Journal of Industrial Aerodynamics, 5 (1979) 1—11

LIFT OFF OF BUOYANT GAS INITIALLY ON THE GROUND

ROBERT N. MERONEY

Fluid Mechanics and Wind Engineering Program, Civil Engineering Department, Colorado State University, Fort Collins, Colorado 80523 (U.S.A.)

(Received June 26, 1978; accepted in revised form October 6, 1978)

Summary

A laboratory model study of the behavior of buoyant plumes when released at ground level in a turbulent shear layer reveals that significant shear flow velocities may delay significant lofting of the plume. The distance to lift off for line, area, or point source released correlates with a buoyancy length scale and the modified Froude number.

---

1. Introduction

The lift off distance of a potentially hazardous buoyant cloud under different meteorological conditions is of interest to safety personnel in both the petrochemical and nuclear industries. When wind velocities are significant near the ground, buoyant gases do not necessarily rise upwards immediately at the source. Whether or not a buoyant plume or puff can lift itself off the ground in the presence of a shear flow will depend upon how vertical forces contributed by buoyancy interact with pressures induced by the ambient fluid velocities which tend to hold the plume against the ground.

When buoyancy is relatively small, a gas cloud stays on the ground and diffuses like a passive gas. If the cloud's buoyancy forces are somewhat larger, the plume may transport upward with enhanced vertical dispersion. Finally, if the force ratios are even larger most material will eventually lift off the ground leaving only a small residual portion behind.

Briggs [1] suggested from dimensional constraints that lift off may be characterized by a lift off parameter L_p defined as

$$L_p = \frac{g H \Delta\rho/\rho_a}{u_\star^2} \tag{1}$$

where $u_\star$ is friction velocity, H is gas layer depth, and $\Delta\rho/\rho_a$ is the relative density of the gas compared to the ambient density. Analytical considerations based on either hydrodynamic pressure arguments or lateral growth rates of a dispersing plume suggest a value of 2 for a critical value. Unfortunately no measurements are available to confirm this number. Briggs admits there may be a factor of ± 4 in accuracy in the numbers he proposed. Order of magnitude

CEP 77-78-66

calculations for typical buoyant plume conditions suggest that plume lift off for many meteorological conditions may be marginal. (A plume where specific gravity $\simeq 0.975$ which has a depth of 2 meters in a wind field at 4 m/sec would not necessarily rise!)

A program is discussed herein to evaluate some aspects of this lift off process. Buoyant gases under point, line, or area release configurations at ground level were examined for lift off visually at various wind speeds in a boundary layer wind tunnel. Plume buoyancy was regulated by changing helium volumetric source strength, and visualization was accomplished by marking with $TiCl_4$ smoke tracer.

2. Experimental techniques

Boundary layer wind tunnel

The facility used was the Industrial Aerodynamics Wind Tunnel (IWT) of the Fluid Dynamics and Diffusion Laboratory. The test section is 1.8 m × 1.8 m in cross section and 16.7 m long. It has an adjustable roof that was used to eliminate any longitudinal pressure variation in the ambient flow over the model sources.

In order to obtain a thick turbulent boundary layer in the wind tunnel, spires were used in addition to the length of the available test section. The spires used were developed by Peterka and Cermak [2]. In addition to the spires a barrier 0.191 m high was located 0.61 m downstream of the spires. No artificial roughness was added to the floor surface. Measurements of mean velocity profiles, local turbulence intensities, longitudinal scales of turbulence, longitudinal velocity spectra and auto-correlations were made by Akins et al. [3] to identify the character of the resultant shear layer. Properties of the boundary layer are summarized in Table 1. Comparing these results against the typical adiabatic atmospheric boundary layer behavior suggested by Counihan [4] suggests that the shear layer represents a 375 to 1 scale model of a neutral boundary layer developed over roughness $z_0 \cong 0.46$ cm.

Model sources

A model line source, area source, and point source were installed in the IWT at a distance 12 meters downwind of the entrance spires and fence (Fig.1). The line source stopped short of the tunnel side walls by 30 cm on each side; however visualization did not indicate any preference for the plume to loft at the edges before the center section. Gases emitted from the line source were released from a slot in the downwind side. Gases emitted from the area source were released vertically through a punched porous plate. The point source configuration was a 1.27 cm diameter tube bent to release gases in the downwind direction.

Pure helium was released from each source for a range of tunnel wind speeds and source flow rates. A reference wind speed was measured at 25 cm by

TABLE 1

Summary of properties — Wind tunnel boundary layer

z/δ	$\bar{u}(z)/\bar{u}(\delta)$	$u'(z)/\bar{u}(z)$	$v'(z)/\bar{u}(z)$	$w'(z)/\bar{u}(z)$	$\frac{\sqrt{-uw}}{\bar{u}(\delta)}$	Λ_x (m)
0.02	0.64	0.128				0.42
0.04	0.70	0.107	0.073	0.045	0.024	
0.06	0.72	0.091	0.071	0.047	0.026	0.33
0.10	0.75	0.086	0.068	0.049	0.029	0.39
0.14	0.77	0.082	0.063	0.049	0.027	0.38
0.18	0.79	0.082	0.062	0.048	0.027	0.44
0.20	0.80	0.072	0.062	0.051	0.030	0.38
0.30	0.83	0.066	0.057	0.048	0.030	0.46
0.40	0.86	0.070	0.051	0.049	0.030	0.48
0.50	0.89	0.064	0.049	0.043	0.029	0.42
0.60	0.92	0.052	0.042	0.038	0.025	0.56
0.70	0.93	0.050	0.038	0.036	0.026	
0.80	0.96	0.042	0.031	0.030	0.021	
0.90	0.98	0.037	0.027	0.026	0.019	
1.00	1.00	0.035	0.026	0.024	0.011	0.32

$u_\star/\bar{u}(\delta) = 0.028$
$z_0 = 1.22 \times 10^{-5}$m
$p = 0.12$
$\delta = 1.27$ m

Assumed properties full scale atmospheric boundary layer:
Assume length scale ratio = 375
then Λ_x (10 m) = 150 m
δ_G = 450 m
z_0 = 4.6×10^{-3}m

means of a Datametric Series 800-L linear flow anemometer. The anemometer was specifically calibrated for a low speed operational range (0.1—2 m/sec). Source flow rate was monitored by Fischer-Porter Rotometers precalibrated for helium against a wet test gas meter. Duplicate runs were also made with air to permit trajectory and dispersal comparison against a passive gas.

Visualization of the plume was obtained by passing the gas mixture through a container of titatnium tetrachloride located outside the wind tunnel. The plume was illuminated with arc lamp beams. A visible record was obtained by means of pictures taken with a Speed Graphic camera. A series of motion pictures were also taken with a Bolex motion picture camera mounted in a movable dolly which traversed the length of the tunnel parallel to the plume at the average wind speed.

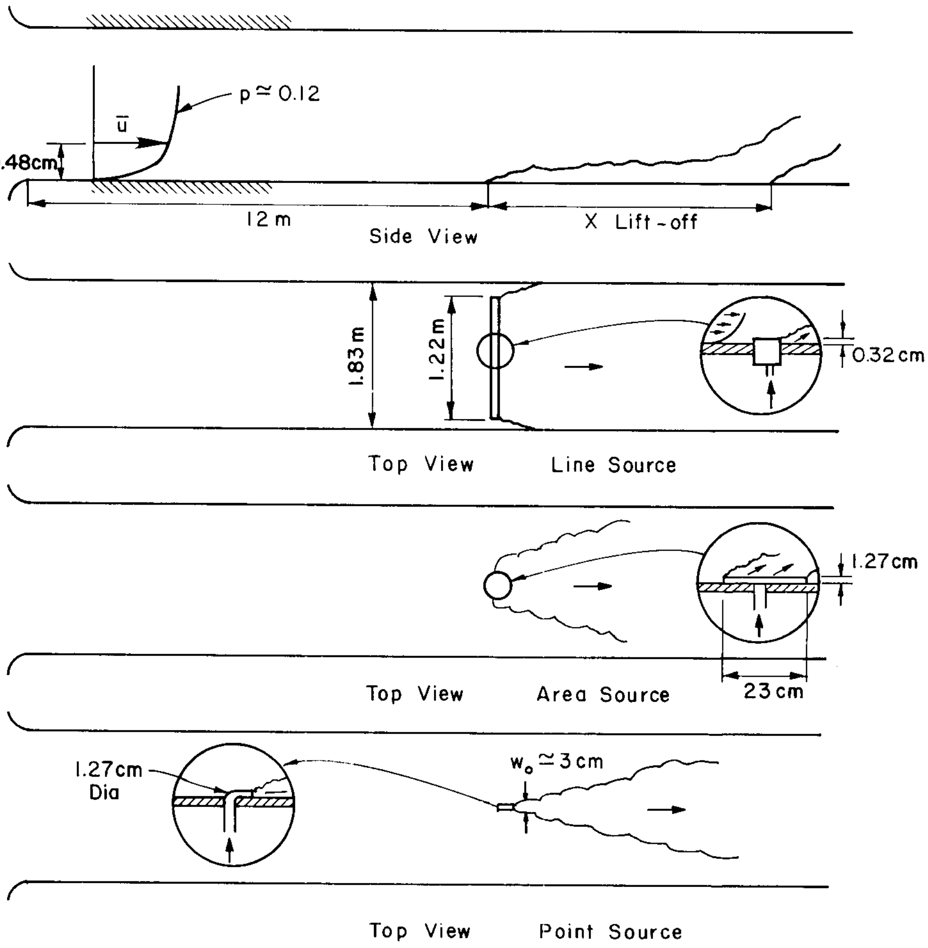


Fig. 1. Line, area, and point source configurations.

3. Results and discussion

The experimental program resulted in a series of photographs and visual estimates of the lift off location for some thirty-four release cases. The downwind distances from source to incipient lift off are recorded together in Table 2. These values represent the average judgment of two observers as to locations where significant clearing of smoke density occurs at the floor surface.

Figures 2 and 3 display the comparative behavior of helium and air when emitted from a ground level point source. The enhanced vertical dispersion for the helium case is evident as the individual buoyant eddies penetrate upwards. Even when the buoyant plume does not loft it has a larger vertical rate of growth than its passive counterpart.

TABLE 2

Approximate distances to lift off for ground released buoyant plumes in a crossflow boundary layer

Line source: y = 1.22 m, x_0 = 12 m from tunnel entrance

Velocity (m/sec)	Flow rate (cc/sec)			
	354	708	1062	1416
Helium and air: (W_0 = 1.22 m), x (m)				
0.17	0.91	0.56—0.61	0.46	0.30
0.23	2.74	1.83	0.61—0.91	0.61
0.46	$x > 4.60$	2.13	1.83	1.22
0.76	$x > 4.60$	$x >$ 3,35	$x > 3.35$	2.13
Area Source: (W_0 = 0.23 m), x (m)				
0.16	0	0	0	0
0.23	0	0	0	0
0.46	0	0	0	0
0.76	0.46	0.30	0.15	0
1.22	$x > 4.60$	$x > 4.60$	2.44	1.52
Point source : ($W_0 \simeq$ 0.03 m), x (m)				
0.76	0.30*	0.15*	0	0
1.22	?	0.46	0.46	0
1.83	?	0.76—0.91	0.61	0.61

*Very unsteady, results are approximate.

Plume kinematics may be expected to be governed by buoyancy and inertial forces; hence the lift off distance, x, may be scaled by the relevant buoyancy length scale, l_b, i.e.,

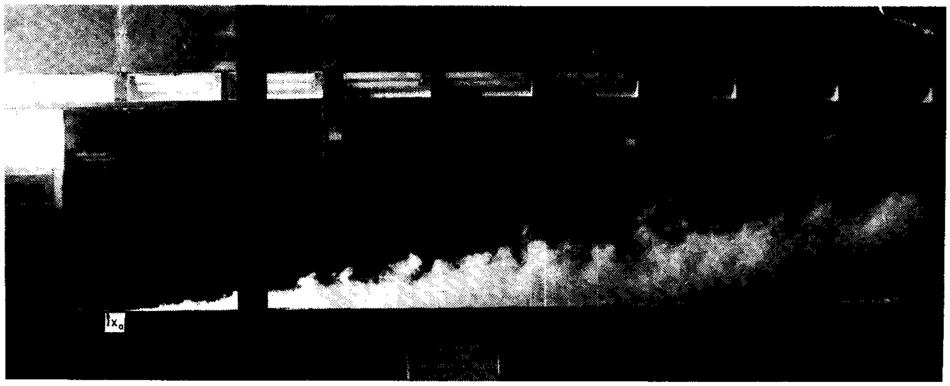
$$\frac{x}{l_b} = \left(\frac{x/g\Delta\rho_0 Q}{\rho_a \bar{u}^3}\right) \tag{2}$$

This length scale will vary depending upon the magnitude of some relevant buoyancy parameter selected to normalize behavior of line, area, or point sources such as a modified Froude number based on source strength per unit width, i.e.,

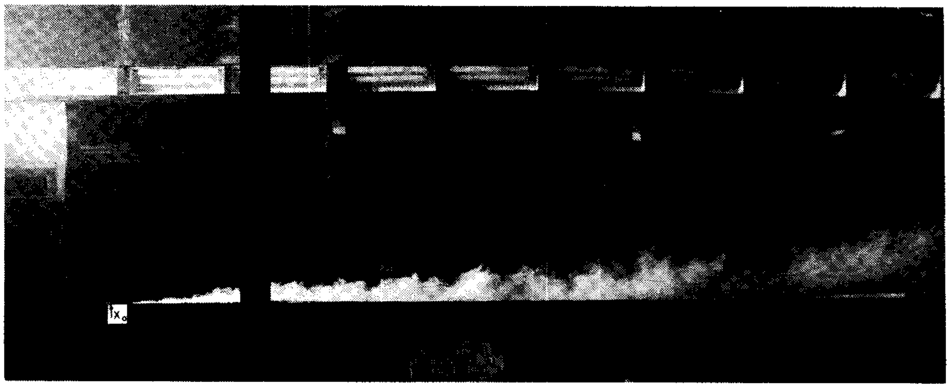
$$Fr = \frac{\rho_a \bar{u}^3 W_0}{g\Delta\rho_0 Q} \tag{3}$$

where $\Delta\rho_0/\rho_a$ is again the relative density of the source gas compared with the ambient density, $\bar{u}$ is a reference velocity, Q is a volumetric source strength, and W is a characteristic source width.

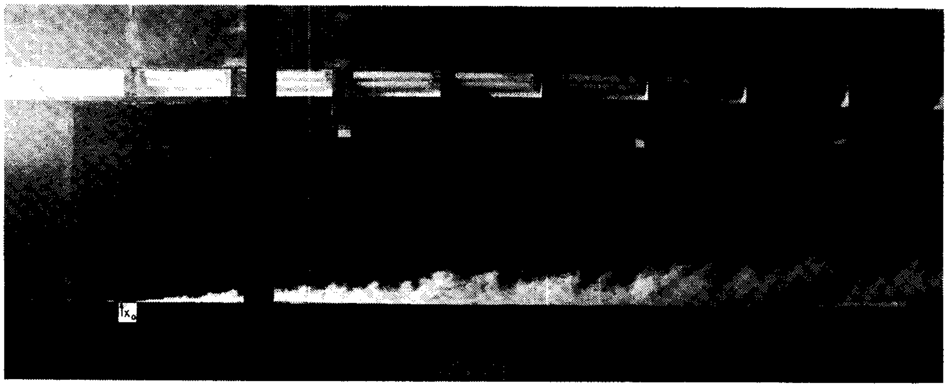
A reference velocity, $\bar{u}$, has been chosen to parallel the definition of buoyancy length scale recommended by previous investigators Hoult and



(a) $\bar{u}$ = 0.76 m/sec.

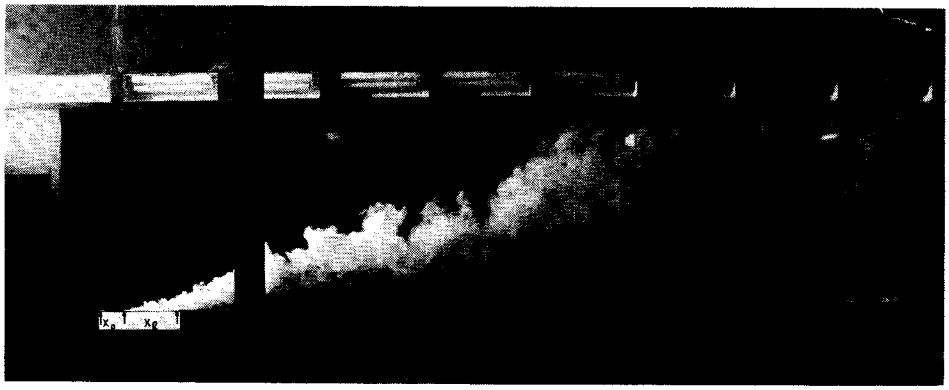


(b) $\bar{u}$ = 1.22 m/sec.

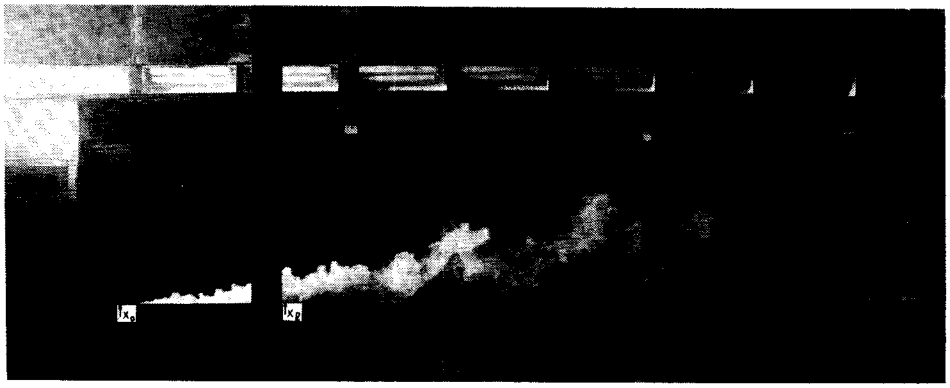


(c) $\bar{u}$ = 1.83 m/sec.

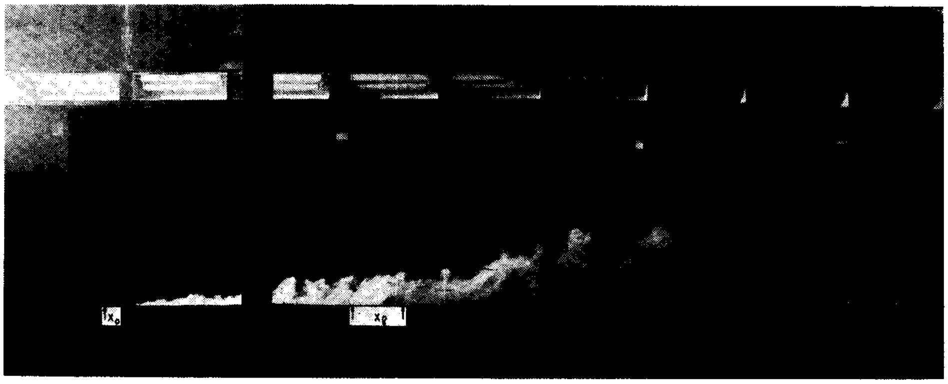
Fig.2. Point source in a shear layer: air. Q = 708 cc/sec, $\bar{u}$ = 0.76, 1.22, and 1.83 m/sec.



(a) $\bar{u}$ = 0.76 m/sec.



(b) $\bar{u}$ = 1.22 m/sec.



(c) $\bar{u}$ = 1.83 m/sec.

Fig.3. Point source in a shear layer: helium. Q = 708 cc/sec, $\bar{u}$ = 0.76, 1.22, and 1.83 m/sec.

Weil [5]. The effect of differing ground roughness could be taken into account by utilizing friction velocity, $u_\star$, instead of $\bar{u}$ in the definitions of l_b and Fr. In any event the velocity scales may be related by means of a surface drag coefficient.

The variables x/l_b versus Fr have been plotted in Fig.4. The data clearly show that for conditions to the right of the solid line a buoyant plume may be expected to remain near the ground surface; whereas for low wind speed or high buoyant flow rate situations lift off may occur for conditions to the left of the line. An empirical formula based on the data observed herein would be

$$x/l_b \geqslant A\,(Fr)^{1.5} \tag{5}$$

where $A \simeq 0.24$.

Data from the line, area, and point source release conditions are all included in Fig.4. Lift off location of the plume from a line source is dominated by vertical diffusion rates, but in order to lift off the ground compensating areas of downdraft must appear. Briggs [1] hypothesized this process would always leave some residual near the ground; however, visualization experiments suggest even fragments of the plume initially left behind eventually disperse upwards. Lift off location of the plume from a point or area source is expected to be dependent on lateral transport as well as vertical diffusion. Nonetheless the data appears to correlate versus a single parameter, Fr, in a consistent manner. The data points presented for point source conditions do lie well above the suggested design correlation; however, this was considered to be largely a result of strong forward jets resulting from high flow rates through the narrow point source aperture.

The formulation suggested by eqn. (5) indicates that given the bulk buoyancy parameter at the source, Fr, a buoyant plume will always eventually "lift off". In some cases this may be at such a great distance that residual gas concentrations will be nearly as great at the ground as at an elevated plume center of gravity. Nonetheless it seems inappropriate to speak of a critical source value Fr.

If one defines a lift off parameter in terms of the local values of H, W or $\Delta\rho/\rho_a$ at incipient lift off as proposed by Briggs a value might be designated as "critical". Briggs' lift off parameter, L_p, may be related to the source parameter Fr if one assumes buoyance flux is conserved, i.e.,

$$\frac{\Delta\rho_0}{\rho_a}Q = \frac{\Delta\rho_0}{\rho_a}H_0 W_0 u_0 \sim \frac{\Delta\rho}{\rho_a}HW\bar{u} \tag{6}$$

and one specifies

$$u_\star = (\tfrac{1}{2}C_D)^{\frac{1}{2}}\bar{u} \tag{7}$$

then

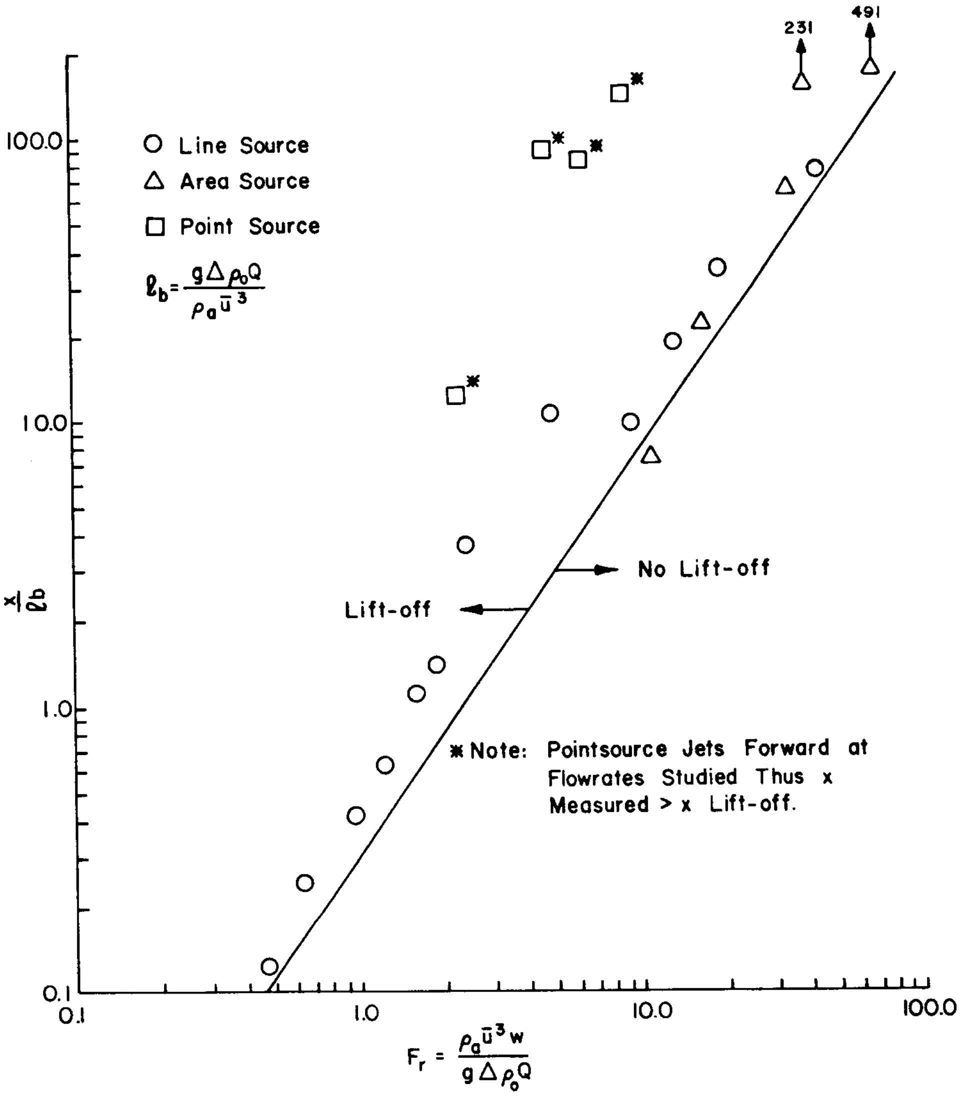


Fig.4. Dimensionless lift off distance versus froude number for buoyant surface released plumes.

$$
\begin{aligned}
L_{\mathrm{p}} &\sim \frac{2}{C_{\mathrm{D}}}\,\frac{g\Delta\rho_0 Q}{\rho_{\mathrm{a}}\bar{u}^3 W} \\
&\sim \frac{2}{C_{\mathrm{D}}}\,\frac{1}{Fr}\,\frac{W_0}{W}.
\end{aligned}
\qquad (8)
$$

This relation suggests that for a line source L_{p} will remain constant; whereas for a point on area source L_{p} will decrease as plume width W increases. It would appear that for continuous point sources L_p decreases continuously after release. Similar conclusions are presented by Briggs [1]. Combining the empirical expression for x/l_b, eqn. (5), with the relation for L_p, eqn. (8), reveals that

$$x \sim (\bar{u}/\bar{u}_\star) L_p^{-1/2}. \tag{9}$$

This relationship is also proposed by Briggs [1].

Over the range of Fr examined a critical value above which the plume did not lift off was not identified. If one considers the point source data for which $W \simeq H$ at lift off then

$$L_p = \frac{B_t}{u_\star^2 \bar{u} W} \sim 9 \text{ to } 27$$

where H is estimated from photographs. Similarly L_p values associated with the line source releases range from 4.5 to 1600. These values all fall well above the upper end of the critical L_p range $(0.5 < L_p < 8)$ proposed by Briggs [1]. Such wide variations in L_p at lift off precludes specification of a single critical value.

4. Conclusions

A laboratory model study of the lift off phenomena for buoyant plumes in a boundary layer wind tunnel suggests that

1. Lift off of a buoyant plume will indeed be delayed by significant shear flow velocities near the ground.
2. The distance to lift off for line, area, or point source releases correlates as $x/l_b > 0.24\, Fr^{1.5}$; hence increased wind speed delays plume lift off, whereas increased buoyancy flux hastens its ascent.

Acknowledgements

Support for this work from the U.S. Energy Research and Development Administration under Contract No. EE77C031364 is gratefully acknowledged.

Notation

Symbol	Definition	Dimension
A	Constant in eqn. (5)	—
B_t	Buoyancy flux for continuous point source	$L^4 T^{-3}$
B_{lt}	Buoyancy flux for continuous line source	$L^4 T^{-3}$
C_D	Surface drag coefficient	—
Fr	Modified Froude number eqn. (3)	—

g	Acceleration of gravity	LT^{-2}
H	Layer depth	L
H_0	Initial layer depth	L
l_b	Buoyancy length scale eqn. (2)	L
L_p	Lift off parameter eqn. (1)	—
p	Power law exponent	—
Q	Volumetric source strength	L^3T^{-1}
$\overline{u}$	Reference velocity at 25 cm	LT^{-1}
$u_\star$	Friction velocity	LT^{-1}
W	Plume width	L
W_0	Initial plume width	L
x	Lift off distance from source	L
z_0	Roughness length	L
ρ	Plume density	ML^{-3}
ρ_0	Source gas density	ML^{-3}
ρ_a	Atmospheric gas density	ML^{-3}
$\Delta\rho_0$	$\rho_a - \rho_0$	ML^{-3}
$\Delta\rho$	$\rho_a - \rho$	ML^{-3}

References

1 G.A. Briggs, Theoretical estimates of lift off of buoyant gas initially on the ground, Atmospheric Turbulence and Diffusion Laboratory Contribution No. 87, NOAA, Oak Ridge, Tennessee, 1973, 10 pp.

2 J.A. Peterka and J.E. Cermak, Simulation of atmospheric flows in short wind tunnel test sections, Colorado State University, Fluid Mechanics Program, Technical Report CER73-74JAP-JEC32, 1974, 52 pp.

3 R.E. Akins, J.A. Peterka and J.E. Cermak, Mean force and moment coefficients for buildings in turbulent boundary layers, J. Ind. Aerodyn., 2 (1977) 195—209.

4 J. Counihan, Review paper: Adiabatic atmospheric boundary layers: A review and analysis of data from the period 1880—1972, Atmospheric Environment, 9 (1975) 871—905.

5 D.P. Hoult and J.C. Weil, Turbulent plume in a laminar cross flow, Atmospheric Environment, 6 (1972) 513—531.