Wind Tunnel Simulation of Wind Turbine Wakes in Neutral, Stable and Unstable Offshore Atmospheric Boundary Layers

Philip E. Hancock, Frauke Pascheke, and Shanying Zhang

Abstract. Relatively little is known about wind turbine wake development in stable and convective wind flow. From the UpWind [1] study wind conditions in areas of the North Sea are significantly non-neutral for about 70 percent of the time. The stable atmospheric boundary layer is particularly complex, and if the stability is sufficiently strong the boundary layer depth is comparable with the tip height of large wind turbines. The 'imposed' condition, the potential temperature gradient above the boundary layer, is therefore important. In a first phase of work, measurements have been made in the wake of a model wind turbine in neutral, stable and unstable offshore atmospheric boundary layer simulations, the neutral case being the reference case. The stable case is for weak surface-layer stability, but typical strong imposed stability above. The wake deficit decreases more slowly, consistent with the lower level of boundary layer turbulence, but after about 3 rotor diameters it ceases growing in height as a direct consequence of the imposed stability. Temperature and heat transfer are increased in the wake, the latter though only from about 3 diameters. The unstable cases show more rapid reduction of the velocity deficit, and higher levels of turbulence. The greater depth of the unstable layer means that conditions above are much less important.

1 Introduction

Understandably, a widely-made assumption in the wind power industry regarding wind resource is that the wind flow is neutrally stable or nearly so, and that unstable and stable periods roughly balance out and are equivalent to neutral conditions. (See for instance [2] regarding wake prediction.) However, the mean wind profile and the level of turbulence in the atmospheric boundary layer (ABL) are dependent

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upon stability, and wind flow turbulence has long been recognised as promoting wake diffusion and a more rapid deficit reduction (see for example [3]), potentially allowing a smaller streamwise separation between turbines. Turbulence and mean shear from an upwind turbine adds to the load imposed on a turbine over and above that of the turbulence and mean shear arising in the undisturbed wind flow. Modelling wakes is therefore of major practical importance. However, relatively, little is known quantitatively about how wakes develop under stable or unstable wind flow conditions.

The convective motions in an unstable ABL give rise to higher intensities and greater depth, while the buoyancy forces in the stable case reduce the intensities and depth. Importantly in this latter case, the depth of the boundary layer can be reduced enough for the top of it to be below the top of the rotor disk of a large wind turbine (say 5MW, where the top of the rotor disk is at about 150m). In the neutral and unstable cases the whole height of the turbine is immersed in the ABL. The stable ABL is particularly complex, and the condition imposed from above by the stable temperature gradient, $d\theta/dz$, is as much a principal parameter as those of the surface layer. This is an important point for wind power meteorology because there is little field data for temperature and velocity profiles up to heights of 200m.

The work reported here is part of a programme of work within the UK-EPSRC Supergen-Wind consortium. A first series of wind tunnel measurements have been made of a single turbine in stable and unstable boundary layers.

2 Wind Tunnel and Turbine Models

The EnFlo wind tunnel is designed to simulate neutral and stratified atmospheric boundary layers. Stable or unstable stratification is created by cooling or heating the floor surface, assisted by heaters upstream of the working section that can provide a temperature gradient at the inlet. A heat exchanger removes heat at the end of the working section. Irwin-type spires [4] at the working section inlet together with surface roughness are used to generate mean velocity and turbulence profiles with typically correct characteristics. Here, the neutral case was based on the guidelines of ESDU [5, 6], assuming a mean wind speed of 10m/s at a height of 10m. The working section is 20m long, 3.5m wide and 1.5m high, and the simulation was done at a scale of 300:1. The three-blade model turbine has a diameter of 416mm and a hub height of 300mm, with a design tip-speed-ratio of 6. The rotor drives a four-quadrant motor-generator through a gearbox. A consequence of scaling is that the temperature gradient $d\theta/dz$ above a stable boundary layer must be such that

$$(\frac{D}{U_{ref}})^2 \frac{d\theta}{dz} = constant, \tag{1}$$

where U_{ref} is a reference velocity, D the rotor diameter and z the height from the surface. This implies that the gradient in the wind tunnel must be much larger than in the atmosphere; non-dimensionally, LN/U_{ref} will be the same for both for similarity, where L and N are the Obukhov length and the Brunt-Vaisala frequency, respectively.

Velocity was measured by means of a Dantec FibreFlow two-component frequency-shifted LDA probe, mean temperature by thermocouples and fluctuating temperature by a cold wire held close to the measuring volume in order to measure the instantaneous heat fluxes. The cold wire was calibrated against the traversed thermocouple. Each measurement point was sampled for a minimum of 2 minutes, at a mean sampling rate of about 90Hz for the LDA, and at 3kHz for the fluctuating temperature, interpolated to coincide with the LDA samples. The largest error is expected to be in the statistical averaging, taken to be within about $\pm 1\%$ for mean velocity and $\pm 10\%$ for the second-order moments. The technique, including details about the frequency response for the temperature fluctuations, is described in more detail by [7].

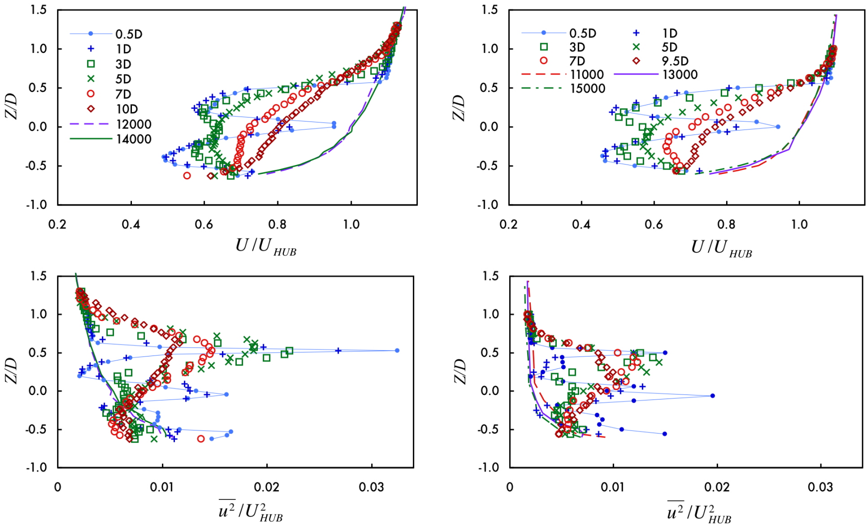

Fig. 1 Wake profiles of mean velocity and Reynolds direct stress $\overline{u^2}$ between 0.5D and 10D from the turbine. Left side, neutral, right side stable. Lines indicate respective undisturbed profiles (at distances from the working section inlet (mm)).

3 Results

Figure 1 shows profiles of the mean velocity U and streamwise Reynolds stress $\overline{u^2}$, normalised by the hub-height velocity, U_{HUB}. The left side of the figure is the neutral case and the right the stable case, for which L/D was 3.0. Here, z is from the hub axis. The lines in the figures show the undisturbed profiles at X from the working section inlet, in units of mm.

There are number of immediately notable features. The momentum deficit is larger for the stratified case, as is to be anticipated by the lower level of turbulence in the ABL. However, the vertical growth rate is also clearly less at the downstream stations, and in fact has ceased, as can be seen by the comparison given for the last two stations in figure 2 (a feature also seen in other quantifies). A closer examination of the profiles shows that the growth rates are very similar up to about 3 diameters, but is suppressed from 5D onwards. This is inferred as a direct effect of stratification, while the larger deficit in the earlier part of the wake is an indirect one, arising from a lower level of ABL turbulence. The Reynolds stress ($\overline{u^2}$) profiles are noticeably smaller in magnitude in terms of "added" turbulence of $\overline{u^2}$ - the undisturbed level. That the stress is smaller in magnitude for the earlier profiles is interesting in that the mean shear is larger in the stable case.

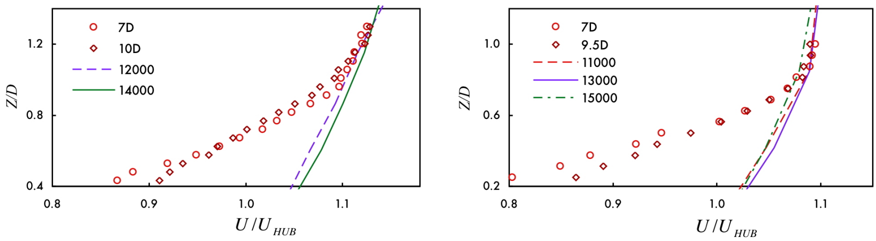

Fig. 2 Mean velocity profiles, near the profile edge, from figure 1

Also noticeable is the *lower* level of $\overline{u^2}$ w.r.t. the unperturbed ABL profile, but only in the neutral case. Tentatively, it is thought this may be due to an impeding effect of the turbine on axial fluctuations in the upstream flow, though [11] attributed it to a decrease in mean velocity gradient, but by either mechanism it should also be present in the stable case.

Qualitatively similar results to that seen here of a larger wake deficit were also seen in field measurements by Magnusson and Smedman [8], and opposite to wind tunnel experiments by Chamorro and Porte-Agel [9], contrary to expectation, for reasons that are not understood, though it may be linked with a smaller (but not zero) imposed condition in their case.

Figure 3 shows the mean temperature profiles and the heat flux profiles, where the latter are normalised by the level in the undisturbed ABL. As in figure 1, the lines in the figure indicate the undisturbed profiles. Above the wake, the temperature gradient is about 20K/m which, from equation (1), is equivalent to 0.01K/m at full scale. (D was in the ratio of 1:300, model-to-full scale, and $U_{ref} intheratioof$ 1.5:10.) This a typical strong gradient. See, for example, [10]. The imposed condition is therefore 'strong', but at the surface, from L, the stratification would be classed as 'weak'.

The wake has a significant effect on the mean temperature profile, giving a distinct increase below about hub height, at all stations. In contrast, the heat flux measurements show little initial response; it is only from 3D onwards that a dramatic

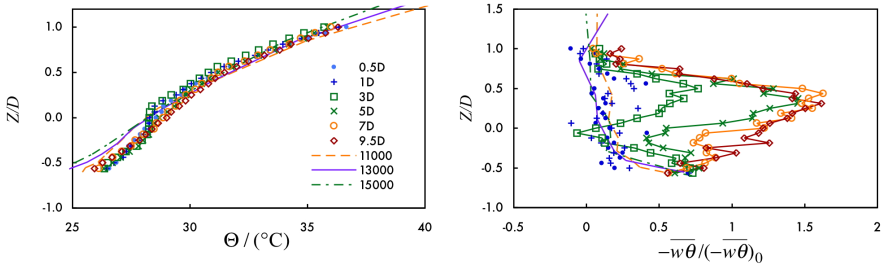

Fig. 3 Mean temperature profiles (left) and vertical heat flux profiles (right), the latter normalised by the unperturbed surface value

change takes place, with a peak level exceeding the surface value by a factor of about 1.6, and the steep change in heat flux, once at the surface, is now at the top edge of the wake. The change in response after about 3D is consistent with the observations above about development of the mean velocity profiles being affected directly by stratification only after about 3D.

Figure 4 shows contour plots of mean velocity and Reynolds shear stress $\overline{uw}$ for two unstable surface conditions, L/D. The mean velocity deficit can be seen to decrease more rapidly with decreasing $|L|$, and the shear stress becoming more intense. The shear stress contours also indicate a more rapid growth rate. These latter measurements are preliminary in that the undisturbed ABL was still evolving spatially, while for the stable case, as can be seen in figs 1 and 3 there was a negligible or small change. Simulation improvements are the subject of current work.

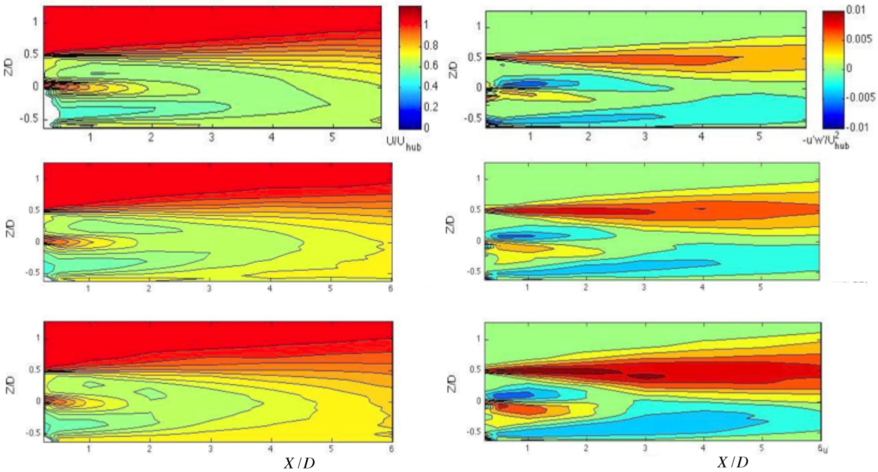

Fig. 4 Contours of mean velocity U and Reynolds shear stress $\overline{uw}$, normalised by U_{HUB}. Top pair, neutral; middle, $L/D = -2.8$; bottom, $L/D = -1.6$.

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