Wind-tunnel simulation of stably stratified atmospheric boundary layers

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Abstract. Results are presented of simulations of a stable boundary layer of moderate surface condition and zero overlying inversion strength. The layer depth is matched to model scale by artificially thickening the boundary layer by means of flow generators (‘spires’) at the working-section inlet. A non-uniform inlet temperature profile is essential in order to preclude the upper part of the layer retaining neutral conditions. The layer behaviour is sensitive to the prescribed form and care is needed in its specification. The results also show that the surface cooling should be started some distance downstream of the working-section inlet. The developed flow is closely horizontally homogeneous.

1. Introduction
The characteristics of the wind approaching any wind turbine depend upon a large range of factors. In overall terms, these include velocity mean shear, turbulence levels and spectral distribution, upstream conditions, and change of upstream conditions, such as a topographical feature, wakes of upstream turbines, and the presence of buoyancy forces in the atmosphere. While on a long-term average (over, say, a year) the wind is usually about neutrally buoyant, over shorter timescales it is far from neutral. Various studies of wind conditions for offshore wind farms have shown substantial periods of moderately or strongly stable or convective states [1, 2], and for these states to significantly affect the output of single turbines and arrays [2-4]. Optimisation of power output against fatigue-life cost is highly desirable for good economic performance of wind farms, and the variability of the wind therefore requires operation according to short-time-scale prevailing conditions (e.g. hour-by-hour). Predicting and forecasting of short-time-scale output is important for grid supply management against demand. These critically require understanding of the influences of stable and convective conditions that pertain in particular to the diurnal variations in the atmospheric boundary layer, and that vary widely.

This paper is part of a series of studies of wind-tunnel simulations of non-neutral airflow conditions, using the facilities of the EnFlo environmental flow wind tunnel [5-9]. In each of these studies we have employed the approach of wind engineering in using flow generators and surface roughness to generate airflow with typical characteristics [10, 11], but developed further to provide simulation of stable and convective conditions, with substantially more parameters to consider. The main concern in wind engineering is loads on structures at high wind speeds, where the flow can be safely regarded as neutral or near-neutral, and the purpose of the generators and roughness is to generate flow characteristics that are typical of full-scale wind. While the use of generators is standard practice for these purposes, much more work is to be done in extending this technique to stable and convective winds for studies on wind turbines and other areas such as pollution dispersion.
The generators and roughness also amount to artificially thickening the boundary layer and in effect making the wind-tunnel working-section development length much longer than it is. In addition, the greater depth has advantages in matching boundary layer and model scales, and is advantageous for obtaining a higher Reynolds number and for instrumentation.

Stable boundary layers are much shallower than neutral layers, and shallower still than convective layers, and the depth can be comparable or even less than the blade-tip-top height of large wind turbines, while that height may be only one-tenth the depth of a convective layer. In simple terms a stable boundary layer is straightforward – one of rising potential temperature with height, but in practice it is far from simple. Two local boundary conditions are important: the surface heat flux (or, equivalently, the surface Obukhov length) and the inversion strength (the temperature gradient) above the boundary layer. In the work of [5] – our initial phase of work – stable stratification was achieved simply by imposing a constant temperature gradient in the upstream flow, giving a typical inversion strength, but with only a weak surface-heat-flux condition. Also, as acknowledge there, the turbulence intensity above the stable layer was overly high owing to the height of the generators.

The present work is intended to form, part of a systematic investigation of the separate effects of surface condition and inversion strength, and also upstream conditions. Within this, there is the issue of the ‘boundaries’ between moderate, transitional, and strong stability [12] where, in the latter, the strength of stability is sufficient for turbulence to be heavily suppressed and for wave motions to develop. However, at this stage only moderate stability is being considered. Even so, many cases were considered over several months arising from the number of independent parameters. Earlier work [5] has shown the near-surface flow readily conforms to Monin-Obukhov similarity. The same is true here, but the principal concern is the flow above the surface layer and how this can be simulated in a wind tunnel. The present paper is a summary of key conclusions. Some of the findings are likely to be relevant to computational simulation, particularly those associated with inlet and initial conditions, though only in a qualitative sense.

The nocturnal boundary layer develops from an ‘initial condition’ of a decaying convective layer as a consequence of surface cooling and the cessation of convective motions. The initial conditions of the stable layer are therefore very varied. With a substantial reduction of turbulent mixing it is to be anticipated that the influence of initial conditions are likely to be long lasting. Long-lasting influence is certainly seen in the present measurements.

2. Wind tunnel, flow simulators and instrumentation
The EnFlo open-return meteorological wind tunnel has a working section of length 20 m, width 3.5 m and height 1.5 m. A system of horizontal heater elements, in banks 100mm high, immediately upstream of working-section inlet allows the vertical temperature profile, measured by a rake of thermistor probes, to be specified at the inlet. Floor-cooling panels allow a negative surface heat flux to be generated (with step change if desired). The cooling was provided by a chilled-water system in which recirculation allowed control of the chilled-water temperature to within, typically ±0.2K. Because of the stratification capability the wind tunnel does not have a contraction upstream of the working section, as is conventional for wind tunnels. As a consequence, as will be seen, there is a residual non-uniformity of the free-stream velocity profile, but this is not significant in the present investigation. Careful control of the recirculating flow entering the wind tunnel from the laboratory meant that the variation of temperature across the inlet (upstream of the heaters) was within about ±0.1K, measured by an array of thermistor probes. Irwin-type spires [11] were employed to generate, in the first instance, the reference neutral wind. These spires were 600 mm high, 60 mm wide at the base, and 4 mm wide at the top, spaced laterally 266 mm, and are a geometrically scaled-down version (by a factor of 0.4) of those used previously [5], so as to simulate the lower height of a stable boundary layer. The surface roughness was a pattern of discrete blocks as employed previously [5]. Scaling from full- to model-scale is discussed in [5].

Velocity measurement was by means of two-component laser-Doppler anemometry (LDA), via a Dantec 27 mm FibreFlow probe. Fluctuating temperature measurement was made using a calibrated fast-response cold-wire probe, held close to the LDA measuring volume so as to allow measurement
of the turbulent heat fluxes. Mean temperature was measured by means of a calibrated thermistor probe. The effect of temperature inhomogeneity and fluctuations on LDA measurements is considered in [5] and shown to be negligible.

In the results presented below, $X$ is the distance from the working-section inlet, $Z$ is the distance from the wind tunnel floor, and $Y$ from the centre-line. An ultrasonic anemometer was used to provide a reference velocity, $U_{\text{ref}}$, placed at $X$, $Y$, $Z = 5\,\text{m}$, $1\,\text{m}$, $1\,\text{m}$. It had no discernable affects on the downwind measurement stations. Nominally, the first half of the working section length is required for the flow to adjust to the influence of the spires, to settle to horizontally homogeneous flow. $U$ denotes the streamwise mean velocity, and $u$, $w$ and $\theta$ the fluctuating streamwise and vertical velocities and fluctuating temperature, respectively.

3. Results

Three cases are given here. The first is the baseline neutral flow in which any temperature differences were negligible (typically $\pm 0.1\,\text{K}$). The second is for a flow in which only the lower part of the boundary layer depth was stable, and the third (in subsection 3.2) is where the whole depth was stable.

3.1 Preliminary results

For a given set of flow generators (spires) at the working-section inlet there are in essence three practical temperature controls; maximum temperature difference between the free stream and the cooled wind-tunnel floor (which, with the free stream velocity, provides a bulk Richardson number); the distance downstream of the inlet after which the floor cooling is applied; a distribution of inlet temperature $T(Z)$ below the height of the free stream edge. (The inversion gradient was zero.)

![Figure 1. Profiles of mean velocity and Reynolds stresses, for the neutral flow.](image)

Figure 1 shows the variation of mean velocity and Reynolds stresses with height at three streamwise stations on the wind tunnel centre-line, for the neutral case. The mean velocity profiles do not change very much in shape between the three stations, least of all between the last two. From these it can be seen that the height, $h$, of the boundary layer is between about $550\,\text{mm}$ and $600\,\text{mm}$, as to be anticipated, based on the height of the spires. The Reynolds stress profiles also show a comparable but slightly larger height, the same at each station. Profiles at the first station ($X = 6400\,\text{mm}$) are nominally in the development region, while the later two stations show very comparable profiles,
indicating closely horizontally-homogeneous flow. The higher levels at the third station compared 
with that at the second can partly be accounted for by the higher free-stream velocity, and partly by 
residual development. Increasing free-stream velocity with distance arises because the working 
section walls are parallel and there are growing boundary layers on the ceiling and side walls. 
(Measurements at the first two or three heights in figure 1 are affected by the local influence of the 
roughness elements, exhibiting non-monotonic behaviour, and the same is true in the following cases.)

**Figure 2a.** Profiles of mean velocity and Reynolds stresses, for a *uniform* inlet temperature profile.

**Figure 2b.** Profiles of mean temperature, turbulent heat fluxes and temperature mean square, 
for a *uniform* inlet temperature profile.
A stable (or convective) boundary layer growing spatially from zero thickness – as could be the case in a wind tunnel – is in fact initially a neutral layer. This is because, even though the gradients of temperature and velocity are initially very large, the gradient of velocity dominates over that of the temperature, as can be seen in terms of the gradient Richardson number, 
\[
\left(\frac{g}{T}\right)\frac{dT}{dZ}/\left(\frac{dU}{dZ}\right)^2,
\]
which may also be written as a bulk Richardson number, 
\[
\left(\frac{g\Delta T(h)}{T_0 U_h^2}\right),
\]
g is the gravitational acceleration, \(T\) is the air temperature, \(T_0\) the surface temperature, and \(U_h\) the velocity at height \(h\). (All else constant, the Richardson number grows linearly with height, the layer becoming increasingly stable.) After the initial but unsatisfactory trials with non-uniform inlet profiles, it was decided that the inlet profile should be uniform. A related point was observed by trial and error by [13] in large-eddy simulation. It was also supposed that a uniform temperature profile might be best for the early development of the flow around and immediately downstream of the spires.

However, it was found that upper part of the boundary layer remained unaffected by stability, as can be seen from the Reynolds shear stress profiles in figure 2a. The invariance in \(-\overline{uw}\) in the upper part of the layer for the three streamwise stations is in distinct contrast to that in the middle of the layer, where the three profiles are clearly different from each other. The feature seen in the shear stress is more marked in \(\overline{w^2}\) but almost invisible in \(\overline{u^2}\), for which there is virtually no significant variation between the three stations. In the lower part of the layer the respective profiles are again in close agreement with each other, consistent with surface-layer similarity. Overall, the Reynolds stresses are smaller in magnitude in the stable case, as is to be expected. As for the neutral case, the mean velocity profiles are comparable with each other, exhibiting very similar features and development to that seen in figure 1. They are also quantitatively close to the respective profiles of figure 1. The layer height, \(h\), is the same in the two cases.

Figure 2b shows quantities involving temperature. As can be seen, there is very little variation of mean temperature above \(Z \approx 300\) mm, and the other quantities are comparatively very small above this height. The uniformity of temperature at the inlet has been in effect advected downstream and consequently the temperature in the upper part of the boundary layer has remained constant; that part of the flow has therefore remained neutral. In the lower part of the layer, on the other hand, there

![Figure 3](image-url)
is a large mean temperature gradient and clear gradients of (kinematic) heat transfer, $\overline{w\theta}$ and $\overline{u\theta}$, and mean-square temperature fluctuation $\overline{\theta^2}$. The lower part has features of an internal layer, but is bounded on its upper side by the middle layer – an adjustment region – that sits between the stable lower part and the neutral upper part.

The fact that stability has the tendency to suppress turbulence might be supposed to contribute to the persistence of the advected neutral flow in the upper part, but with reduced turbulence levels. However, the Reynolds stresses are close to that of the neutral flow in figure 1, as can be seen in the comparison in figure 3. Against this, the invariance in the upper part in figure 2 is more striking.

As had been assumed at the outset, the effect of artificially thickening a boundary layer necessarily requires a non-uniform profile of temperature at inlet, but early attempts at this had not worked, underlining the carefulness required in setting up a stable boundary layer, in contrast to a convective layer where it had worked easily [7].

3.2 Final results

After carefully investigating a family of inlet temperature profiles it was found that boundary layers can in deed be created in which stability effects are present over its full depth. Figure 4 shows profiles at four streamwise stations of the same quantities as given in figure 2. Clearly, a mean temperature gradient exists over the full depth of the layer (figure 4b), as defined by the mean velocity and Reynolds stress profiles, and $\overline{w\theta}$, $\overline{u\theta}$ and $\overline{\theta^2}$ only become zero at the top of the layer. As also could be seen from other cases (not given here) the shape of their respective profiles is linked with the profile of mean temperature, but not in a simple way. For example, large peaks in $\overline{\theta^2}$ were created in the middle of the layer for some of these cases, at about where the adjustment region lies in figure 2. The inlet temperature profile is shown in figure 5. Its shape is clearly different from that of the downstream stations, but not in a wholesale way. The profiles of each quantity in figure 4 are seen to be closely horizontally homogeneous, more so in fact than the neutral case of figure 1.

As mentioned earlier, another parameter is the extent of uncooled floor, where the temperature of this part of the floor is determined in essence by the inlet temperature profile rather than the temperature of the cooled surface. It was found that cooling the whole of the floor could cause a ‘mismatch’ between the lower and upper part of profiles of the Reynolds stresses rather like that seen in figure 2. It was found that the length of uncooled floor has to be decided in conjunction with the inlet temperature profile. For the case in figure 4 the uncooled length was 5m while that for figure 2 it was 1m. Increasing the length of uncooled floor for the inlet profile employed for the case of figure 2 would have reduced the ‘mismatch’, but would still have left the upper part a neutral flow.

This case in figure 4 is one of moderate surface condition (in terms of surface Obukhov length, $L_0$) and zero-strength overlying inversion, and first of progressively stronger cases to be considered. Here $h/L_0 \approx 0.68$, where $L_0 = \frac{1}{\kappa \rho^2 g} \frac{(\overline{u^2}/\overline{w\theta})}{\overline{w\theta}}$. $\kappa = 0.40$ is the von Karman constant, $u$ is the friction velocity, and $\overline{w\theta}$ denotes the surface heat flux. The free-stream turbulence intensity, $\overline{(u^2)^{1/2}/U}$ is about 1% compared with 4% in [5]. The characteristics exhibited in figure 4 are comparable with field observations of [14].

4. Conclusions

A methodology has been established for wind-tunnel simulation of stable boundary layers of specified depth (controlled essentially by the spire height), at least for moderate stability. Careful control of the prescribed inlet temperature profile is essential in order to achieve a well-behaved layer – also desirable for progress in physical modelling. While the temperature gradient remains strongest at the surface, an initially uncooled length of floor is a means by which the Reynolds stress profiles can be controlled in the lower half (thereabouts) of the layer. The results achieved provide a framework in which earlier work [5] can be taken forward in a systematic manner.
Figure 4a. Profiles of mean velocity and Reynolds stresses for a non-uniform inlet temperature profile.

Figure 4b. Profiles of mean temperature, turbulent heat fluxes and temperature mean square, for a non-uniform inlet temperature profile.
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