BUILDING DOWNWASH OF PLUMES AND PLUME INTERACTIONS

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1. SUMMARY

This paper presents a number of wind tunnel measurements of building induced downwash effects on the plume in a neutrally stable boundary layer. Vertical and horizontal profiles of mass concentrations of the exhausts from stacks on a rectangular model building were measured downwind of the buoyant source in the near wake. These experiments were conducted in a simulated natural wind over open country terrain for various freestream wind speeds with different stack and building configurations. Significant downwash effects from the building below the stack were observed in all tested configurations. In this preliminary study, only mean concentrations were evaluated and are presented in non-dimensional form.

2. INTRODUCTION

Wind tunnel modelling of buoyant plumes has been undertaken in Monash University in both neutrally stable [1] and convective [2] wind flows. Although thermal stratification may significantly alter the flow around the building, dispersion studies in neutrally stable conditions are still essential to provide a database for further investigations into this already complicated problem dominated by the complex, unsteady flow in the building wake.

When the momentum and buoyancy of the exhausts discharged from the stacks are insufficient to overcome the low pressure suction in the wake, the plume is entrained rapidly downward into the low pressure wake region. This aerodynamic downwash of plume in the immediate lee of the stack has been studied for neutrally buoyant plumes [3]. This stack-tip downwash generally does not occur if the stack exit velocity is more than 1.5 times the wind speed at stack height. The downwash due to the building wake has been shown not to occur if the stack height is more than 2 to $2\frac{1}{2}$ times the building height. Detailed measurements of the building downwash were made [4], but with the effluent source mainly at ground level. The intent of this paper is to present an initial measurement of the building downwash of plumes from stacks on the roof of the building. Also, the interaction effects of one plume on another nearby plume were investigated. The results can then be used for mathematical model development and guidance in similar situations.

3. EXPERIMENTAL DESIGN

The experiments were carried out in the 4x3m working section of the 450 kW close-return type Boundary Layer Wind Tunnel at Monash University. The basic model of a rectangular building, 240mm by 80mm by 62mm high, was tested in a 1/200 scale model of the natural wind flow over open country terrain. The natural wind boundary layer model was generated using roughness elements and vorticity generators upstream of the model, which accurately simulated the turbulent wind characteristics of neutral conditions with a freestream vertical profile of mean velocity followed a power law with an exponent of 0.15 and a longitudinal turbulence intensity of 0.18 at building height.

The short stream-wise length of the building was oriented parallel to the freestream flow so that no re-attachment occurred. Four stacks were located at the centre of the building roof, with the stack separation width 5m side by side and 6m in tandem full scale. The stack height above the roof tested ranges from $\frac{1}{2}$ to 2 times building height, such that building downwash always occurs. The full scale stack exit temperature is 90°C, the exit diameter is 1.3m, the exit velocity is 8.7 m/s and thus the stack-tip downwash would be less than one stack diameter below the top of the stack.

A helium and air mixture was used to model the buoyancy and momentum of the discharge gas in the measurements.

Density of discharge gas at full scale temperature

= a x Density of helium at model temperature
+ $(1 - a)$ Density of air at model temperature

where a is the percentage of helium in the mixture.

For undistorted geometric, kinematic and dynamic similarity, i.e. strict Froude scaling, it follows that the velocity scaling, model to full scale ratio

$$V_r = \sqrt{L_r}$$

$\frac{V_m}{V_p} = \sqrt{\frac{L_m}{L_p}} = \sqrt{\frac{1}{200}}$ $V_m = \sqrt{\frac{1}{200}}\, V_p$ (V_p = 10.7 m/s)

where L_r = model length scale = 1/200

∴ the discharge flow rate ratio

$V_m \approx \frac{10.7}{14.14} \approx 0.7$ m/s

$$Q_r = V_r L_r^2 = L_r^{2.5}$$

The helium and air flow rates were metered to a plenum from where the gas mixture was discharged through the stacks. Helium in this type of experiment is used as a tracer and for scaling of the buoyant discharge. The concentration of helium, and hence discharge gas, in a downstream air sample was measured by a mass spectrometer tuned to helium.

$$\text{Mass concentration} = \frac{\text{Density of discharge at full scale temperature}}{\text{Density of air at model temperature}} \times \text{Volume concentration measured}$$

$$= \frac{1}{a} \times \frac{\text{Density of discharge at full scale temperature}}{\text{Density of air at model temperature}} \times \text{Volume concentration of helium measured}$$

The spectrometer output was sampled at 1000 Hz over a model scale period of 250 seconds (equivalent to approximately an hour in full scale time) and low-pass filtered at 30 Hz i.e. approximately 2 Hz equivalent in full scale. This modelling technique is accurate in the near-field where the dispersion of exhaust gases is dominated by large scale turbulent motions generated by the topographical boundary layer and building wake flows. The procedure used to obtain each data point was to set the model to the desired configuration and then to measure the concentration of exhaust gas in ambient air, at various locations on a horizontal plane traverse at ground level and a vertical plane traverse at the centre downstream of the discharge. In full scale terms the hourly mean, standard deviation and peak of exhaust gas concentrations in ambient air by mass ratio, were determined. The mean mass concentrations are presented in this paper in the following non-dimensionalised form.

$$\text{Concentration coefficient } \chi = \frac{\rho\, C_M\, U\, H\, B}{\rho_s\, \omega\, A_s}$$

mean?

where	C_M	=	mass concentration
	ρ	=	air density
	ρ_s	=	stack exhaust density
	U	=	freestream wind velocity
	ω	=	stack exit velocity
	H	=	height of building
	B	=	width of building
	A_s	=	area of stack

4. RESULTS AND DISCUSSION

High concentrations are seen to occur at wind speeds approximately 10.7 m/s at heights up to at least 2 to 3 buildings heights above the stack heights, 2 to 3 buildings widths wide and 5 to 50 building widths downstream. Plume interactions, where the plume buoyancy of the downstream stack raises the upstream plume, are seen to reduce the highest ground level concentration by 40% near the building and by 10% farther away 5 buildings widths downstream. A small air gap under the building is seen to decrease the high ground level concentrations behind the building, but only moves the high concentrations due to downwash further away from the building. The addition of downstream buildings increases entrainment and is seen to increase the downwash effect. As the stack height increases to 2 building heights, the downwash effect decreases and the highest ground level concentration is reduced by 50%.

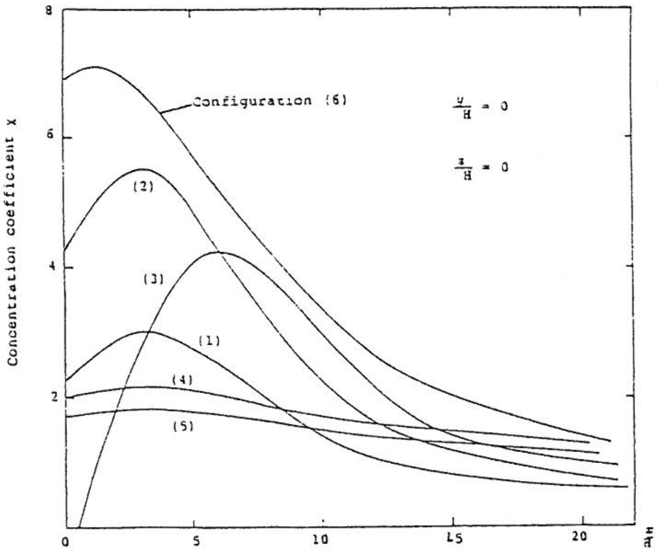
References

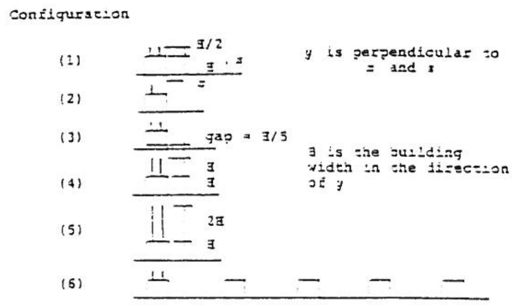
[1] Melbourne, W H (1968) "Wind tunnel modelling of buoyant chimney plumes", Proc. 3rd Australasian Conf. on Hydraulics and Fluid Mechanics, Inst. of Engineers, Australia, pp 81-85.

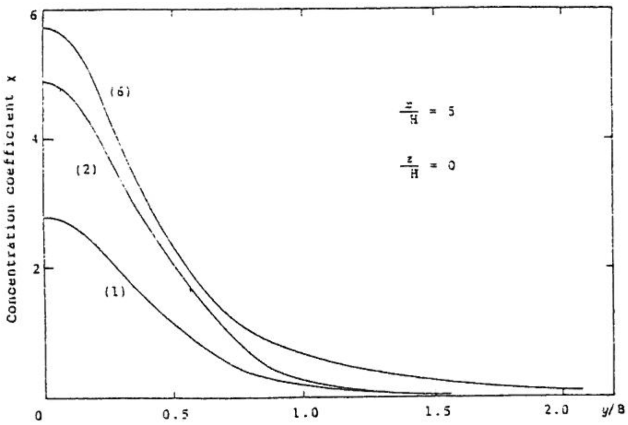
[2] Melbourne, W H, Taylor, T J and Grainger, C F (1993). "Dispersion modelling in convective wind flows", Prepared for submission to Atmospheric Environment.

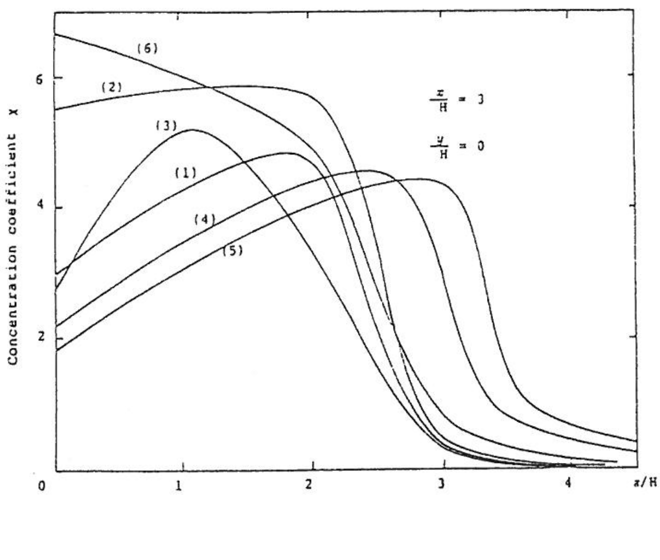
[3] Snyder, W H and Lawson, R E (1991) "Fluid modelling simulation of stack-tip downwash for neutrally buoyant plumes", Atmospheric Environment, Vol 25A, No.12, pp 2837-2850.

[4] Huber, A H (1991) "Wind tunnel and Gaussian plume modelling of building wake dispersion", Atmospheric Environment, Vol 25A, No.7, pp 1237-1249.


Concentration coefficient χ
Configuration (6)
(2)
(3)
(1)
(4)
(5)
y/H = 0
z/H = 0
x/H
0
5
10
15
20
2
4
6
8


Configuration
(1)
(2)
(3)
(4)
(5)
(6)
B/2
gap = B/5
2B
y is perpendicular to z and x
B is the building width in the direction of y


Concentration coefficient χ
(6)
(2)
(1)
x/H = 5
z/H = 0
y/B
0
0.5
1.0
1.5
2.0
2
4
6


Concentration coefficient χ
(6)
(2)
(3)
(1)
(4)
(5)
x/H = 3
y/H = 0
z/H
0
1
2
3
4
2
4
6