Wind-tunnel simulations of wind-turbine arrays in neutral and non-neutral winds

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Abstract. Wind tunnel simulations have been made of a neutral atmospheric boundary layer (ABL), a stable layer and an unstable layer, typical of offshore conditions, in order to better understand wake development and turbine-wake interactions. Measurements of the wake of a single turbine showed a slower reduction of the velocity deficit for the stable case, and a more rapid reduction for the unstable case, compared with the neutral. It is proposed that there are two effects of non-neutral conditions, indirect and direct. Indirect effects are seen in the earlier part of the wake, influenced by the turbulence level in the ABL but not by buoyancy forces directly; direct effects, caused by buoyancy forces, are seen further downstream. In the stable case, direct effects were seen from about 3 rotor diameters, while for the unstable case they were not seen until about 10 diameters. Two-point measurements in the wakes of four turbines aligned with the flow, compared with those of the ABL, exhibited very different flow characteristics, suggesting a lateral oscillation of the wakes of the later turbines. The effects of laterally adjacent turbines, in a 3-wide × 4-deep array, but with closer-than-typical lateral spacing (2.4 diameters) so as to give early interaction in the short array, were also investigated, and showed only limited interaction.

1. Introduction

Wind turbines operate in the atmospheric boundary layer (ABL) where the mean flow and turbulence is driven by mechanical production and, in convective (i.e. unstable) conditions, by buoyancy production, while for inversion conditions the turbulence is reduced by the stabilizing effect of buoyancy forces, except in neutral or near-neutral flow conditions where neither effect is significant. However, assessments of wind resource for wind farms assume neutral-flow conditions (see e.g. Sanderse et al. [1]), and little is understood in the context of wind turbines about the influence of non-neutral conditions. Inversion conditions exist predominantly in the nocturnal boundary layer, while convective conditions predominate in daytime conditions. They are most significant in light-wind conditions, and it is light-wind conditions (above the cut-in speed) that are arguably of particular interest in optimization of wind farm output, where one turbine extracting too much power can ‘starve’ one or more downwind turbines because of a wake deficit that is too large.

The ABL is characterized by several parameters. In a neutral wind flow this can be the boundary layer height, \(h\), the mean wind speed at a given height, and either the friction velocity (\(u_f\)) or the aerodynamic roughness length scale (\(z_0\)); assuming a law-of-the-wall logarithmic velocity distribution, one of the latter pair imply the other. In the non-neutral case more parameters come into play. In the surface layer, which is roughly about 0.1 of the boundary layer height, key parameters are the surface temperature (\(\Theta_0\)), the surface heat flux (denoted here by \((w \Theta)_0\)), and the thermal roughness length.

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scale \((z_{0s})\). The surface heat flux can also be represented by the \((surface\) Obukhov length, \(L_0\),
defined by \(L_0 = -\Theta u_s^3/(\kappa g (w \theta)_s)\), where \(\Theta\) is the absolute temperature, \(\kappa\) is the von Karman constant, and \(g\) is the acceleration due to gravity. In the mixed layer of a convective ABL above the surface layer other parameters come into play. The top of the ABL, whether convective or neutral, is usually defined in terms of an inversion layer; above this height the (potential) temperature is rising with height, \(z\). Also, above the height, \(h\), the turbulence is small compared with the levels in the ABL. Against a neutral ABL, where the height \(h\) is roughly 1 km (say), the height of a stable boundary layer might be \(< 200\) m, while for a convective boundary layer it might be \(> 2\) km. Given the size of current large wind turbines - for a 5 MW turbine the hub height and blade length would typically be 90 m and 60 m, respectively – the rotor will be subjected to a wide range of energy-containing length scales in the oncoming flow, with the tip-top height possibly exceeding the height of a stable ABL. Therefore, for a stable wind flow, the strength of the inversion above the ABL, the ‘imposed’ condition, is clearly an important condition, while for convective ABL the strength of the inversion is likely to be less important.

In terms of simulating a wind flow in a wind tunnel, an obvious parameter is the ratio of, say, the turbine rotor diameter to the Obukhov length, \(D/L_0\). So, too, is the strength of the inversion. In both Hancock et al. [2] and Hancock and Pascheke [3], for unstable and stable boundary layers, respectively, it is shown that the strength of the temperature gradient of the imposed condition to that at full scale is given by the relationship \(\left(\frac{D}{U_R}\right)^2 \frac{\partial \Theta}{\partial z} = \text{constant}\), where \(U_R\) is a reference velocity at some geometrically equivalent height. For further details see these papers.

As well as the change of length scale, \(h\), with the influence of stabilizing or convective effects, there is also a very marked change in the levels of turbulence to which a wind turbine and its wake is subjected, as will be seen in the examples in this paper. Now, an increase of turbulence level can be expected to subject the turbine blades to increased levels of fluctuating incidence and therefore increased levels of fluctuating lift and drag, and to influence the growth and deficit decay of the blade wakes. But, for this interaction, the length scale associated with these motions will be the length scale of energy containing motions of the ABL, which will be orders of magnitude larger than that of the blade boundary layers and blade wakes\(^2\). Thus, since the effects of stability or instability are primarily large-scale effects, it can be anticipated that there will be no ‘direct’ effects of stability or instability on the turbine blades; the effects will be merely ‘indirect’ because of stability or instability in the ABL changing the level of turbulence. However, the wake of the turbine - once it has developed sufficiently from the wakes and tip and hub vorticies of the blades - will have a length scale that is of order the rotor diameter, which is two orders of magnitude larger than that of the blade chord for a typical turbine. Therefore, for large turbines, once the wake has developed sufficiently far, it is to be anticipated that there will be direct effects of stability or instability in the wake, which will affect its development further downstream with implications for its effect on downwind turbines. Indeed, Hancock and Pascheke [4] inferred indirect and direct effects in their case of a stable boundary layer, with direct effects occurring from about 3\(D\) onwards.

Wind tunnel studies of wind turbine wakes in non-neutral flow have been made by Chamorro and Porté-Agel [5] for a stable ABL, and by Zhang et al. [6] in a convective flow. Both these give a review of related work, which will not be repeated here. The present work gives further insight into the physics associated with non-neutral conditions.

2. Experimental setup
Details of the wind tunnel, the flow simulation, and the model turbines are given below. Further
details can be found in Hancock et al. [2] and in Hancock and Pascheke [3, 4].

\(^2\) The energy of length scales in the ABL turbulence of the order the blade length scale is assumed here to be negligible.
2.1. **The EnFlo Meteorological Wind tunnel**

The working section of this suck-down wind tunnel is 1.5 m in height, 3 m in width (to the internal side walls, used to improve lateral uniformity) and 20 m in length, with a speed range of 0.3 to 4 m s$^{-1}$. The wind profile was generated by means of Irwin-type spires (Irwin [7]) at the working section inlet complemented by surface roughness elements, with the neutral-flow mean velocity and turbulence profiles based on ESDU [8] guidelines, assuming a 10 m s$^{-1}$ mean wind speed at 10 m height, at a model scale of 1:300.

In the presentation of results, X (axial), Y (lateral) and Z (vertical) denote distances from the model turbine tower hub, and z from the surface. U is the mean velocity in the X direction, and u, v and w are the fluctuating velocities in the X, Y and Z directions, respectively. X is zero on the plane defined by the turbine blade pitch axis. The free stream reference velocity, $U_{ref}$, was taken at a fixed upstream location from an ultrasonic anemometer.

Velocity measurements were made using a Dantec two-component 40 MHz frequency-shifted laser Doppler anemometry (LDA) system, and a standard 27 mm Fibre-flow probe with a 300 mm focal length lens. This optical set-up produced a measurement volume of 0.138 mm in diameter and 5.52 mm in length. The seeding particles with a nominal size of 1 µm in diameter were generated from the sugar solution aerosol by a hydrosonic seeding machine. Temperature fluctuations, $\theta$, and mean temperature, $\Theta$, were measured, respectively, by means of a cold-wire probe and by either a thermocouple or thermister.

For the two-point velocity measurements two such probes were used, run from one two-colour (i.e. two-component) system. The two probes were supported separately. LDA signals are non-periodic, depending upon the arrival a seeding particle in the control volume. To form the two-point correlations threshold conditions where imposed so that only pairs of samples close enough in time were used. Tests were made to ensure that the results presented here were not significantly affected by the threshold.

![Figure 1. View of wind turbines in the working section, looking upstream.](image)

2.2. **Model wind turbines**

Each turbine comprised a three-blade rotor with a diameter of D of 416 mm, a micromotor with a gear box mounted on a solid steel tower 13 mm in diameter at a hub height of 300 mm, a modified representation of the SUPERGEN 5MW exemplar turbine. The blade was made of carbon fibre with a shape of a twisted thin flat plate, 0.8 mm thick, without an aerofoil cross-section. The chord and twist angle were calculated to give a constant lift coefficient of 0.6 along the blade span, at a tip speed ratio of 6. The turbine was controlled through a 4-quadrant controller in order to maintain a constant rotation speed with an uncertainty less than about 1 rpm. An array of 12 turbines in the wind tunnel is shown in figure 1, where the surface roughness elements and the Irwin spires can also be seen.
Further details are given by Hancock and Pascheke [4].

As reported by Hancock and Pascheke [4], the thrust coefficient, $C_T$, (for a single turbine) defined as the axial force divided by $\frac{\sqrt{2}}{2} \rho U_{\text{Hub}}^2 A$, where $\rho$ is the air density and $A$ is the rotor cross-sectional area and $U_{\text{Hub}}$ is the mean velocity at hub height, was estimated to be about 0.48 for the stable case and the corresponding neutral case (figure 2). For the unstable case, and its corresponding neutral case (figure 4), where a slightly different blade pitch setting was used, it was estimated to be about 0.42. The difference is not important as reference neutral data is given for the two cases. This latter value also applies to the other cases given here in sections 3.3 and 3.4.

3. Results

Salient data for the stable and unstable cases in the absence of any turbine is given in Table 1. At full scale, assuming a wind speed of 10 m s$^{-1}$ rather than of $\approx 1.5$ m s$^{-1}$ of these experiments, the imposed conditions are equivalent to about 0.01 K m$^{-1}$ for the stable case and about 0.002 K m$^{-1}$ for the unstable case. Both are typical. Further details are given in Hancock and Pascheke [3], including length scale spectral information, and in Hancock et al. [2]. The table also gives the streamwise turbulence intensity at the turbine hub height.

| Table 1. Parameters for the stable, unstable and (reference) neutral cases. These are based on averages for the profiles given in the figures. |
| --- |
| Neutral | Stable | Unstable |
| $h$ (mm) | $\approx 1050$ | $\approx 500$ | $\approx 1200$ |
| $\kappa$ | 0.4 | 0.4 | 0.4 |
| $z_0$ (mm) | 0.10 $\pm$0.01 | 0.11 | 0.10 |
| $z_{90}$ (mm) | - | 0.0004 | 0.002 |
| $h/L_0$ | - | 0.40 | $-1.26$ |
| Imposed gradient above $h$, (K m$^{-1}$) | - | $\approx 20$ | $\approx 3$ |
| $\Theta_0$ (°C) | - | 16 | 45 |
| $((\vec{u}^2)^{1/2} / U)_{\text{Hub Height}}$ (%) | 7.3 | 4.5 | 9.5 |

3.1. Stable boundary layer

Figure 2 shows profiles in a vertical plane aligned with the hub axis between $0.5D$ and $10D$ downstream of an isolated turbine, and reference profiles for the undisturbed (i.e. the ‘upstream’) flow, for both the baseline neutral case and the stable case of Hancock and Pascheke [3, 4]. (For the stable-flow measurements the turbine was placed at 11 m from the working section inlet, and at 10 m for these neutral-flow measurements, as the stable ABL developed more slowly.) The profiles of mean velocity $U$ show two key features. Firstly, it can be seen that the momentum deficit is larger in the stable case at each corresponding station. That is, the deficit is slower to decrease. The same has been observed from field measurements by Magnusson and Smedman [9], while the wind tunnel measurements of Chamorro and Porté-Agel [5] showed the opposite effect of a more rapid decrease, contrary to what would be anticipated. The reasons for the contradictory behaviour are not clear, but Zhang et al. [6] suggest there is an effect of a stronger mean shear leading to stronger turbulence in their stable case. Secondly, figure 2, shows that the vertical growth rate is completely or almost completely suppressed. Hancock and Pascheke [4] argue, on the basis of the height and width of the wake deficit, that the effect of stability is indirect for the first part of the wake, and direct from about 3D onwards. The effect seen here on the height, and perhaps consequentially on the width (not
shown), is probably primarily caused by the imposed condition, rather than the surface heat flux condition. Further experiments are needed to separate the two effects.

The profiles of $u^2$ and $w^2$ in figure 2 show the clear differences in the turbulence levels between the stable and neutral wind flows, and clear differences in the levels of turbulence in the wake. These levels in the wake, whether they are taken as just those above the undisturbed levels (so called ‘added turbulence’) or as absolute levels, are generally lower in the stable case. The heights at which peaks occur are lower in the stable case, and this is also the case of the height of maximum mean velocity deficit, and is probably a consequence of the stability caused by the imposed condition.

Figure 3 gives profiles in the vertical plane of mean temperature and of vertical (kinematic) heat flux, $w\theta$, normalised by the heat flux in the undisturbed flow. The mean temperature profiles show there is an increase below about hub height at each of the stations, with increases occurring above this height only in the later part of the wake. The heat flux at first shows no effect, except near the tip-top height, and then a marked increase but only above hub height, at $3D$. Beyond this distance from the turbine the heat flux is increased across the whole of the wake.

**Figure 2.** Wake profiles in a stable boundary layer, compared with that in a neutral boundary layer. Neutral, left; stable, right. Symbols denote distance, $X$, from turbine in term of $D$. Lines with no symbols show profiles in the undisturbed flow, with distance in units of m from working section inlet. Line with symbol shows profiles at $X/D = 0.5$. 

![Figure 2](image-url)
Figure 3. Profiles of mean temperature and vertical heat flux, stable flow. Lines with no symbols show profiles in undisturbed flow.

Figure 4. Wake profiles in an unstable boundary layer. Neutral, left; unstable, right. Symbols denote distance from turbine in term of $D$. Lines with no symbols show profiles in the undisturbed flow, with distance in units of m from working section inlet. Line with symbol shows profile at $X/D = 0.5$. 
3.2. Unstable boundary layer

Figure 4 shows profiles in a vertical plane aligned with the hub axis, between 0.5D and 10D downstream of an isolated turbine, and reference profiles for the undisturbed (i.e. the ‘upstream’ flow), for both the baseline neutral case and the convective case of Hancock and Zhang [10]. (For these measurements, the turbine was placed at 12 m from the working section inlet.) From the references profiles of $\overline{u^2}$ and $\overline{w^2}$ in it can be seen that there is still some streamwise development of the flow. Further details are given by Hancock et al.[2]. As a general comment, it was found that $\overline{w^2}$ was the slowest to settle to horizontally homogeneous conditions in any of the ABL simulations. In contrast to the neutral and stable cases it can be seen that the turbulence levels in the convective ABL are substantially larger, even though the flow is only weakly unstable (a point that is discussed in [2]). The strength of the mean velocity deficit decreases more rapidly in the unstable case (compared with the neutral), as would be anticipated from the higher level of turbulence, and also seen in field studies of Magnusson and Smedmann [9] and in the wind tunnel experiments of Zhang et al. [6]. Clearly, too, the height of the boundary layer is increasing more rapidly, as can be seen from the mean velocity and turbulence profiles.

Figure 5 shows the wake height, $H$, above hub height, and also the width of the wake, $W$, at hub height, for both the neutral and convective cases. The height and width are based on the distances from the hub axis at which the velocity deficit is 0.1 of the maximum deficit. As can be seen, the growth of the height and width are larger in the convective case, as would be anticipated because of the higher level of ABL turbulence. Also, the growth rates are linear, at least to a reasonable approximation. It is inferred from this increase, and the linear behaviour - as also seen in the neutral case - that the effect of the unstable ABL on the wake development over this, or nearly this, streamwise extent is an indirect one. However, perhaps significantly, the shape of the mean velocity profile at $X/D = 10$, in figure 4d, is noticeably different from those further upstream in the wake. Below about tip-top height (i.e. below about $Z/D = 0.5$), the shape has become more like that of the undisturbed ABL flow. From this, and evidence from the vertical heat flux measurements discussed below, it is inferred that direct effects are occurring, at least for this case, from about 10D onwards.

Profiles of mean temperature and (kinematic) heat flux in the vertical plane are shown in figure 6. The trends for the mean temperature are less clear than they are for the stable case, but there appears to be an overall increase in the wake. An increase could be expected as a result of increased mixing. The behaviour of the heat flux, by comparison, differs fundamentally from that seen for the stable case. In the early part of the wake there is a substantial reduction. However, by about 3D there is a marked increase in the lower part of the wake, reaching the undisturbed level, while at the same time there is no change above hub height. In the stable ABL, at this station, the increase was in the upper
part. But, by 10D the whole of the profile in the wake is close to that of the undisturbed flow. This last point lends support to the suggestion above that the wake at this distance from the turbine has become directly influenced by buoyancy effects. Moreover, perhaps the distance before which direct effects are seen, compared with that in the stable case, is larger because of the higher level of ABL turbulence.

Figure 6. Profiles of mean temperature and vertical heat flux, unstable flow. Lines with no symbols show profiles in undisturbed flow

Finally, a feature seen in the early part (i.e. first and second stations) of the neutral and unstable wakes, but not the stable wake, is the decrease of $\overline{w^2}$ below the respective undisturbed levels. Hancock and Pascheke [4] attributed this to the blocking effect of the turbine on the upstream flow, rather than an effect via suppressed turbulence production (Hassan, [11]). Clearly, the effect is stronger in the unstable case, where it is also seen in the behaviour of $\overline{w^2}$.

3.3. Two-point correlations

Two-point LDA measurements are shown in figures 7 and 8, made at hub height and separated laterally by the distance, $\Delta Y$ (i.e. with the measuring points at $\pm \Delta Y/2$ from the turbine axis). Those in figure 7 show profiles between 0.2D and 4D upstream of the (first) turbine, from which it can be seen that there is no noticeable difference from one to another. Figure 8, by contrast shows the same measurement upstream of a second turbine directly behind the one of figure 7. Clearly, in the wake flow, as would be anticipated, there is a very different behaviour. The curves decrease more rapidly, consistent with the smaller integral length scale of the wake flow turbulence, but they also fall well below zero, giving double-negative minima at 4D and 3D upstream. However, by 2D upstream the inner minimum has disappeared, though at this distance the upstream influence of the second turbine is itself still very small, while it is not small at 0.2D upstream. A negative cross-correlation coefficient of comparable size was found in the wake of a porous-gauze representation of a turbine by España et al. [13].

Figure 9 shows profiles of the correlation coefficient at 3D downstream of each of four turbines on the wind tunnel centreline, together with the profile for the undisturbed flow. It is particularly striking that profiles after the second, third and fourth turbines (i.e. at 9D, 15D and 21D) all decrease at about the same rate, or slightly faster, than that at 3D, and become negative to a significant level over a large part of the flow. They fall markedly below that of the undisturbed profile, and only start to rise (towards zero) for $\Delta Y$ larger than the rotor diameter, over a larger distance than for the undisturbed flow. It is inferred that the observed behaviour may be the result of the wakes oscillating laterally; a quasi-steady oscillation with probes either side of the centreline would lead to a negative correlation.

Two-point measurements behind three turbines in a row in the unstable flow gave correlation coefficient profiles close to those in figure 9 at the same respective station, except that at $X/D = 3$ – i.e. in the wake of the first - where it did not rise to the second maxima, but continued to fall to the second minimum.
Figure 7. Two-point cross-correlation coefficient at hub height, upstream of first turbine. Neutral flow.

Figure 8. Two-point cross-correlation coefficient at hub height, upstream of second turbine (6D downstream from first). Symbols as in figure 7. Neutral flow.

Figure 9. Two-point cross-correlation coefficient at hub height 3D downstream of each of 4 aligned turbines. Reference upstream coefficient also shown. Neutral flow.

3.4. Effect of laterally adjacent turbines (neutral flow)
The effect of placing two rows of four turbines, either side of the central row, as shown in the photograph of figure 1, on profiles of mean velocity at hub height are shown in figure 10. The lateral spacing of the side rows from the central row of only ±2.4D has the intended advantage, as will be seen, of a progressive interaction that for wider spacing would require a larger number of turbines in the streamwise direction, and a longer working section. This particular spacing also makes the sidewalls planes of symmetry, so that in effect the array is infinitely wide, if the boundary layers on the side walls can be ignored. The profiles in figure 10 are 3D downstream of each of the turbines on the central row. In this figure, and also in figure 11, the velocity is given with reference to the wind tunnel reference velocity. At 3D and 9D, the effect of the adjacent turbines can be seen in a slight increase in the velocity at the edge of the wake, as is to be expected because of the increased blockage. The velocity minima at these two stations are also slightly higher, which again would be
expected because of the higher velocity external to the wake (as a result of the blockage). At 3D there is a clear region at the edge of the wake in which $U$ is constant, while at 9D there is no such region, implying that the adjacent wakes are impinging on the wake of the second central turbine. The interaction is strong enough for the maxima at 15D to fall below those at 9D, and the maxima at 21D to fall below those at 15D. The minima at these latter two stations are still slightly higher. Another point to note, is that the wakes are slightly narrower, which is also to be anticipated as a result of the blockage of the adjacent wakes.

![Figure 10](image)

Figure 10. Mean velocity profiles, $U/U_{ref}$, at hub height against $Y/R$, at 3D downstream from each turbine, for a single line of 4 turbines (o), for an array of 12 turbines (+). Velocity normalised by $U_{ref}$

Profiles of the streamwise Reynolds stress $\overline{u^2}$ at the same stations as in figure 10 are given in figure 11. Inside a certain point, profiles for the 12-turbine array are coincident with those of the single row of four – at each of the four stations. It is assumed this must be fortuitous. If the profiles for the central turbines were normalized on a width inferred from the mean velocity profiles, the two sets would no longer coincide (because the width in the 12-turbine case is smaller, as can be seen from figure 10). Another point to make is that the peak levels are also virtually no different. It would be anticipated that the wakes of adjacent turbines would give rise to higher peak levels, as a result of the wake turbulence generated by them. The result of a simple superposition of profiles of $\overline{u^2}$ is shown in figure 12. Superposition of $\overline{u^2}$ would apply if the two turbulence fields, with velocity fluctuations $u_A$, $u_B$ say, were uncorrelated (so that $\overline{u_A u_B} = 0$) and did not interact. The red line in the figure is that at $X/D = 15$ in figure 11. The blue line (○) is the same profile but shifted laterally to $Y = 2.4D$, and the green line (□) is simply the addition of the two. Clearly, the present measurements in figure 11 do no behave in this way.

Although not shown here, a very closely comparable set of profiles of two-point velocity-cross-correlation coefficients to that in figure 9 was obtained in the twelve-turbine array. Thus, the phenomena observed there also is unaffected by the presence of adjacent wakes.
Figure 11. Profiles of $\frac{u'^2}{U_{Ref}^2}$ at hub height against $Y/R$ at 3D downstream from each turbine, for a single line of 4 turbines (o), for an array of 12 turbines (+).

Figure 12. Superposition of $\overline{u'^2}$ from supposed adjacent wake. Red line (o) is profile from figure 11.

4. Concluding comments
The issue of atmospheric boundary layer depth in relation to the size of a wind turbine for neutral and non-neutral conditions is discussed, as is the issue of direct and indirect effects of stratification, and the issue of scaling from full scale to wind-tunnel scale. Single-point velocity and turbulent heat-flux measurements have been made in the wake of a single turbine in stable and unstable flow. Compared with the base-line neutral flow, the velocity deficit decreases more slowly in the stable case and more quickly in the unstable case, while the height of the wake increases less rapidly and more rapidly,
respectively. For the stable flow, direct effects of stability are seen after about $X = 3D$, principally in this case as a result of the inversion (i.e. the imposed condition) above the ABL, while for the convective case direct effects where only seen from about $X = 10D$, probably because of the higher turbulence level in the ABL. The effects on turbulent heat flux for the two stability cases are opposite; initially small in the near wake but large in the far wake in the stable case; initially large in the near wake but small in the far wake (where ‘far’ is taken in this instance as $X/D = 10$). Two-point velocity cross-correlation measurements in neutral flow showed substantially different structure of the wake-flow turbulence compared with that of the undisturbed flow. Though change of structure was expected, the strength of the negative cross-correlation was not, reaching to a coefficient of $-0.4$, the earlier part of the wake exhibiting two negative peaks. For turbines in a line, aligned with the flow, the strong negative peak persists and is significant over a separation of greater that $2D$. It is inferred the cause is a lateral oscillation of the wake. The behaviour is much the same in a convective ABL. The presence of adjacent rows of turbines (in neutral flow), separated laterally by only $2.4D$, showed wakes that meet but interact in a quite restricted way with, for example, no clear change in peak turbulence levels.

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