11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

A WIND TUNNEL MODEL OF AN INVERSION-CAPPED CONVECTIVE BOUNDARY LAYER

T.J. TAYLOR and W.H. MELBOURNE

Department of Mechanical Engineering
Monash University
Clayton, VIC 3168, AUSTRALIA

ABSTRACT

An experiment has been undertaken in the Monash Environmental Wind Tunnel with the aim of developing a model inversion capped convective boundary layer suitable for the modelling of plume dispersion. Heating near the ceiling at the begining of the working section was used to produce a stably stratified capping inversion layer above a convective region developed below by the use of further heating on the floor. Velocity and temperature profiles of the resulting flow are presented showing two distinct regions of flow were established, an upper stably stratified region with a more turbulent, convective region below. Although the turbulence level in the convective region increased with increasing energy supply to its base, the depth of this region was not found to increase, but rather a general temperature rise across the whole working section resulted. Some of the difficulties that arose with velocity and temperature measurements in the non-uniform temperature environment are also discussed.

INTRODUCTION

Convective boundary layer (C.B.L) flows are surface temperature forced atmospheric circulations that can have a marked influence on the dispersion of stack emissions. Maximum ground level concentrations often occur under such conditions which in some operations result in shutdown when the atmospheric conditions become highly convective. With many of the major emissions in Australia, from mining operations and power stations, occurring in regions where high solar insolation results in high ground surface temperatures producing highly convective wind flow conditions, the development of improved modelling techniques for such conditions is essential for the optimization of design. A large wind tunnel with working sections of up to $5m$ high by $12m$ wide and $40m$ long is being built at Monash University for the modelling of dispersion within atmospheric flows of varying stability, to assist in the design and location of emission sources. The capabilities of such facilities to model C.B.L phenomena have been discussed by Meroney and Melbourne (1992) with the conclusion that the use of sufficiently large wind tunnel facilities will provide a means to study the atmospheric sublayers associated with the C.B.L.

With convective conditions and the effect of complex terrain being of primary concern the ability to accurately physically model individual situations and obtain dispersion measurements relatively quickly for many different conditions would greatly assist the design process. Preliminary physical modelling of the unstable C.B.L has been undertaken in the Monash Environmental Wind Tunnel using rod heating elements on the floor to simulate the heated ground surface. For the results published to date (Melbourne et.al, 1992), the ceiling of a $5m$ high, $10m$ wide and $25m$ long working section was used to simulate the height of the capping inversion. This produced promising results in the bulk of the mixed layer, but the flow characteristics closer to the inversion height were not as encouraging in the absence of entrainment from a stably stratified layer above.

With the imminent completion of the upstairs return section of the tunnel, with its $4m$ high, $12m$ wide and $40m$ long working section specifically for the modelling of low windspeed atmospheric flows and dispersion of plumes within them, improvements in the C.B.L modelling technique to produce more characteristic flows were sort. As a preliminary investigation, experiments were undertaken in a $2.7m$ high, $6m$ wide and $18m$ long working section of the tunnel using heating near the ceiling to produce a model stably stratified inversion layer along the ceiling to act as the capping inversion for the C.B.L developed beneath. This technique of developing a capping inversion above the C.B.L in the wind tunnel will allow control of the height of the developed C.B.L and thus give the ability to vary the aspect ratio of the width to the inversion height. With an aspect ratio greater than 4 required to avoid secondary circulations and obtain flow characteristics consistent with an infinitely large homogeneous layer (Willis and Deardorff 1974), a capping inversion of at least $1m$ deep will be required in the $4m$ high by $12m$ wide section.

EXPERIMENTAL ARRANGEMENT

An $18m$ long false ceiling was inserted into a $5m$ high by $6m$ wide section of the Monash Environmental Wind Tunnel producing a $2.7m$ high working section. The ceiling was constructed modularly from five $3.6m$ by $6m$ panels, the lower surfaces of which were coated with insulation and covered with aluminium to reduce heat losses and thermal inertia. The joints between the panels were taped to smooth intersections and remove leaks.

A stably stratified layer was developed beneath the false ceiling by heating the air with three vertical arrays of 10 heating elements each, suspended from the first panel at the entrance to the working section as shown in Figure 1.

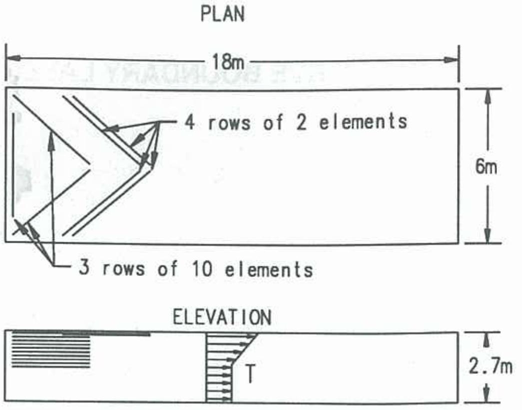

Figure 1: Arrangement of the ceiling heating elements producing the stably stratified capping inversion layer in the 2.7*m* high by 6*m* wide and 18*m* long working section of the Monash Environmental Wind Tunnel.

Eight more elements were distributed downwind in four arrays of two elements each to act as booster elements. Each element was 4*m* in length and individually rated at 1.8*kW* for a 240 volt potential.

To simulate the heating effect of the high ground surface temperature, more heating elements were supported 40*mm* above the floor as shown in Figure 2. These elements were also rated at 1.8*kW* for a 240 volt potential, but were adjustable so the amount of heat supplied could be controlled. Although each element was rated at 1.8*kW*, a substantial, unknown amount of energy was lost through radiation to the surroundings preventing an accurate estimate of the convective heat flux from the known amount of electrical energy supplied. After the tunnel and elements were switched on the flow was allowed to stablize for a period of at least one hour before any measurements were taken.

TSI hot wire anemometers were used with a cross film to resolve the longitudinal and vertical velocity components of the flow. The cross film was calibrated for velocity and temperature in a temperature controlled low windspeed calibrator. Another TSI film mounted in close proximity was used as a resistance wire temperature sensor. The outputs from the cross film and temperature sensors were low pass filtered at a frequency of 100*Hz* and recorded digitally on a computer at a sampling rate of 200*Hz* using software developed at Monash University. Data was collected for a period of 5 minutes at each sampling location. After collection the voltage outputs from the cross film and temperature sensor were processed to give the longitudinal and vertical velocity components and temperature at an equivalent sampling frequency of 40*Hz* by taking every fifth sample point from the raw data collected. This was a simple way of minimising the phase lag in the collection of the three outputs.

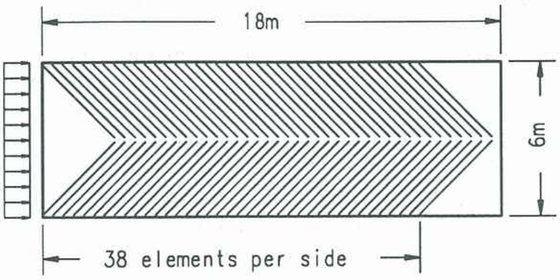

Figure 2: Arrangement of the floor heating elements used to simulate the high ground surface temperatures and develop a C.B.L below the stably stratified inversion layer.

An array of 10 shielded thermocouple probes was also used to obtain vertical profiles of the mean temperature over the upper metre of the working section. The position of this array was kept constant and measurements were taken between hot film measurements. Thus any ambient temperature fluctuations throughout the day could be monitored and corrected for in later analysis.

Initially it was planned to use a Dobbie Instruments sonic anemometer to record all three velocity components as well as the temperature. This would have given a more comprehensive set of measurements, enabling the recognition of secondary cross flows within the tunnel and the calculation of correlations between all the velocity components as well as the temperature. Unfortunately the electronics within the sonic anemometer were severely effected by the temperatures within the tunnel resulting in the corruption of data for all but a few sampling periods. As well as the problems with the electronics, the distances between the transducers on the instrument were found to be too large to resolve the the higher frequency components of the flow for this smaller scale experiment in the 2.7*m* by 6*m* section. In the 4*m* by 12*m* working section it is believed that the doubling of the scale of the boundary layer will enable the sonic anemometer to resolve well into the dissipation range of the spectrum if the electronics overheating problem can be solved by cooling with external air.

RESULTS AND OBSERVATIONS

Measurements of velocity and temperature were taken for three differing amounts of energy supplied to the heating elements laid out on the floor of the tunnel. Initially the elements on the floor were left switched off. This did not mean there was zero or negative heat flux from the floor surface to the air flow, as radiation from the ceiling elements caused the floor to warm slightly. Following this, measurements were taken with the floor elements switched on to $\frac{1}{6}$ and $\frac{1}{2}$ of full power, supplying what was estimated to be approximately $200Wm^{-2}$ and $500Wm^{-2}$ of heat flux to the air flow respectively. The elements suspended from the roof were supplied with a constant amount of energy for all three cases.

The mean temperature profiles for the three situations, shown in Figure 3, are relatively similar with a positive temperature gradient producing a stably stratified capping inversion over the upper metre of the working section. For the lower, or convective, 1.5*m* of the working section a reasonably constant temperature exists, although with the addition of heat this increased slightly towards the floor. When the floor heating elements were on, the temperature gradient of the upper section appeared less steep than that occurring without floor heating, while the depth of the inversion remained virtually constant with the addition of floor heating.

The variation of the standard deviation of temperature with height is presented in Figure 4. With no floor heating the standard deviation remained reasonably constant throughout the depth of the working section. With

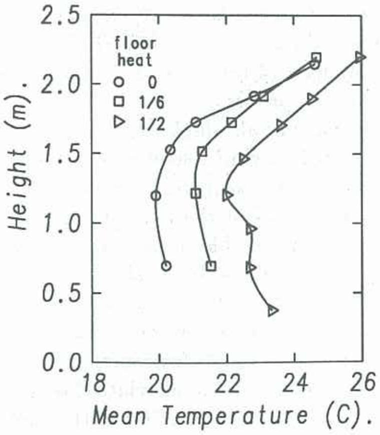

Figure 3: Variation of the mean tunnel temperature with height above the tunnel floor for the three different conditions of floor heating.

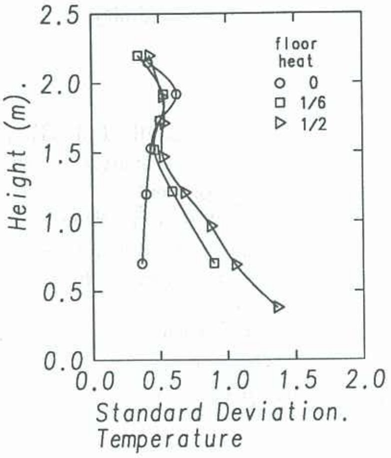

Figure 4: Variation of the standard deviation of the temperature with height above the tunnel floor for the three different conditions of floor heating.

the addition of floor heating there was an increase in the temperature fluctuations up to the height of the stable layer, with the magnitude of the increase being greater with the supply of more heat from the floor. Within the stable capping inversion the magnitude of the temperature fluctuations remained similar for all three tests.

The mean longitudinal velocity profiles for the three test conditions are shown in Figure 5. With no floor heating, the mean longitudinal velocities remained virtually constant within the stable layer. A sharp velocity gradient existed below this level with a significant increase in the mean velocity. Applying heating from the floor reduced the sharp velocity gradient, although there was still an increase in the mean velocity below the height of the temperature gradient. In both cases with floor heating, the velocity gradient was steepest at the interface between the stable layer, above, and convective layer, below, with the velocity profiles both above and below this interface being found to be reasonably constant.

In Figure 6 the longitudinal turbulence intensity profiles for the three test situations are presented. In both the convective and stable layers the longitudinal turbulence intensity increased with the addition of heat at the floor. Whereas in the interface region between these two

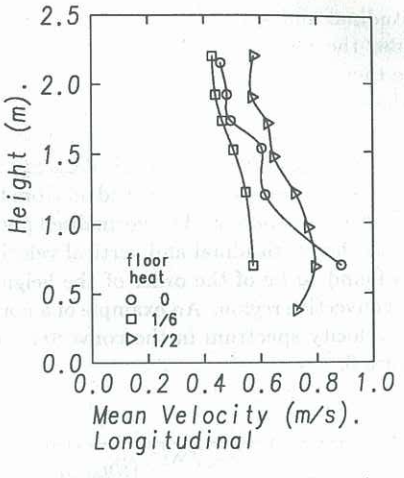

Figure 5: Vertical profiles of the longitudinal mean velocity for the three different conditions of floor heating.

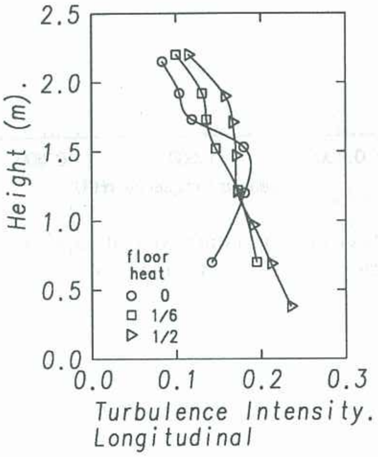

Figure 6: Longitudinal turbulence intensity profiles for the three different conditions of floor heating.

layers the turbulence was found to be greatest when no floor heating was applied. This may have resulted from the large shear evident between the two layers when floor heating was not applied. A similar result was found with the vertical turbulence intensity which is presented in Figure 7.

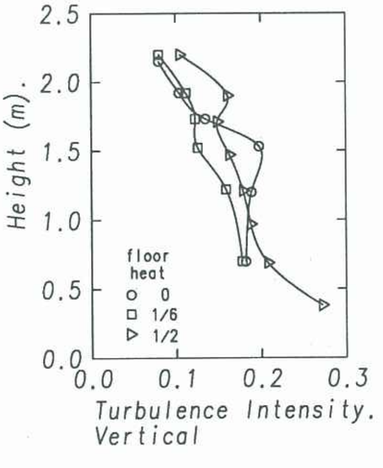

Figure 7: Vertical turbulence intensity profiles for the three different conditions of floor heating.

Longitudinal and vertical velocity spectra were also obtained from the measurements. When normalised by the variance there was no appreciable variation found between the shape of the various spectra over the depth of the working section as well as between the various heating conditions. A marked decrease in turbulent energy between the convective and stable regions was evident from the non-normalised form of the spectra. The normalised peak wavelength for both the longitudinal and vertical velocity components was found to be of the order of the height of the depth of the convective region. An example of a normalised longitudinal velocity spectrum in the convective region is given in Figure 8.

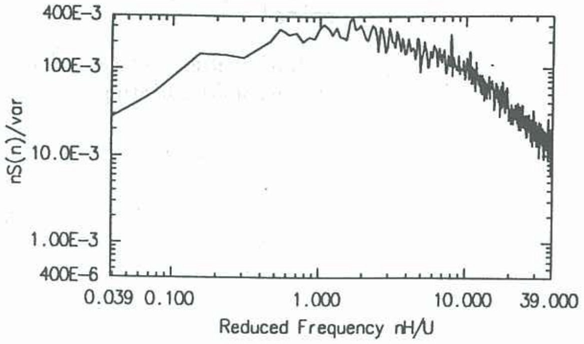

Figure 8: A typical longitudinal velocity spectrum in the convective region of the wind tunnel flow.

DISCUSSION

An experiment as been performed in a 2.7m high, 6m wide and 18m long working section of the Monash Environmental Wind Tunnel to produce a model of an inversion capped convective boundary layer suitable for the modelling of plume dispersion within the C.B.L. The results presented show two distinct regions of flow were able to be established. The upper region had a stable temperature gradient resulting in a reduction in the turbulent energy and temperature fluctuations. Below this was a region where an unstable temperature gradient resulted in an increase in both temperature fluctuations and turbulent energy.

With an increase in energy supplied to the base of the unstable layer, the turbulence level and temperature fluctuations within the unstable region were found to increase, but there was no evidence of an increase in the depth of this region. There was also an increase in the turbulent fluctuations of the velocity components within the stable region when the heat input to the base of the convective region was increased, as well as a general temperature rise across the whole working section. Thus it appears that although two regions of flow were established, the very hot parcels of air coming off the hot line heat sources of the convective region could be penetrating well into the stable layer above, and remaining there, increasing the temperature of this region. In this way the depth of the stable layer was maintained, while its overall mean temperature increased by a similar amount as that of the convective region below. Therefore it appears that the typical situation of a developing C.B.L, with the warming air of the convective region eroding into the capping inversion, and thus increasing the depth of the convective region, is not being portrayed in the model situation. If this is the case, then the development of a more even method of supplying the heat input to the base of the convective region could be a means of solving this problem.

The experiment has also highlighted some of the difficulties of measuring low wind velocities, especially in a non uniform temperature environment. Although, with the use of a cross film, estimates of the longitudinal and vertical velocity components were able to be made, the actual velocity vector was not able to be established nor were the effects of cross velocities on the estimates of the other velocity components. Although it is believed that the use of a sonic anemometer, with cooled electronics, in the larger 4m by 12m section of the tunnel will alleviate this problem, it's sampling frequency is limited to 20Hz with a path length between transducers of 100mm. Thus the development of a smaller, accurate, higher frequency three component velocity and temperature measurement method would also be advantageous. It is hoped that this can be achieved by the use of two split films with a resistance wire temperature measurement probe all in close proximity.

REFERENCES

MELBOURNE, W H, TAYLOR, T J, GRAINGER, C F (1992) Dispersion modelling in convective wind flows. submitted Atmospheric Environment.

MERONEY, R N, MELBOURNE, W H (1992) Operating Ranges of Meteorological Wind Tunnels for the Simulation of Convective Boundary Layer Phenomena. submitted Bound. Layer Meteor..

WILLIS, G E, DEARDORFF, J W, (1974) A Laboratory Model of the Unstable Planetary Boundary Layer. J. Atmos. Sci., Vol. 31, pp 1297-1307.