Convective boundary layer flows for dispersion modelling.

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Summary
The requirements of a convective boundary layer for the modelling of plume dispersion are discussed in terms of strict Froude and enhanced scaling. Results of an enhanced convective boundary layer model produced in the environmental wind tunnel at Monash University, by the use of rod heating elements, are presented and discussed.

1. INTRODUCTION

Convective boundary layer (CBL) circulations are surface temperature-forced atmospheric circulations capped by an inversion at a finite height, z_i, of 1-2km. They are observed daily over most of the earths surface and have a marked influence on the dispersion of stack emissions with abnormally high ground-level concentrations occurring during such conditions. The importance of studying the nature of turbulence and diffusion within this layer has been recognized for many decades. However the very large temporal and spatial variations associated with plume looping complicate the measurement and prediction of dispersion within the CBL. The development of improved models of turbulent dispersion under convective conditions is essential for the production of design data.

The overall objective of this project is to provide dispersion design data in

a) complex stability, and

b) complex terrain

for varying wind speed, wind direction, stability and stack height and location using a physical model. To achieve this objective, it is first necessary to produce a satisfactory model of the atmospheric convective boundary layer. Meroney and Melbourne (1992) have set out the criteria which have to be met to achieve satisfactory models. The objective is to achieve these criteria in the new environmental wind tunnel at Monash University. One extreme condition, as far as the modelling requirements are concerned, is to achieve a Pasquill Gifford Category A down to $4ms^{-1}$ fullscale.

2. MODEL SCALING REQUIREMENTS

A sketch describing the convective boundary layer and buoyant plume parameters is given in Figure 1. In order to model a buoyant plume in unstable conditions, the following ratios must be matched correctly, Melbourne (1985).

1. $$\frac{plume\ exit\ momentum}{freestream\ momentum} = \frac{\rho_s\, w_s^2\, D_s^2}{\rho\, U^2\, z_i^2}$$

2. $$\frac{plume\ exit\ buoyancy}{freestream\ momentum} = \frac{\Delta\rho_s\, D_s\, g\, w_s}{\rho\, U^3}$$
$$= F_{r_m} \quad \text{a modified Froude number}$$

3. $$\frac{plume\ buoyancy}{freestream\ convective\ buoyancy} = F_* = \frac{(D/2)^2\, w_s\, g\, (\Delta\rho/\rho)}{z_i\, U\, w_*^2}$$

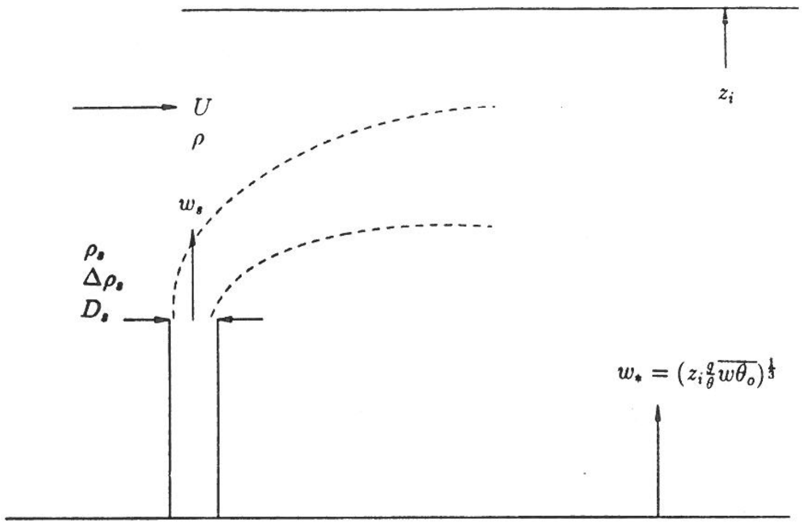

Figure 1: Parameters used in the description of a buoyant plume in a convective boundary layer

Now

$$F_* = \frac{\Delta\rho\, D_s{}^2\, g\, w_s}{4\,\rho\, z_i\, U\, w_*{}^2} = F_{r_m}\, \frac{1}{4}\left(\frac{D_s}{z_i}\right)\left(\frac{U}{w_*}\right)^2$$

So the joint stipulation that the velocity ratio w_*/U, length ratio D_s/z_i and modified Froude number F_{r_m}, are similar is equivalent to equality of the buoyancy parameter F_*, defined as the ratio of plume exit buoyancy to free stream convective buoyancy.

2.1 Strict Froude scaling

Maintenance of the same fluid densities in model and fullscale leads to strict Froude scaling and kinematic similarity, (ie : *velocity ratio* = $\sqrt{length\ ratio}$). Hence for a model scale of 1:200 and a fullscale velocity, $U_p = 4ms^{-1}$, the corresponding model velocity required is, $U_m = 0.28ms^{-1}$. Thus the consequences of strict Froude scaling is either very large geometric ratios or very low model wind speeds.

2.2 Enhanced scaling

An attractive characteristic of the buoyancy parameters F_{r_m} and F_* is that they allow the enhancement of model velocities through the distortion of plume densities. By using a low density gas, such as helium, as the model plume, typical model wind speeds can be increased 2.5 times. Model plume Reynolds number also increases by a factor of 2 which encourages the emission of a turbulent plume.

Using the example in Meroney and Melbourne (1992), a comparison of the 1:200 scale model requirements for a typical power station plume in a convective flow at $4ms^{-1}$ for the two scaling techniques is given in Table 1. It is evident that the enhanced scaling technique results in increased freestream and convective velocities as well as requiring an increase in surface heat flux to produce the stronger thermal convection.

Problems associated with enhanced scaling are:

1. Distortion of kinematic ratios at the stack exit, ie w_s/U is not constant whilst w_*/U is constant.
2. The mass ratios (plume to freestream) are not constant requiring corrections to concentration measurements.
   In terms of model to fullscale ratio in subscript r.
   $$C_{m_r} = \rho_{s_r} \frac{w_r}{U_r}$$

Table 1: Comparison of strict Froude and enhanced scaling for a typical power station

Typical Power Station	1/200 Scale Model		
	$w_*/U = 0.56$	Strict Froude	Enhanced
$h_{s_p} = 140m$	h_{s_m} (m)	0.7	0.7
$D_p = 6.0m$	D_m (m)	0.03	0.03
$\rho_{s_p} = 0.85$	ρ_{s_m}	0.85	0.17
$\Delta\rho_p = 0.349$	$\Delta\rho_m$	0.349	1.029
$w_{s_p} = 15ms^{-1}$	w_{s_m} (ms^{-1})	1.06	6.22
$U_p = 4ms^{-1}$	U_m (ms^{-1})	0.28	0.73
$z_{i_p} = 1000m$	z_{i_m} (m)	5	5
$w_{*_p} = 2.23ms^{-1}$	w_{*_m} (ms^{-1})	0.16	0.41
$F_{*_p} = 0.0193$	F_{*_m}	0.0193	0.0193
$Q_{o_p} = 400Wm^{-2}$	Q_{o_m} (Wm^{-2})	29	490
	Re_m	770	1555

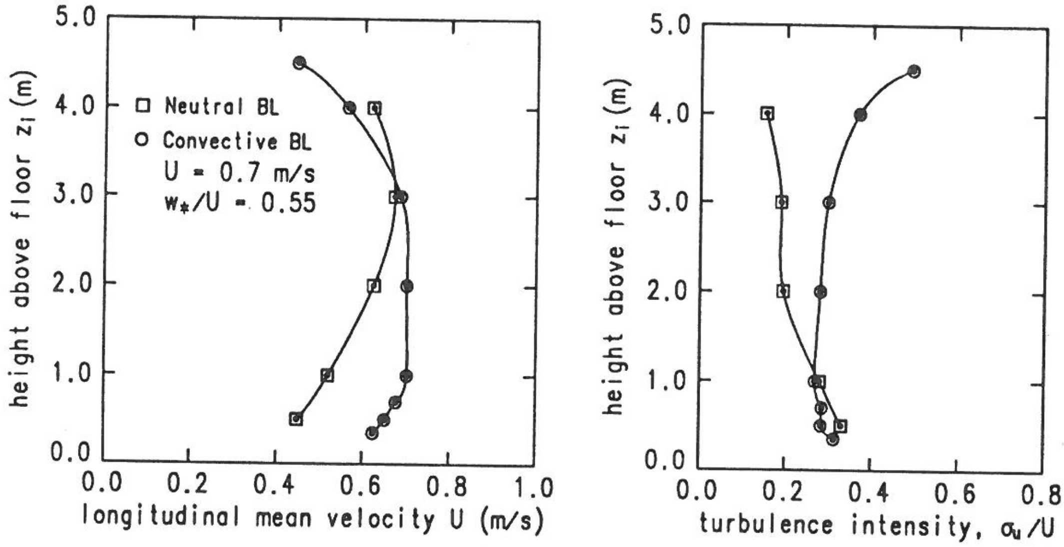

Figure 2: Longitudinal mean velocity and turbulence intensity profiles of the model neutral and convective boundary layers.

3. TEST PROCEDURE

Tests were performed in the $10 \times 5m$ working section of the new environmental wind tunnel at Monash University. The convective boundary layer was achieved by heating the floor with two rows of 4m length rod heating elements (diameter = 10.2mm) spaced 0.4m apart along the length of the tunnel. The rod heaters were 40mm above the tunnel floor and supplied $1kWm^{-2}$ of heat energy, about half of which was lost through radiation. A sonic anemometer was used to record the instantaneous velocity components and temperature. Sampling was at 20Hz for periods of 10 and 30 minutes.

4. RESULTS

The longitudinal mean velocity and turbulence intensity profiles of both the neutral (without heat) and convective (with heat) boundary layers developed in the tunnel are given in Figure 2. It is evident that the convective boundary layer mean velocity profile is constant from a height of 1 to 3m, but above 3m the mean velocity begins to decrease, as does the neutral boundary layer mean velocity. This was due to the formation of a thick boundary layer on the roof of the tunnel over the 20m fetch. The decrease in the mean velocity leads to the marked increase in turbulence intensity of the convective boundary layer as the standard deviation stays constant. The mean temperature and normalised heat

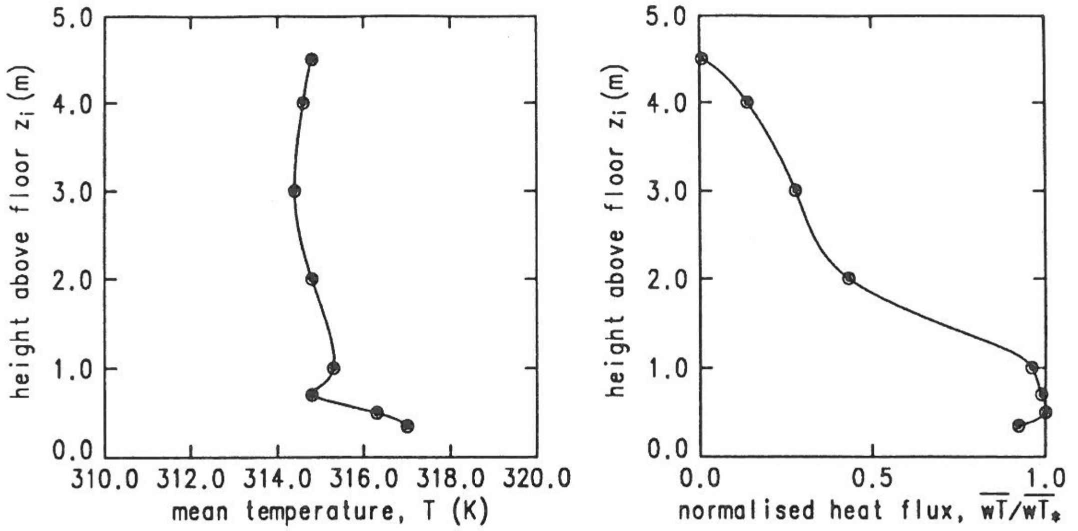

Figure 3: Mean temperature and normalised heat flux profiles of the convective boundary layer.

flux profiles of the convective boundary layer are given in Figure 3. The mean temperature profile is constant except for the bottom 10% of the profile were the temperature increases as expected. This is consistent with the fullscale atmospheric convective boundary layer. The heat flux was normalised with the largest heat flux recorded close to the floor of the tunnel. This was at a height of 0.5m above the floor as measurements below this height were dependent on position between the heating rods. The normalised heat flux results obtained were consistent with fullscale measurements, decreasing from 1 at the ground to 0 at the top of the convective boundary layer (see ref Caughey, S.J.)

5. CONCLUSION

In order to successfully produce a model convective boundary layer suitable for plume dispersion modelling in a wind tunnel it is advantageous to use the enhanced scaling technique, as opposed to strict Froude scaling, due to the very low wind tunnel speeds required for strict Froude scaling. An enhanced convective boundary layer model of between Pasquill Gifford Category A and B has been produced in the environmental wind tunnel at Monash University using rod heating elements. The characteristics of the model boundary layer agree well with those of measurements of fullscale convective boundary layers except in two small regions. One, close to the floor where the separation of the heating rods, as opposed to the constant heating of a flat surface, produces horizontal inconsistencies in measurements. The other at the top of the convective boundary layer where a decrease in the mean longitudinal velocity was due to the formation of a turbulent boundary layer along the roof of the tunnel.

6. REFERENCES

Meroney, R.N. and Melbourne, W.H. (1992), Operating ranges of meteorological wind tunnels for the simulation of convective boundary layer phenomena, submitted to Boundary-Layer Meteorol.

Melbourne, W.H. (1985), unpublished communications.

Caughey, S.J. (1984), Observed characteristics of the atmospheric boundary layer, Atmospheric Turbulence and Pollution Modelling, (ed. F.T.M. Nieuwstadt and H. van Dop), D. Reidel Pub. Co., Boston, pp.107-158.