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MODELLING OF PLUME DISPERSION IN AN URBAN ENVIRONMENT UNDER NEUTRAL AND STABLY STRATIFIED CONDITIONS

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ABSTRACT

The dispersion of a plume emitted from a stack into an urban environment has been physically modelled in the Monash Environmental Wind Tunnel under neutral and stably stratified flow conditions. An inverted model technique is employed with density stratification being obtained by heating the air flow under a false ceiling inserted in the tunnel working section and attaching an inverted model to the ceiling. The dispersion with and without the effects of major downwind highrise structures is considered in a variety of stratification conditions. It is found that while the strength of the stable stratification is the important parameter for the dispersion prior to impingement on the urban area, further downwind the scale of the turbulence developed from the local surface roughness appears to be the important parameter.

INTRODUCTION

The physical modelling of atmospheric dispersion in isothermal wind tunnels has limited studies to consider only wake interaction and near field dispersion in a neutrally stable atmosphere. It was not possible to take into account the effect of buoyancy forces within the atmospheric boundary layer that can either enhance or suppress the turbulent mixing and thus plume dispersion. With the development of the new Environmental Wind Tunnel at Monash University the facility now exists to physically model flows of varying stability, from the highly stable Pasquill Classes G and F to the highly unstable convective situation of Class A, and the dispersion of plumes within these flows.

The dispersion of a plume emitted from a stack into the atmospheric boundary layer is dependent upon turbulent mixing resulting from the turbulence within that boundary layer. The turbulence within the atmospheric boundary layer is in turn dependent upon both the surface roughness, and the buoyancy forces within the boundary layer either enhancing or suppressing the roughness induced turbulence. Under relatively calm conditions, overnight cooling of the earth's surface can lead to the creation of a stable ground based inversion (GBI). With such conditions suppressing the surface roughness induced turbulence, and thus plume dispersion, the prediction of plume concentrations for design purposes becomes more complicated. This is especially so in the urban environment where the plume can impinge directly upon nearby tall buildings, which can act to block the flow and create wakes which complicate the dispersion process.

Wind tunnel tests have been conducted on a 1/200 scale model, under neutral and stable stratified natural wind boundary layer models that simulate an Australian urban area, to determine the dispersion of exhaust gases discharged from a stack in the urban environment. Due to the close proximity of high rise buildings, up to twice as high as the stack, investigations were made into the concentrations of discharge that may impinge directly upon such buildings under both neutral and stably stratified flow conditions. The effect such buildings may have on the plume dispersion under the various stability conditions was investigated by obtaining plume concentration profiles with and without interference from major downstream buildings in flows of increasing stability.

MODEL SCALING REQUIREMENTS

A sketch showing the notation used in describing the exhaust and dispersion of a buoyant plume into a stably stratified flow is given in Figure 1. In order to correctly physically model a buoyant plume exhausted from a stack, various dimensionless parameters must be matched to ensure similarity between model and prototype plume behaviour. The similarity criteria and scaling parameters for fluid modelling are discussed in Snyder (1981).

To achieve geometric similarity of the initial plume path, similarity of the ratios of the initial plume momentum and buoyancy relative to the freestream momentum are required, (Melbourne et al. 1992). This gives rise to firstly

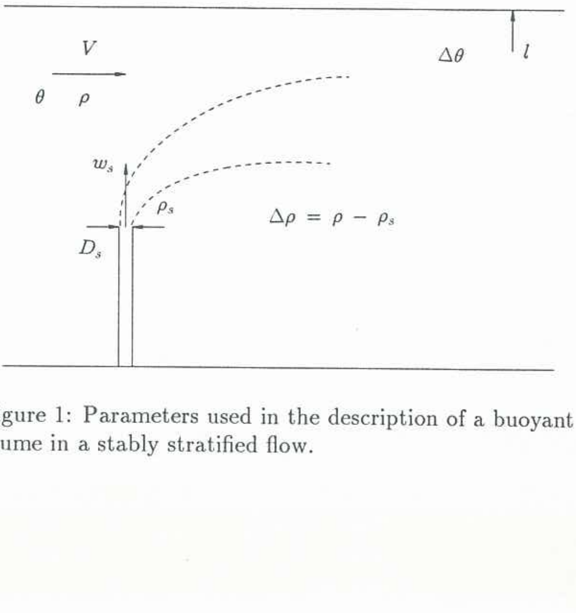

Figure 1: Parameters used in the description of a buoyant plume in a stably stratified flow.

the momentum parameter, which is the ratio of the stack gas exit momentum to the momentum of the freestream air flow,

$$M_p = \frac{\rho_s\, w_s^2\, D_s^2}{\rho\, V^2\, l^2}, \tag{1}$$

and secondly, the buoyancy parameter, which is the ratio of the stack gas exit buoyancy to the freestream momentum,

$$B_p = \frac{\Delta\rho\, D_s^2\, g\, w_s}{\rho\, V^3\, l}, \tag{2}$$

where ρ_s and w_s are the stack gas density and exit velocity respectively, D_s is the stack diameter, ρ and V are the freestream density and mean velocity respectively and l is a freestream characteristic length.

As well as producing a model boundary layer of correctly scaled velocity and turbulence characteristics, correct scaling of the strength of the stable stratification also has to be achieved. By maintaining the Bulk Richardson number of the freestream stable layer,

$$R_b = \frac{g\, \Delta\theta\, l}{\theta\, V^2}, \tag{3}$$

constant between model and full scale, similarity of the flow can be obtained. θ is the mean potential temperature of the freestream.

By maintaining geometric similarity between the model and full scale (ie. $D_r = l_r$, where subscript 'r' refers to the ratio between model and full scale) and assuming that $\rho_r = 1$ (ie. the test fluid is air), expressions for the velocity ratios, between model and full scale, are obtained for the freestream air,

$$V_r = \sqrt{\frac{\Delta\rho_r\, D_r}{\sqrt{\rho_{sr}}}}, \tag{4}$$

and the stack gas exit velocity,

$$w_{sr} = \frac{V_r}{\sqrt{\rho_{sr}}}. \tag{5}$$

An expression for the ratio of the temperature difference across the stable layer,

$$\Delta\theta_r = \frac{V_r^2\, \theta_r}{l_r} \tag{6}$$

is also obtained.

STABLE MODELLING TECHNIQUE

Conventionally, stable stratification in wind tunnels has been simulated using cold tunnel floors and heated air. Such a configuration requires either floor refrigeration or the use of cryogenic temperature gases such as liquefied air or sublimated CO_2 from dry ice. Due to the size of the Monash Environmental Wind Tunnel, up to 12m wide, 5m high and 40m long, refrigeration of the floor would be prohibitively expensive. Thus an inverted model arrangement, similar to that of Britter (1974) is used, where a heated stable layer is developed along a false roof inserted in the tunnel. Electrical heating elements are used to heat the air flowing along the roof as it comes into the working section.

In using the inverted model technique scaling for the buoyancy of a hot plume, which is less dense than the ambient air, has to be achieved by the use of a model plume with greater density than the ambient air. (ie. as the model is upside down, the model plume needs to be denser than the ambient air, thus the buoyancy forces cause it to fall away from the model ground level along the false roof.)

By taking the characteristics of the power station plume to be modelled, as follows:

$$\rho_{s_p} = 0.87\ kg\, m^{-3}$$
$$\rho_p = \rho_m = 1.2\ kg\, m^{-3}$$
$$\Delta\rho_p = 0.33\ kg\, m^{-3}$$

where subscript 'p' refers to the full scale prototype and subscript 'm' the model. And if the density decrement is kept constant (ie. $\Delta\rho_m = \Delta\rho_p$) we get

$$\rho_{sm} = \rho_m + \Delta\rho_m = 1.53\ kg\, m^{-3}. \tag{7}$$

as an inverted model is being used. For a model to full scale length ratio of $D_r = 1/200$, values can be calculated for the ratios mentioned above, as given below:

Velocity ratio,	$V_r = 0.061$
Stack velocity ratio,	$w_{sr} = 0.046$
Potential temperature ratio,	$\Delta\theta_r = 0.75$.

Thus, for a typical GBI with windspeeds of the order of $5ms^{-1}$, the model tunnel windspeeds will be of the order of $0.5ms^{-1}$, while the the temperature difference across the model inversion will be of the order of the potential temperature difference across the full scale GBI. Smaller model scales result in even lower velocity ratios, thus the need for the large wind tunnel to accommodate larger scale models, and avoid the Reynolds number problems associated with low windspeed flows, is evident.

PROFILE DEVELOPMENT

An 18m long by 6m wide false ceiling was constructed modularly from five 3.6m by 6m panels and inserted in a 6m wide working section of the Monash Environmental Wind Tunnel, 2.7m above the tunnel floor. The lower surface of the false roof was coated with insulation and covered with aluminum to reduce heat losses and thermal inertia. The joints between the panels were taped to smooth intersections and remove leaks.

A 1/200 scale model of the neutral natural boundary layer, equivalent to flow over suburban terrain (Category 3), was developed along the false ceiling of the wind tunnel working section by the use of vorticity generators, trips and various roughness elements. The heating elements used to generate the stably stratified profiles were in place for the development of the neutral profile, but turned off. The vertical profile of the mean velocity followed a power law with an exponent of 0.23, with an Integral Length Scale, based on fitting a Von-Karman spectrum, of $Lu_x = 0.5m$. Velocities were measureed with a temperature corrected hot film calibrated for low velocities against a sonic anemometer.

Heating to produce the stably stratified boundary layers was produced by 3 vertical arrays of 30 heating elements in total, suspended from the first panel of the false ceiling. Eight more elements were distributed downwind in four rows next to the roof to act as booster heaters. Each element was individually rated at 1.8kW for a 240 volt potential, but the on/off times were adjustable so the amount

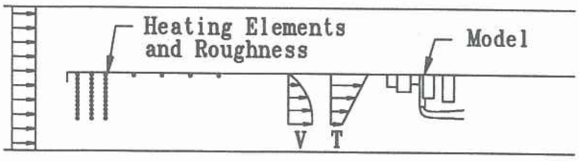

Figure 2: Tunnel and heating element configuration for the inverted model technique used for modelling stably stratified flows in the Monash Environmental Wind Tunnel.

of heat supplied could be controlled. The tunnel and heating element configuration is shown in Figure 2.

Stable natural wind boundary layer models were generated by using the heating elements to heat the neutral boundary layer model and develop a vertical temperature gradient across the profile to a model depth of at least $1m$, simulating a full scale GBI depth of $200m$. Temperature measurements were obtained by using an array of ten shielded thermocouple probes, 0.1m apart on a mobile traverse stand. By adjusting the amount of heat supplied, various temperature gradients were produced to simulate differing degrees of stability to an extreme, equivalent to $0.032\ Km^{-1}$ in full scale. The velocity and turbulence intensity characteristics of the three profiles of varying stability are shown in Figure 3.

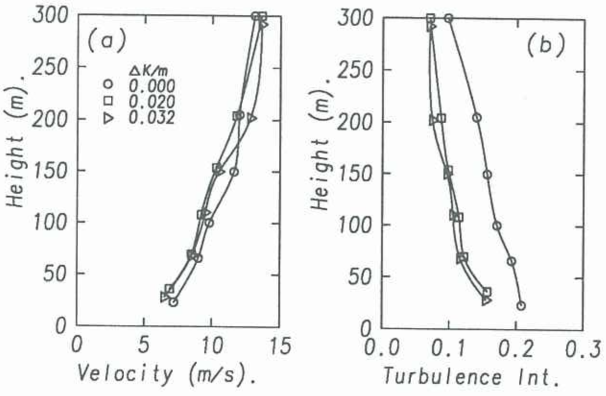

Figure 3: Velocity, (a), and turbulence intensity, (b), profiles developed along the false ceiling for the three boundary layer models of varying stability.

CONCENTRATION MEASUREMENTS

To model a buoyant plume with an inverted model a negatively buoyant (plume density greater than air density) model plume is required. This resulted in a mixture of helium and argon being used as the discharge gas in the model studies. The helium and argon flow rates were measured with flow meters to a mixing plenum, then discharged through the model stack. The helium was used as a tracer with concentrations being measured by a mass spectrometer tuned to helium. Estimates of the concentration of the exhaust plume were obtained by dividing the measured concentrations of helium by the helium concentration at the model stack discharge.

Mean ($C_{\overline{M}}$) and standard deviation (σ_{C_M}) concentration measurements were obtained, and used to calculate the peak (3 minute mean maximum concentration) per hour from the following equation:

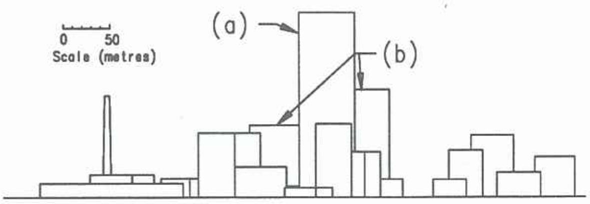

Figure 4: Elevation of the model showing the stack and major large building (a) and group of buildings (b), that were removed for measurements without building interference.

$$C_{\hat{M}} = C_{M_{3min.max}} = C_{\overline{M}} + 3.5\sigma_{C_M}. \qquad (8)$$

Measurements were taken at a full scale distance of 200m and 400m downwind of the stack with and without major interference from some downstream buildings (a) and (b) up to twice as high as the stack as shown in Figure 4. Vertical concentration profiles were obtained, followed by a horizontal traverse at the height of the maximum concentration, for the three separate wind profiles of increasing stability. The results of the concentration measurements, in parts per thousand by mass, are shown plotted for the case without building interference in Figure 5 and with building interference in Figure 6.

It is evident from the plots without major building interference that increasing the stability of the flow resulted in an increase in the maximum mean and peak concentrations measured and a decrease in the plume width. This was more evident closer to the stack, with the max-

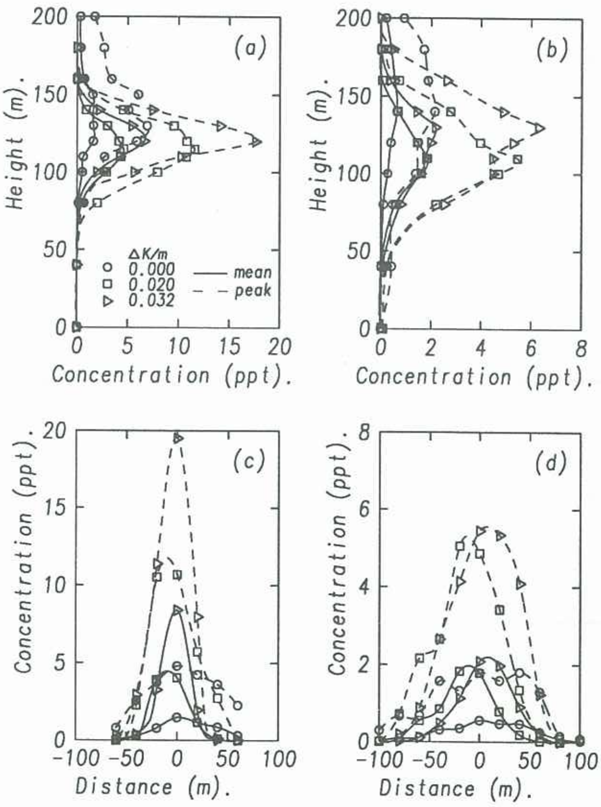

Figure 5: Mean and peak vertical concentration profiles at (a) 200m and (b) 400m downwind of the stack, and the corresponding horizontal profiles (c) 200m and (d) 400m, without interference from major buildings in the three profiles of increasing stability.

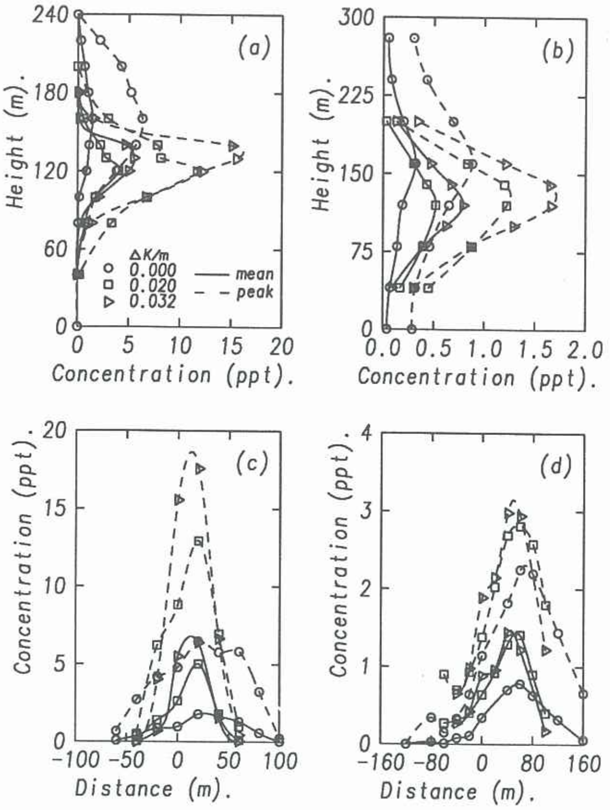

Figure 6: Mean and peak vertical concentration profiles at (a) 200m and (b) 400m downwind of the stack, and the corresponding horizontal profiles (c) 200m and (d) 400m, with interference from major buildings in the three profiles of increasing stability.

imum concentrations almost doubling with each increase in stability for measurements taken 200m downwind of the stack. 400m downwind from the stack, the increase in maximum concentrations was not as pronounced when the stability was increased from $0.020Km^{-1}$ to $0.032Km^{-1}$ as that found 200m downwind of the stack. This may have been due to the effect of surface roughness increasing the turbulent mixing downwind of the model. The minor buildings of about half stack height or less were left on the model when the major interference buildings were removed.

With the major interference buildings in place, the maximum mean and peak plume concentrations 200m downwind of the stack were of a similar magnitude to those obtained without the buildings in place. This was the expected result as the plume had not yet passed through the region effected by the building wakes, and thus the buildings had no influence on the plume dispersion upwind of them. With the addition of the major buildings, and the resulting increase in turbulence in their wakes, the maximum mean and peak plume concentrations measured 400m downwind of the stack significantly decreased, and the effect of the stable stratification became less pronounced. This was a result of the introduction of the large buildings causing the freestream stably stratified flow to be replaced by turbulent freestream flow. Thus the mixing downwind of the buildings increased.

It is also of interest to note that although the turbulence intensities of both stably stratified profiles were similar, the maximum mean and peak plume concentrations measured 200m downwind of the stack increased significantly with stability. It was not until further downstream, when the local surface roughness had taken effect, that similar plume concentrations were measured in the two stably stratified profiles. Thus it appears that it is the scale of the turbulence, not the intensity, that is the important parameter in the mixing of plumes. The high roughness of the urban area could give a turbulent structure virtually independent of the intensity of the stable stratification but more dependent on the dimensions of the sharp edged bluff bodies in the flow. The addition of the thermal stability to the neutral flow could result in the suppression of the larger scale eddies from the flow, giving similar flow structures, for both stably stratified flows, downwind of the local surface roughness, with the neutral profile still containing eddies of a larger scale. This may result in greater mixing giving more dilution, and thus the lower maximum mean and peak concentrations observed in the neutral profile than in the stably stratified profiles. The greater similarity in the observed maximum mean and peak concentrations downwind of the added larger major buildings may have resulted from eddies of a similar scale being developed in all three profiles.

CONCLUSIONS

Wind tunnel model measurements of the concentration of a plume emitted from a stack into an urban environment have been made under neutral and stably stratified flow conditions with the effect of downwind building interference on the plume dispersion being investigated. It was found that the plume dispersion decreased with the increase in stability when the local added surface roughness effects were not present, although turbulence intensities were similar for the two stably stratified flows. When the extra mixing resulting from the added roughness of the local urban environment took effect, the strength of the stable stratification in the approach flow was found to be less significant on the dispersion of the plume. In the extreme case of the plume impinging directly onto a highrise structure, the effect of the incident stability on the plume dispersion downwind of the structure was found to be minimal, while the effect of the building on the upwind dispersion was found to be negligible. This led to the conclusion that the scale of the turbulence could be the important factor in the dispersion of plumes and not the intensity.

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