-rotor arrangement (dimensionless)
\( \overline{C_P} \) average power coefficient of all turbines in multi-rotor arrangement (dimensionless)
\( D \) brim diameter (m)
\( D_{rot} \) rotor diameter (m)
\( D_{th} \) throat diameter (m)
\( H \) projected width of the brimmed diffuser (m)
\( L \) characteristic length (m)
\( L_t \) length of the lens structure (m)
\( n \) number of turbines
\( P_{Turbine} \) power of turbine (W)
\( P_{Wind} \) power in the wind (W)
\( Re \) Reynolds number (dimensionless)
\( s/D \) gap between turbines s / Brim diameter (dimensionless)
\( T/D \) space between center of flat plates T / width of plate D (dimensionless)
\( U \) wind speed (m/s)
\( U_{HW} \) wind speed measured with hot wire (m/s)
\( \lambda \) tip speed ratio (dimensionless)
\( \nu \) kinematic viscosity (m²/s)
\( \rho \) air density (kg/m³)
\( \tau \) torque (Nm)
\( \omega \) angular velocity (rad/s)
\( \%\text{-var.} \) percent variation of power coefficient (%)