Wind tunnel simulation of a wind turbine wake in neutral, stable and unstable wind flow

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Abstract. Measurements of mean velocity, Reynolds stresses, temperature and heat flux have been made in the wake of a model wind turbine in the EnFlo meteorology wind tunnel, for three atmospheric boundary layer states: the base-line neutral case, stable and unstable. The full-to-model scale is approximately 300:1. Primary instrumentation is two-component LDA combine with cold-wire thermometry to measure heat flux. In terms of surface conditions, the stratified cases are weak, but there is a strong ‘imposed’ condition in the stable case. The measurements were made between 0.5D and 10D, where D is the turbine disk diameter. In the stable case the velocity deficit decreases more slowly; more quickly in the unstable case. Heights at which quantities are maximum or minimum are greater in the unstable case and smaller in the stable case. In the stable case the wake height is suppressed but the width is increased, while in the unstable case the height is increased and the width (at hub height) reaches a maximum and then decreases. The turbulence in the wake behaves in a complex way. Further work needs to be done, to cover stronger levels of surface condition, requiring more extensive measurements to properly capture the wake development.

1. Introduction

While offshore wind farms have a number of advantages over onshore farms in coping with increased demand, there remain many issues that need much better understanding in order to achieve high reliability and efficiency. One of these is the development of turbine wakes under various atmospheric wind flow conditions, and the effect of wakes on downwind machines in terms of power output and fatigue. It is well known that lower atmospheric boundary layer (ABL) turbulence intensity causes the wake deficit to decay more slowly than it does in high intensity. Sea surface roughness is lower than land surface roughness, and this results in lower intensities. While the atmosphere is commonly assumed to have neutral stability or, on average, to have neutral stability, such an assumption impairs proper assessment of turbine output and loads. In the context of the North Sea, for example, the atmosphere is unstably stratified for more than one third of the time [1]. While a large number of laboratory studies have been made of wakes of turbines in uniform and sheared flow characteristic of a neutral ABL, almost no studies have been made for non-neutral cases. One such study is that of Chamorro and Porté-Agel [2] in a stable ABL, though their investigation showed unexpected effects, contrary to the measurements reported [3].
In this study, detailed measurements have been carried out on wake flows under a neutral (as a reference case) and two stratified ABL conditions, one stable and one unstable, using a laser Doppler anemometry (LDA) and a near-coincident cold-wire probe to measure temperature fluctuation and, thereby, the turbulent heat flux. The intention is primarily two-fold. One is that the data will provide insight into the physics of the interaction of the wake turbulence with that of a stratified atmospheric boundary layer. The other is that the data will be of sufficient quality to provide quantitative test cases against which to compare predictive models. In both stratified cases the flows are weakly stable and weakly unstable, as inferred from the surface Monin-Obukhov length, though in the stable case there is a strongly stable condition imposed from above, and in the unstable case the flow in the mixed layer has features associated with strong instability.

2. Experimental arrangement

2.1 EnFlo environmental wind tunnel and turbine models

Experiments were performed in the EnFlo stratified-flow wind tunnel. This unique wind tunnel has been heavily used for gas dispersion studies in various atmospheric boundary conditions [4]. The working section of this suck-down wind tunnel is 1.5 m in height, 3.5 m in width and 20 m in length, with a speed range of 0.3 to 4 m/s. It is able to reproduce various ABL conditions by means of a bank of inlet heaters and a heated or cooled floor.

Five slightly truncated Irwin-type spires [5], placed at the working section inlet, were used to assist in generating the correct mean velocity profile. See figure 1. The spires had base and tip widths of, respectively, 300 mm and 10 mm, and were spaced laterally 660 mm. Surface roughness was simulated by a layout of small bricks (16 × 50 × 5 mm, standing on the 50 × 5 mm face) with the spacing of 510 mm in the spanwise direction and 360 mm in the streamwise direction. This combination of spires and surface roughness elements was carefully selected for producing offshore neutral ABL conditions [6], assuming a 10 m/s mean wind speed at a 10 m height, at a model scale of 1:300.

In the presentation of results, x, y and z denote distances from, respectively, the working section inlet, the centre-line and the floor, and X, Y and Z denote distances from the model turbine tower hub (Z = z − 300 mm), parallel to x, y, z, respectively. U, V and W, and u, v and w are respectively the mean and fluctuating velocities in the x, y and z directions. The free stream reference velocity, \( U_{\text{Ref}} \), was taken at \( x = 5 \, \text{m} \), \( y = 1 \, \text{m} \), and \( z = 1 \, \text{m} \).

![Figure 1. View of the model turbine in the working section, showing the spires and surface roughness.](image-url)
The turbine model comprised a three-blade rotor with a diameter of $D = 416$ mm, a micro motor-generator with a gear box and a solid steel tower 13 mm in diameter (and hub height of 300 mm), a modified representation of the Supergen 5MW exemplar turbine. The blade was made of fibreglass and resin with a shape of a twisted thin plate without an airfoil 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 [3]. The turbine was controlled through a 4-quadrant controller in order to maintain a constant rotation speed with a variation less than 1 rpm. It was located at $x = 12$ m, 12 m and 11 m for the neutral, unstable and stable cases respectively, for which the rotor speeds were set at 382 rpm, 380 rpm and 385 rpm. The thrust coefficient, $C_T$, was about 0.48. Further details are given in [3].

Velocity measurements were made using a Dantec two-component 40 MHz frequency-shifted laser Doppler anemometry (LDA) system, and a standard 27mm Fibre-flow probe. This optical set-up produces a measurement volume of 0.074 mm in diameter and 1.57 mm in length. The seeding particles with a nominal size of 1 μm in diameter were generated from the sugar solution aerosol by the hydrosonic seeding machine. To obtain turbulent heat flux, a high data rate, high frequency cold-wire probe was placed at about 3 mm downstream of the LDA measurement volume, after carefully tuning of the location of the cold wire probe. This arrangement enabled simultaneous and co-located measurements of the velocity and the temperature fluctuations to be realized. For a similar arrangement see Heist and Castro [7]. Mean temperatures were measured by means of thermocouples.

### 2.2 Operational conditions

Three stratified boundary conditions were set up to investigate the wake flow development of the wind turbine model operated at a tip-speed-ratio of 6 and a reference freestream velocity of 1.5 m/s. The unstably stratified condition was simulated by heating the wind tunnel floor to a temperatures of 43 °C in the range from 0 m to 18 m downstream of the inlet and together with an inlet temperature profile as shown in table 1, while the stable case was generated by cooling the floor down to 15 °C and with an inlet temperature profile in table 1, and the temperature can be controlled accurately with a comparative uncertainty as low as 0.2 °C.

| Table 2 The Inlet temperature profile for stable and unstable cases. |
|---|---|---|---|---|---|---|---|---|
| Heater | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| $z_1$ [mm] | 1450 | 1350 | 1520 | 1150 | 1050 | 950 | 850 | 750 | 650 | 550 | 450 | 350 | 250 | 150 | 50 |
| $T_1$°C [SABL] | 64 | 61 | 58 | 55 | 52 | 49 | 46 | 43 | 40 | 37 | 34 | 31 | 28 | 25 | n/a |
| $T_1$°C [UABL] | 28 | 27 | 26 | 25 | 24 | 24.25 | 24.45 | 24.75 | 25 | 25.3 | 25.6 | 25.9 | 25.2 | 26.7 | 27.8 |

Table 2 shows the boundary layer parameters for the three stratified atmospheric conditions. Among them, the Monin-Obahkov length, and the Brunt-Väisälä frequency:

$$L = \frac{T_0 u_*^2}{\kappa g T_*} \quad \text{and} \quad N = \left[ \frac{g \partial \Theta}{T} \right]^{1/2}.$$  

$T_0$ is the mean absolute temperature at the surface, $u_*$ the friction velocity and $T_*$ the surface layer temperature scale defined by $T_* = -(w \bar{\theta})_0 / u_*$, where $(w \bar{\theta})_0$ denotes the kinematic surface heat flux. $\kappa$ is the von Karman constant, taken as 0.4, and $g$ is the gravitational acceleration. $\Theta$ is temperature and $T$ is the mean absolute temperature in the flow near the top of the ABL. In Table 2, $z_i$ is a nominal...
height of the ABL, and $z_0$ and $z_{h0}$ are the aerodynamic and thermal roughness lengths, respectively.

Figure 2 compares momentum, temperature and heat flux at the three downstream stations on the central plane $Y = 0$ for the three stratified boundary conditions (i.e. neutral, stable and unstable). Profiles of $U$, $u'^2$, $w'^2$ and $-uw$ are in the top row while those of $\Theta$, $\theta'$, $\bar{u}\theta$ and $\bar{w}\theta$ are in the bottom row, where $\theta$ denotes the instantaneous fluctuation and $\theta'$ its r. m. s. Generally, the profiles at the tree stations in each set concur closely or fairly closely with each other, implying approximate horizontal homogeneity, and are mostly clearly different for each stability case. The profiles of $U$ for the unstable case show a much steeper rise near the surface consistent with much higher levels of mixing.

![Figure 2](image_url)

**Figure 2.** Profiles of mean velocity, Reynolds stresses, mean temperature, mean square temperature fluctuations and heat fluxes at $x = 11$m (○), 13m (●) and 15m (*) under neutral (black), stable (blue) and unstable (red) boundary conditions

Reynolds stresses are largest for the unstable case whereas they are the smallest for the stable case, as shown in Figures 2b, 2c and 2d. Furthermore, near the surface $w'^2$ and $-uw$ increase with height up to $\approx0.3$ m for the unstable case while they constantly decrease for the neutral and stable conditions. These are self-evidently attributed to enhanced flow mixing by the heat flux in the unstable case and the stabilizing force in the stable case, and are as observed in meteorological studies (see e.g. Kaimal & Finnegan [8]).

For the unstable ABL, the temperature fluctuations decrease with height while, except near the surface, they increase for the stable case, which is the consequence of the large temperature gradient in the free stream in this case. Note, the surface temperatures are not shown; in both cases there is a steep gradient near the surface. Interestingly, profiles of the horizontal heat flux
Figure 3. Contours of the mean streamwise velocity on the central vertical plane for the wake flow: (a) Stable; (b) Neutral; (c) Unstable

Figure 4. Contours of the Reynolds shear stress on the central vertical plane for the wake flow: (a) Stable; (b) Neutral; (c) Unstable
are similar in magnitude between the stable and unstable cases while the vertical heat flux ($\bar{w}\bar{\theta}$) shows different trends between stable and unstable cases, which are similar in shape to the profiles of vertical velocity fluctuations and shear stress as shown in figures 2c and 2d.

3. Wake measurements
All the wake measurements were made on a vertical or horizontal plane coincident with the turbine hub axis.

3.1. Momentum and Reynolds shear stress contours on a vertical plane
Figure 3 compares contours of the mean streamwise velocity on the central vertical plane of the wake flow for the three stratified boundary conditions. The velocity deficit is the largest, and the recovery is seen to be slowest for the stable case. For example, the double-peaks velocity deficit areas are ended by $4D$, $5D$ and $6.5D$ downstream for the unstable, neutral and stable cases respectively. Compared with the neutral case, growth in the vertical direction is larger in the unstable case, but negligible in the stable case.

In Figure 4, which shows contours of $-\bar{u}\bar{v}$, the largest positive and negative shear stress regions exists in the wake flow under an unstable ABL, most noticeably at the top tip height. These regions expand upwards and downwards as they develop downstream. In contrast, the stable case does not differ so much from the neutral case, though at the top tip height the peak level does rise and subsequently fall earlier.

![Figure 5](image-url)  
Figure 5. Lateral profiles of mean velocity ($U/U_{hub}$, $W/U_{hub}$), Reynolds stresses ($\bar{u}^2/U_{hub}$, $\bar{w}^2/U_{hub}$, $-\bar{u}\bar{v}/U_{hub}$), temperature ($T$), and heat fluxes ($\bar{u}\bar{\theta}$ and $\bar{w}\bar{\theta}$) at $X = 0.5D$ (+) and $1D$ (o) Black: neutral; red: unstable; blue: stable.
3.2. Momentum, temperature and heat flux on a horizontal plane

Figure 5 compares lateral profiles of momentum \((U, W, \overline{u^2}, \overline{w^2} \text{ and } -\overline{uw})\) and thermal \((\Theta, \overline{u\Theta} \text{ and } \overline{w\Theta})\) parameters in the near wake \((0.5D \text{ and } 1D)\) for the three ABL cases. It can be seen that relatively small differences exist between the profiles at \(X/D = 0.5\) and those at \(X/D = 1\), in each case. Figure 5a shows that the largest velocity deficit which has been produced in the wake flow under the stably stratified condition. For example, the minimum streamwise velocity is close to \(0.5U_{hub}\) compared with \(0.6U_{hub}\) for the neutral conditions and slightly larger still for the unstable ABL. In figure 5c, a small peak of vertical velocity component occurs at the right hand tip \((Y/D = 0.5)\) and a small trough at the left hand side \((Y/D = -0.5)\), arising from streamwise vorticity and wake swirl, the latter clearly evident in the centre of the wake. The variation is least for the unstable case and largest for the stable case, presumably because of the different levels of mixing, and presumably linked with the different levels of deficit seen in the streamwise mean velocity. An asymmetrical variation can be seen in the shear stress distributions in figure 5f, as would be anticipated.

Figure 5b shows that profiles of \(\overline{u^2}\) within wake flow are very similar in shape for these three cases, but an obvious difference existing at the wake edge where \(\overline{u^2}/U_{ref}^2\) reaches the undisturbed levels, such as 0.003 and 0.008 for stable and unstable ABLs, respectively. In fact, the peaks are narrowest in the stable case, and broadest in the unstable case. Also noteworthy is the fact that the level of \(\overline{u^2}\) at about \(Y = \pm 0.25\) is lower than in the undisturbed flow, most noticeably in the unstable

![Figure 5a](image1.png)  ![Figure 5b](image2.png)  ![Figure 5c](image3.png)  ![Figure 5d](image4.png)  ![Figure 5e](image5.png)  ![Figure 5f](image6.png)  ![Figure 5g](image7.png)  ![Figure 5h](image8.png)

**Figure 5.** Lateral profiles of momentum and thermal parameters in the near wake \((0.5D \text{ and } 1D)\) for the three ABL cases. It can be seen that relatively small differences exist between the profiles at \(X/D = 0.5\) and those at \(X/D = 1\), in each case. Figure 5a shows that the largest velocity deficit which has been produced in the wake flow under the stably stratified condition. For example, the minimum streamwise velocity is close to \(0.5U_{hub}\) compared with \(0.6U_{hub}\) for the neutral conditions and slightly larger still for the unstable ABL. In figure 5c, a small peak of vertical velocity component occurs at the right hand tip \((Y/D = 0.5)\) and a small trough at the left hand side \((Y/D = -0.5)\), arising from streamwise vorticity and wake swirl, the latter clearly evident in the centre of the wake. The variation is least for the unstable case and largest for the stable case, presumably because of the different levels of mixing, and presumably linked with the different levels of deficit seen in the streamwise mean velocity. An asymmetrical variation can be seen in the shear stress distributions in figure 5f, as would be anticipated.

Figure 6 shows that profiles of \(\overline{u^2}\) within wake flow are very similar in shape for these three cases, but an obvious difference existing at the wake edge where \(\overline{u^2}/U_{ref}^2\) reaches the undisturbed levels, such as 0.003 and 0.008 for stable and unstable ABLs, respectively. In fact, the peaks are narrowest in the stable case, and broadest in the unstable case. Also noteworthy is the fact that the level of \(\overline{u^2}\) at about \(Y = \pm 0.25\) is lower than in the undisturbed flow, most noticeably in the unstable

![Figure 6](image9.png)  ![Figure 6a](image10.png)  ![Figure 6b](image11.png)  ![Figure 6c](image12.png)  ![Figure 6d](image13.png)  ![Figure 6e](image14.png)  ![Figure 6f](image15.png)  ![Figure 6g](image16.png)  ![Figure 6h](image17.png)

**Figure 6.** Lateral profiles of non-dimensional mean velocity \((U/U_{hub}, W/U_{hub})\), Reynolds stresses \(\overline{u^2}/U_{hub}^2\), \(\overline{w^2}/U_{hub}^2\), \(-\overline{uw}/U_{hub}^2\), temperature \((\Theta)\), and heat fluxes \((\overline{u\Theta} \text{ and } \overline{w\Theta})\) at \(X = 5D\). Black: neutral; red: unstable; blue: stable.
case. Although showing similar trends, the profiles of $\overline{w^2}/U_{hub}^2$ show larger differences between the stable and unstable conditions as revealed in figure 5d. This is a consequence of the high ambient vertical velocity fluctuations for the unstable ABL which is over 5 time larger in terms of $w^2$ at hub height than it is in the stable case.

Figure 5e shows that lateral variation of mean temperature has no clear trend for the wake flow in the unstable ABL (against the background of slight overall non-uniformity). In contrast there is a clear variation for the stable case. Clearly, for the stable case, the positive vertical velocity carries cold air up and negative vertical velocity warm air downwards. It is assumed this mechanism is too weak to be seen for the unstable ABL.

Horizontal heat flux ($u\theta$), figure 5g, shares much the same profile for the stable and unstable conditions although it is more scattered for the stable case. However, this pattern is not seen in the vertical heat flux, $\overline{w\theta}$, figure 5h. Instead, heat transfer is mostly reduced in the unstable case but mostly increased in the stable case. (The heat flux, normalized by the surface heat flux, is positive in both cases.)

At $X = 5D$, the wake flow is clearly quite different between these three stratified conditions, as shown in figure 6. For example, the streamwise velocity recovers to $0.75U_{hub}$ in the unstable condition, and only $0.6U_{hub}$ for the stable case. Furthermore, the profiles of the $W$ and $\overline{w^2}$ show one dominant peak for the unstable condition instead of two peaks for the stable ABL (figures 6c and 6d), and the asymmetry seen in the stable case for $-uw$, and the horizontal heat flux (figures 6f and 6g) is absent in the unstable

![Figure 7](image)

**Figure 7.** Vertical profiles of mean velocity ($U/U_{ref}$), Reynolds stresses ($\overline{u^2}/U_{ref}^2$, $\overline{w^2}/U_{ref}^2$, $-\overline{uw}/U_{ref}^2$), mean temperature ($T$), r.m.s. temperature fluctuations ($\theta'$), and heat fluxes $u\theta$ and $w\theta$ at $X = 0.5D$ and $1D$. Black: neutral; red: unstable; blue: stable.
3.3 Momentum, temperature and heat flux on the vertical plane

Figure 7 compares vertical profiles in the near wake under the three stratified conditions. For the unstable ABL, profiles of the streamwise and vertical velocity fluctuations and the vertical heat flux have shapes that resemble each other (figures 7b, 7c and, less markedly, 7h), while the shape of the shear stress resembles that of the horizontal heat (figures 7d and 7g). In the stable ABL, the vertical and horizontal heat fluxes have relatively small amplitudes and show a weaker wake effect of the turbine in the near wake, as revealed in figure 7g and 7h.

The wake flow has a larger mean velocity deficit in the stable case which, it is supposed, is connected to the lower level of velocity fluctuations in both the ABL and the wake flow, as seen in figures 7b and 7c. Furthermore, at the top tip height \( Z/D = 0.5 \), \( \bar{u}^2 \) and the shear stress are about 50% lower in magnitude than that in the unstable condition.

At \( X = 5D \), figure 8a shows that the centre of the velocity deficit is seen to have shifted slightly downwards to about \( Z = -0.23D \) for the stable condition while it moves upwards in the unstable case. Similarly, the peaks of \( \bar{u}^2 \), the shear stress and the horizontal heat flux shift down to \( Z = 0.4D \) for the stable condition while it moves up to \( Z = 0.6D \) for the unstable case, as revealed in figures 8b, 8d and 8g.

![Figure 8](image)

**Figure 8.** Vertical profiles of mean velocity \( (U/U_{ref}) \), Reynolds stresses \( \bar{u}^2/U_{ref}^2 \), \( \bar{w}^2/U_{ref}^2 \), \( -uw/U_{ref}^2 \), mean temperature \( (T) \), r.m.s. temperature fluctuations \( (\theta') \), and heat fluxes \( \bar{u}\theta \) and \( \bar{w}\theta \) at \( X = 5D \). Black: neutral; red: unstable; blue: stable.

3.4 Development of the wake flow

The height and width of the wake are defined by the vertical and lateral locations where the velocity deficit reaches the 0.1ΔU (i.e. 0.1 maximum velocity deficit ΔU). Figure 9 shows the development of the wake flow in the vertical and lateral directions, as inferred from measurements on vertical and
horizontal planes coincident with the turbine hub axis. In the vertical direction, as is to be expected, the wake growth is the fastest for the unstable case. For example, it increases roughly linearly with a gradient of 0.11 in the unstable case. In contrast, the wake flow keeps at a roughly fixed height of 0.6D for the stable condition, probably because of the strong imposed condition. In the lateral direction, the development of the wake reveals an opposite trend. The wake expands for the stable condition and has increased by about 80% at X = 9.5D, while it ceases to grow beyond 3D downstream, and has even shrunk at 10D downstream, for the unstable case. However, it must be remember that the measurements were only on a single horizontal plane at hub height, and measurements at other heights might have exhibited a different picture. In deed, the aforementioned reduction in width might only be apparent, and may be accounted for a bodily rise in the wake in the unstable case, consistent with peaks in quantities occurring at greater height, as seen in figure 8, for example.

Figure 9. Development of the wake in vertical (left) and lateral (right) directions for neutral, stable and unstable ABLs

4. Concluding comments

Three stratified boundary conditions (neutral, stable and unstable) were generated by heating and cooling the wind tunnel floor combined with different inlet temperature profiles. In terms of surface conditions both non-neutral flows were weakly non-neutral, but the inversion in the stable case was ‘strong’. Wake flows for these three cases were investigated using detailed measurement on the vertical and horizontal planes. These show, for example, that the velocity deficit is the largest for the stable ABL and the smallest for the unstable ABL, at all measurements stations from X = 0.5D to X = 10D. The heights of maxima and minima in various quantities are moved upwards in the unstable case, and downwards in the stable case.

Stratification has a large affect on the wake in its height and width. Compared with the neutral case, the wake height grew much more rapidly in the unstable case, as did its width as far as about X = 3D beyond which growth ceased and then decreased. However, this last feature may at least in part be apparent, rather than real, caused by the wake lifting bodily upwards in the convective case. In the stable case the wake height stayed at a near-constant level over most of its length, probably because of the imposed condition, but grew more rapidly in width. Loosely, the wake might be described as “squashed” in the stable case. The turbulence in the wake behaves in a complex way.

It must be remembered that these results are for one specific case of stable ABL and one specific case of unstable ABL. Stronger levels of surface condition need to be investigated in order to cover the parameter ranges of practical interest, for both stable and unstable wind flow conditions. Variation of the imposed condition is also required for the stable case. An imposed condition (an inversion) above an unstable flow is less likely to be important as the inversion layer is at a substantially greater height for an unstable wind flow. Lateral-profile measurements at heights above and below the hub height will be needed in order to properly capture the effects of wake distortion caused by non-neutral flow.
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