ATMOSPHERIC BOUNDARY LAYER WIND TUNNEL DESIGN

Leow Wah Wei and Lim Chin Liang Desmond

Turbulence Energy & Combustion Group (TEC),
The University of Adelaide, Adelaide SA 5005, Australia.

ABSTRACT

It has been proposed that a design for an atmospheric boundary layer wind tunnel be built at the Adelaide University Thebarton Campus specifically to provide a testing facility for assessment of atmospheric wind flows on various engineering fields. The working section is to be 3 m in length with a cross section of 1.5 m × 1.5 m and a boundary layer development section of 20 m. The simulation of the atmospheric boundary layer can be achieved by inserting appropriate turbulence and velocity profile generators together with surface roughness elements. The design is based on the use of an existing 18 kW, axial-flow fan with a volumetric flow rate about 31 m^3/s but also allows for a new fan of larger capacity. In this paper the design process is summarised and factors leading to particular design decisions are detailed.

KEYWORDS: Atmospheric Boundary Layer, Wind Tunnel Design, Roughness Elements

INTRODUCTION

Over the past thirty years, wind engineering researchers have shown that turbulent boundary layer flow over the floor of a wind tunnel can provide a reasonable simulation of the 'atmospheric boundary layer' (ABL). Wind tunnel modelling of the ABL has allowed wind tunnel testing to become a useful design tool for high-rise structures. Most of the wind codes are based on studies undertaken in this way. Where modern codes permit alternative methods of estimating wind loads, these methods must invariably be qualified using atmospheric boundary layer wind tunnel (ABLWT) testing [1]. The tunnel application is not limited to building structures alone. Recently more and more research is done using ABLWT, such as in the area of industrial aerodynamics, air pollution, soil erosion and recreation (eg. Sydney 2000 Olympic Cauldron) [2]. Due to limited ABLWT availability in Australia and increasing consulting projects involving the assessment of atmospheric wind flows received by TEC group, it is proposed that an ABLWT to be built at the Adelaide University Thebarton Campus.

The basic physical requirements of an ABLWT are a uniform cross sectional flow and a long working section together with appropriate floor roughness elements to develop a boundary layer with flow that varies significantly from the test section floor to the ceiling. The roughness elements basically act as earth surface roughness to artificially simulate the earth's ABL. However there are tunnels, which have additional devices such as spires, vortex generators and trips to accelerate the rate of growth and produced a fully developed boundary layer [3]. There are also tunnel with heating and cooling facilities to produce a thermally stratified ABL. Due to the limited cost and complicated tunnel configurations, only the use of roughness elements and spires will be considered in the design and the heating-cooling facilities are ignored. However future work to stimulate a stratified ABL in the tunnel is proposed.

ATMOSPHERIC BOUNDARY LAYER

The atmosphere from ground level up to 300-500 m, where effects of surface drag forces on airflow become negligible, is known as the ABL. In this layer, the wind speed varies from zero at the ground to the geostrophic value, U_g when pressure gradients and the Coriolis forces reach equilibrium at an elevation corresponding to the gradient-wind level, Z_g. For wind engineering application, the Z_g is usually taken as the maximum wind speed of the ABL and is also taken as the ABL thickness, δ [4]. The value δ varies from place to place depending on the earth's surface characteristics. Increasing the roughness of the earth surface across which the air moves increases the turbulence, thus resulting in a different thickness. For example, the boundary layer over an open sea (smooth surface) might be as low as 300 m compared with a thickness of approximately 500 m in an urban area with significant surface roughness. .

The air motion in the ABL can be categorised into two motions, namely the 'main flow' and 'boundary layer flow' [5]. In the main flow, the viscosity (fluid friction) plays a negligible role, while in the boundary layer flow, the fluid friction is influential. There are several factors that affect the air motion in the ABL. The earth's surface roughness (described previously), the distance from earth and the temperature all play an important role in influencing the air's motion. The average speed of the wind increases with the distance from the earth, while the intensity of the turbulence or gusting decreases. The temperature difference within the atmospheric boundary layer affects both wind speed and intensity of turbulence in complex ways and is classified by the stability of the atmosphere.

The variable given above shows that the flow in a boundary layer is difficult to model mathematically. However, the empirical power law has found its wide acceptance in the area of wind engineering applications [1]. The power law is usually expressed as

$$\frac{u}{u_\delta} = \left(\frac{z}{\delta}\right)^{\frac{1}{n}} \quad \text{or} \quad \frac{u}{u_\delta} = \left(\frac{z}{\delta}\right)^{\alpha} \tag{1}$$

where z is the height for the floor/earth surface, u is the mean free stream velocity, u_δ is the mean velocity at z = δ and the exponent 1/n or α depends, for an aerodynamically smooth surface, on the Reynolds number and, for a rough surface, on the roughness length. Figure 1 indicates approximately what is implied in the matching of the parameters of the power law profiles for different surface roughness.

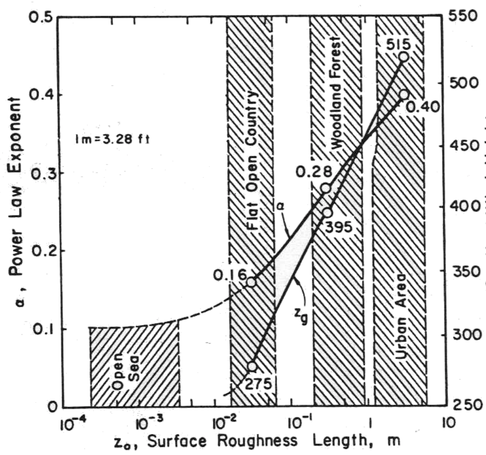

Figure 1: Empirical relationship between ABL parameters [4].

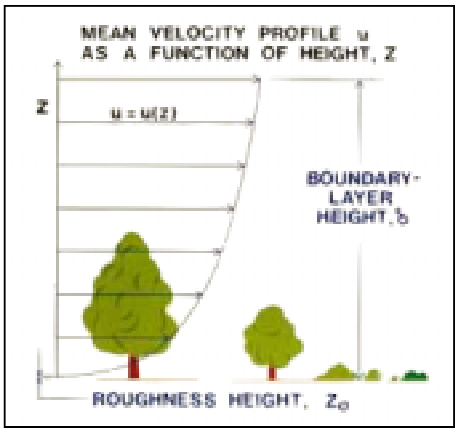

Figure 2:Velocity profile of an ABL [5].

FUNDAMENTAL SIMILARITY CRITERIA

The structure of an ABL is complex and cannot be modelled exactly in a wind tunnel. However, by selecting certain similitude parameter that need not be strictly matched, one can obtain a good stimulation. Cermak [4] has described a few important requirements that need to be matched to simulate a natural ABL. These requirements are:

1. Similarity of relative surface roughness.
2. Kinematic simulation of airflow, boundary layer velocity distribution and turbulence.
3. Matching of Reynolds Number; R_e ($\rho Vw/\mu$), Rossby Number; R_o ($V/L\Omega$) and Richardson Number; R_i ($(\Delta T_o/T_o)(L_o g_o/u_o^2)$).
4. Matching the zero pressure gradient found in the real world.

TUNNEL DESIGN

System Component

In order to achieve a cost-effective design capable of performing the required tests and experiments, the tunnel was designed with several criteria in mind.

- Open Circuit
- A budget of A$ 5000
- Use of existing 18 kW, axial flow fan but design must be account for a new fan later
- Available space – 1.9 m × 35.0 m (Within the lab of the Thebarton Campus)
- Ease of maintenance and accessible test section
- Maximum boundary layer height possible to maximise model size and Reynolds number

The choice of an open circuit design for the tunnel was made at a very early stage. This was influenced partly by cost, but primarily by the severely limited lateral and vertical dimension of the site. The boundary development section of the tunnel was chosen to be 20 m in length and 1.5 m × 1.5 m cross section with an adjustable ceiling. This configuration is based on the requirements of a long boundary development section, to achieve a fully developed boundary layer, and a zero pressure gradient. The tunnel will be a blow-down configuration. Other general tunnel requirements are to provide a the working section of 3 m in length with spin table, 2 screens at the entrance of the boundary development section to produce a uniform flow, appropriate spires and roughness elements on the boundary development floor and a diffusion section with area ratio of 2.5:1. All the above configuration will be discussed in detail in the next section.

Fan, Motor and Controller

The design of the ABL tunnel was based on the existing 1.2 m diameter axial flow fan. An 18kW three-phase induction motor drives the fan and the speed is controlled by a variable frequency power supply. The duct downstream from the fan incorporates a transition from circular to square cross section (1.2 m × 1.2 m). Due to the tunnel having cross sectional section of 1.5 m × 1.5 m, there is a need for a wide-angle diffuser to join the fan and the tunnel. Experiments have been carried out to determine the flow characteristics of the fan. The results from the experiments show that with maximum fan speed, the fan has an average volumetric flow of 31.0 m^3/s which can produce approximately 14 m/s wind speed in the tunnel. The free stream r.m.s. turbulence intensity of the fan is between 15 % to 20 %. The average sound pressure level measured when the fan operates at the maximum speed is 106 dB (A). A new bigger fan is proposed with a higher velocity and less noise. The selection of the new fan will be included as the future work of this project.

Flow Conditioning

Having screens in a wind tunnel will basically reduce the mean velocity variations leading to prevention or delay in boundary layer separation and turbulent fluctuations. In order to remove the large amount of swirl and turbulent fluctuations from the flow caused by the fan, several screens are required in series to reduce turbulence to an acceptable level, and mean-velocity variations are almost eliminated. In the design of this wind tunnel, honeycomb and screens will be employed to straighten the inlet flow.

The entry section will be designed according to the recommendations of Metha and Bradshaw [6]. It is recommended that honeycomb should be situated at the front of the entry section, to straighten flow and reduce swirl, and that screens be placed behind it, to obtain low turbulence. The spacing between the screens was suggested by Metha and Bradshaw [6] to be 0.2 times the diameter of the entry section. The material chosen for the screens will be stainless steel. The advantages of stainless steel over a metal mesh or nylon are that it is non-corrosive and can be tensioned due to the high velocity in the tunnel. Considerations are undertaken for access to be made available to the screens by fixing each one and the honeycomb into separate sections, all of which are be bolted together, enabling easy dismantling to clean the screens as dirt builds up, which would otherwise reduce the screens effectiveness. Calculations for the loss factor will be done using [6].

Diffuser Design

The diffuser is a gradually expanding passage in which the flow of the air speed decreases and the pressure rises. The recovery of pressure from kinetic energy reduces the power needed to drive the tunnel, which is in the case of open-circuit tunnels; the diffuser also reduces the velocity of air flow in the laboratory.

For this wind tunnel two diffusers will be considered. One will be a wide-angle diffuser and the other is the exit diffuser. A wide-angle diffuser will be required from the blower to join with the working section of the tunnel. A wide-angle diffuser fitted with screens is intended to produce a rapid expansion in area, without any pressure recovery. Although the flow may separate from the walls of the rapid expansion, the extent of separation is limited by the screens, which smooth out velocity variations from one side of the screen to the other. Design rules for wide-angle diffusers are discussed in Metha and Bradshaw [6].

The aspect ratio of the exit diffuser was chosen to be 2.5:1. An ideal diffuser shape is a gradually decreasing rate of expansion but this is difficult to build. Therefore in this wind tunnel, which will be used for tests of building models big enough to disturb the flow in the diffuser, it is safest to keep to a conservative angle from the start.

This is achieved by limiting the included angle of the diffuser to 7.5° [7], which will prevent any flow separations from the diffuser walls and ensure that maximum pressure recovery is achieved. However for this ABL tunnel, an included angle of 7.5° would make the diffuser 8.5 m long. Therefore it was decided to increase the included angle to 10.5°. By doing this, the length of the diffuser would be reduced to only 6 m. Metha and Bradshaw [6] suggest that a maximum of two wire screens was required to ensure attached flow within the diffuser. The reduction in length of the diffuser by 2.5 m is necessary due to the space constraint in the laboratory.

Boundary Layer Development Section

Cermak [8] states that a wind tunnel without any boundary layer thickening devices installed at the entrance or at any sections of the working section can form a boundary layer thickness of approximate 50 cm at a distance of 15 m from the entrance of the boundary layer development section. Use of spire arrays combined with floor roughness will enable thick turbulent boundary layer to be simulated in a short wind tunnel. It was proven that the combination of spires and roughness elements could increase the boundary layer thickness in the working section by 33% [4] compared to a tunnel without any boundary layer thickening devices. The boundary layer thickness for this wind tunnel was calculated using Irwin [9] and Gartshore, Croos [10].

Proposed Spire Design: The momentum balance of the boundary layer development section is analysed assuming that uniform flow exists upstream of the spire array and that at some point downwind of the spires, a boundary layer is formed with a power law velocity profile. The power law is defined in (1). Based on the research work done by Irwin [9], it shows that by calculating the appropriate height (h) and width (b) and the distance between the spires, it can produce the required boundary layer at a distance 6 times the height of the spire (6h) downstream of the spire array. The distance 6h downstream of the spire array has been found to be sufficient to ensure lateral uniformity of the flow when the spires are spaced with their centrelines at intervals of approximately h/2 [9]. Having calculated the spire height and width (61 cm and 9 cm), a boundary layer thickness of 50 cm will be created at a distance 3.66 m downstream of the spire array.

Proposed Roughness Element Design: With the boundary layer thickness determined at 6h downstream of the spire array, the additional boundary layer thickness produced by the roughness element design followed. As the boundary layer development section of this tunnel is 20 m in length, therefore the roughness elements will be placed at the distance after 3.66 m from the spire array to 16.34 m. In order to estimate the roughness, which is required to produce the desired boundary layer, it would be necessary to understand the relationship for the wall shear stress in terms of other boundary layer properties. The flow around individual roughness element at high Reynolds numbers is not yet predictable in detail from the equations of motion [9]. Therefore it is necessary to relate the shear stress to the displacement thickness (δ^*). However it is also possible to relate the roughness height and spacing to the wall shear stress [11]. Using the formulations by Gartshore and Croos [10], the roughness element height and spacing were determined. With roughness height of 3 cm and spacing between each element at 9.5 cm, the tunnel can create an additional boundary layer thickness of approximate 45-50 cm after the distance 6h. Therefore the maximum boundary layer thickness can be produced by this wind tunnel is approximately 100 cm. Considerations are undertaken to design the boundary layer development section such that the various sets of roughness elements can be used or changed to cater for different boundary layer thicknesses.

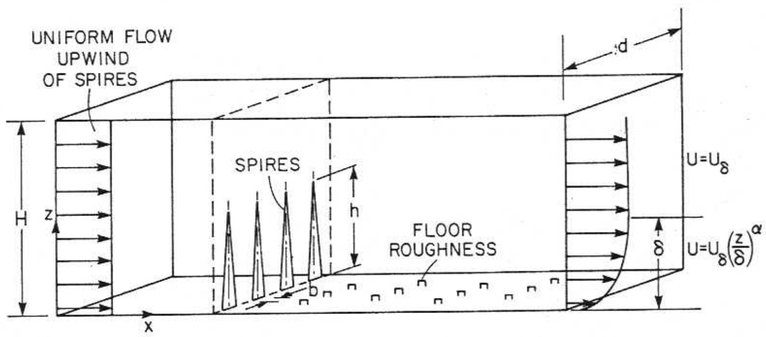

Figure 3: Spires and roughness element in the boundary development section [9].

CONCLUSION

The design of the tunnel was based purely on papers, literature reviews and works done by other ABLWT designer. However, the design has been proven successful at simulate the ABL in other ABLWT. The major design stage of the ABLWT is completed but few minor designs need to be considered and refined. The tunnel's material selection, costing, zero pressure gradient (how much the tunnel ceiling need to be expanded), selection of a new fan and structural design of the tunnel need to be consider as the future work of this project.

ACKNOWLEDGMENTS

The project team members would like to acknowledge the followings: Project Supervisor; Dr. Gus Nathan and Dr. Richard Kelso for their assistant, advice and guidance, Dr. Peter Lanspeary for his assistant with the boundary layer theory and last but not least Mr. Graham Kelly, for his lab support.

REFERENCES

[1] Y.W. Zhao, E.J. Plate, M. Rau and R. Keiser, "Scale effect in wind tunnel modelling", J. Wind Eng. Ind. Aerodyn. , Vol. 61 (1996), 113 – 130.

[2] W.H. Rae, Jr. and A. Pope, "Low-speed wind tunnel testing", John Wiley & Sons Inc., 2nd Edition (1984).

[3] J. Counihan, "An improved method of simulating an atmospheric boundary layer in a wind tunnel", Atmos. Environ., Vol. 3 (1969), 197 – 214.

[4] J.E. Cermak, "Atmospheric boundary layer modelling in wind tunnels, in: Proc. Int. Symp. on the Experimental determination of wind load on civil engineering structures, Uni. of Roorkee, New Delhi, India (Oxford and IBH Publishers, 1990).

[5] B.R. White, "Physical modelling of atmospheric flow and environmental applications", Proc. 51st Anniversary Conf. KSME (2000).

[6] Metha, R. D., and P. Bradshaw, "Design rules for small low speed wind tunnels", Aeronautical J., (1979), 443-449.

[7] J. Milbank, S. Watkins and R. Kelso, "Development of a small-scale aeroacoustic open jet, open return wind tunnel for cavity noise and component testing", SAE Technical Paper Series (2000), 2000-01-0867.

[8] J. Cermak, "Wind tunnel design for physical modelling of atmospheric boundary layers", J. Eng. Mech. Div., ASCE, Vol. 107(3) (1981), 523 – 642.

[9] H.P.A.H. Irwin, " The design of spires for wind simulation", J. Wind Eng. Ind. Aerodyn., Vol. 7 (1981), 361 – 130.

[10] I. S. Gartshore and K. A. De Croos, "Roughness element geometry required for wind tunnel simulations of the atmospheric wind", J. Wind Eng. Ind. Aerodyn., Vol. 60 (1995), 107 – 132.

[11] Dvorak, F. A., "Calculation of turbulent boundary layers on rough surfaces in pressure gradient," AIAA J., Vol. 7 (1969), 1752 – 1760.