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Reynolds-number and surface-modeling sensitivities for experimental simulation of flow over complex topography

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ABSTRACT

This paper documents the development of an experimental approach for determining the wind characteristics over complex topography. Using fast-response pressure probes, vertical wind profiles were measured over wind-tunnel models representing the complex topography of a wind farm currently under construction. A terraced-model approach was taken to simplify the manufacturing of the topographic models, providing the added benefit of enhanced surface roughness from the terraced steps. A preliminary study in a small wind tunnel identified restrictions on the Reynolds number and terrace step size that are required for attaining adequate high-Reynolds-number boundary-layer characteristics at a scale of 1:1500. Subsequent measurements over the entire wind-farm topography were compared to site measurements from meteorological masts, from which recommendations for improved experimental simulation techniques are identified.

1. Introduction

With the strong growth of Canada's wind-energy sector, a need was recognized to reduce wind-farm planning and development times. Canada has a strong wind resource in mountainous and coastal regions where the topography is complex. As a result, such complex environments often require long evaluation and planning processes due to the necessity for long periods of site measurements to characterize accurately the wind resource. A methodology is being developed at the National Research Council Canada (NRC), based on physical modelling in a wind tunnel, to determine precisely the wind characteristics over a relatively large area with complex topography under neutral conditions. The main application is to provide a tool to wind-farm developers for wind-resource assessment and turbine siting. A secondary objective is the improvement of our understanding of the sub-scale physical modelling techniques that must be addressed to carry out successful wind tunnel investigations of the flow over a complex model.

To be effective the approach needs to provide a short turn-around time and cost savings, relative to extensive long-term on-site meteorological surveys. It must also provide precision measurements of important quantities for the planning of a wind farm and the selection of wind turbines: vertical profiles of both the mean wind speed and turbulence characteristics at several locations as a function of wind direction, and the vertical wind angle at hub height (approx. 80 m full-scale) for the same locations. Precision is important because the power output is proportional to the cube of the mean velocity.

Currently, numerical simulation techniques are the methods of choice for detailed wind resource evaluation. Recent work of the wind-energy community in numerical modelling for complex topography has shown improvements for such techniques. Castro et al. (2003) conclude that a high-order transient scheme with a variable-roughness turbulence model provided a reasonable representation of the flow over the Askervein Hill, a classic test-case for complex terrain studies. The primary difficulty involved capturing the separated-flow region on the lee side of the hill. In a follow-up study, Silva Lopes et al. (2007) showed that similar deficiencies were still present when utilizing the more-expensive large-eddy simulation approach. The recent Bolund Experiment (Bechmann et al., 2011), a blind test of the flow over mildly complex topography, showed varied results compared to field measurements even between similar numerical techniques.

With proper control of the boundary conditions, experimental techniques can provide the correct physics for the flow-regions of interest under neutral conditions. As such, these experimental techniques can be used in concert with numerical procedures to allow a complete characterization of the wind resource for a region with complex topographic features under any atmospheric stability conditions. A hybrid approach, described by Derickson and Peterka (2004), combining physical modelling using a topographic model with a meso-scale (100–3 km resolution)

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atmospheric numerical model with micro-scale capability (3–100 m resolution) has been used to predict the flow characteristics in complex terrain. The physical model is used to calibrate the numerical model in regions with rapid changes of topography and surface roughness for neutral conditions where the numerical model fails. Once calibrated, the numerical model is used to predict the wind characteristics for stable or unstable wind conditions where temperature and stratification effects are important and cannot be modelled easily in a wind tunnel. Derickson and Peterka (2004) conclude, however, that for topographic features with rapid change of elevation such as for escarpments and cliffs, the wind tunnel is the tool of choice for evaluation of the wind characteristics, even more so if the slope of the escarpment is in excess of 60°. The issue of Reynolds number was not addressed for their terrain studies and while a discussion on the use of the terraced approach versus the smooth approach for the reproduction of the topography was provided, no conclusion was reached as to which approach provides results closest to full scale conditions.

The physical modelling technique is commonly used to model terrain surrounding structures in wind-engineering studies, and has been studied for use in atmospheric boundary layer simulation. A strong history of atmospheric-boundary-layer modelling at the NRC provides the benefit of approaching the problem using experimental techniques in a wind tunnel. The work by Bowen (2003) can be directly applied to the development of our physical modelling technique using topographic models. Aerodynamic roughness and roughness Reynolds number are defined by Bowen and limits are given for an adequate simulation in model scale. He concluded that the scale ratio of the roughness height to boundary-layer thickness should be smaller than 1:500 for the best similitude. For smaller scale ratios, e.g. 1:1000–1:1500, an exaggeration of the model surface roughness is needed to increase the local turbulence levels to obtain an adequate simulation. To maintain a boundary layer in equilibrium, a balance between surface roughness and boundary layer depth should be maintained. This can be achieved using a terraced-model approach.

The majority of the data used by Bowen (2003) for the establishment of his empirical limits were extracted from model-scale experiments at several scales in a relatively low-speed wind tunnel. These limits can easily be reached in NRC's larger wind tunnels given the high wind-speed capabilities and the large dimensions of the test sections. For example, a minimum Reynolds number of 100,000 based on the hill height is recommended for an adequate simulation of the flow over a hill. In the NRC 3 m × 6 m Propulsion and Icing Wind Tunnel, a Reynolds number of 400,000 can be reached for a small 0.15 m high hill (model scale), representing a 150 m high hill at a geometrical scale of 1:1000. Bowen's work clearly steers away from the use of scales exceeding 1:3000 topographic model studies. Studies at such scales were used in the 1980s for the evaluation of flow over complex terrain for wind energy applications (e.g. Neal, 1983; Meroney, 1980). More recently, Petersen et al. (2011) identify the need for more thorough Reynolds-number sensitivity analyses and better documentation of experimental modelling for wind-tunnel studies of complex topography to ensure adequate simulation of the flow.

To prevent the need for a long fetch over which a boundary layer can grow to the desired thickness, spires are commonly used to simulate the atmospheric boundary layer, and have been adopted for the current project. Early studies showed the applicability of such devices in correctly simulating the velocity profiles, turbulence levels, and spectra of such layers (Irwin, 1979). It is also important to understand and account for the potential differences due to a large disparity in Reynolds number between the model and prototype flows. Again, Bowen (2003) discusses some of the issues of importance in complex terrain simulations, of which turbulence characteristics in the near-wall region are a major issue. The drag-producing mechanisms in the near-wall flow, which influence the turbulence throughout the boundary layer, must be reproduced adequately to obtain a correct simulation of the prototype flow. As implied by the discussions of Bowen (2003) and the experimental study of Snyder and Castro (2002), the proportionally high viscous forces observed at low Reynolds numbers, as a result of the viscous sub-layer, can be mitigated by the use of roughness elements with sharp edges that generate drag through a separation-induced form-drag mechanism at the surface. This minimizes the Reynolds-number dependence of the boundary layer and provides better simulation of the high-Reynolds-number prototype flow.

Hunt and Morrison (2000) and Hunt and Carlotti (2001) discuss the "high-Reynolds-number" turbulent boundary layer and identify the differences in the observed flow-structures as compared to "low-Reynolds-number" layers. In particular, they note the presence of an "eddy surface layer" (ESL) in which internal boundary layers are formed inside the large-scale eddies that are drawn towards and impinge on the surface. The ESL is only present for $Re_\delta \gtrsim 10^4$, where Re_δ is based on the boundary-layer thickness and friction velocity, however, it generally covers only a small proportion of the boundary-layer height, $h_{ESL} \approx < \delta/100$ (Hunt and Carlotti, 2001). It is conceivable that the presence of sharp-edged roughness elements at low-Reynolds-number provide similar turbulence structures as observed in the ESL that otherwise would not occur in the viscous sub-layer. Hunt and Carlotti (2001) also note that in engineering and laboratory flows that satisfy the high-Reynolds-number criteria, the ESL may occupy a substantially greater part of the near-wall boundary layer up to about $\delta/3$. Although the logarithmic mean velocity profile is sustained through the ESL, the velocity spectra show some distinctly different characteristics than typical laboratory boundary layers. The primary difference observed in the ESL is the presence of a self-similar spectral characteristic in which the spectral drop-off is proportional to k^{-1} for $k \approx < 1/z$, where k is the wavenumber $(=2\pi f/U)$. This is unlike the $k^{-5/3}$ spectral decay generally associated with the inertial sub-range. These "high-Reynolds-number" characteristics can be further emphasized in strongly inhomogeneous flows such as those over complex topography.

One of the pivotal goals of the project described herein is to demonstrate that rapid fabrication of the topographic model (built-up from topographic layers and thus presenting a stepped or "terraced" surface) can provide the same aerodynamic fidelity as that obtained with an exact replica of the terrain. This stepped-surface technique will be less expensive to fabricate than an exact replica with its fine detail of the terrain.

This paper describes the techniques employed by NRC in simulating the flow over complex topography, and demonstrates the ability of these methods for simulating the correct flow physics. The project was divided in two phases. This first phase addressed the secondary objective, that is, the development of a competency in physical modelling of complex topography while the second phase directly addressed the primary objective of demonstrating the ability to model accurately the flow over a wind farm in complex topography.

2. Material and methods

2.1. Site selection

The Gros-Morne wind farm, currently under construction in the Gaspésie region of Québec, Canada, was selected as the prototype site for the project. Fig. 1 shows the terrain elevation for the region of interest. This wind farm, which will consist of