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Journal of Hazardous Materials 59 (1998) 123–130

JOURNAL OF HAZARDOUS MATERIALS

Lift-off of ground-based buoyant plumes

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Received 5 June 1997; accepted 2 September 1997

Abstract

If a ground-based plume has enough buoyancy to overcome the effects of ambient turbulence and other physical processes, it will rise or lift-off the ground, thus reducing the health and environmental impacts of chemicals released accidentally to the atmosphere. The approach described below was developed using wind tunnel observations of plumes for which buoyancy was conserved, but we also propose it for use for plumes whose buoyancy flux varies with distance; this can occur due to the presence of aerosols, depolymerization, reactions with water vapor or other chemicals to form new products, and evaporation and condensation processes. It is assumed that the lift-off phenomenon can be parameterized by defining a dimensionless buoyancy flux, $F** = F/u^3W$, where F is the local plume buoyancy flux, u is the local effective wind speed advecting the ground-based plume, and W is the local lateral plume width. All variables can vary with plume travel time or downwind distance. It is suggested that the effects of plume lift-off can be accounted for by multiplying the calculated ground-level concentration in the absence of lift-off by the term $\exp(-6F**^{0.4})$. Special emphasis is given to the development of simple empirical lift-off equations for buoyant plumes which are trapped in building wakes. In this case, the empirical formula that is proposed combines the $\exp(-6F**^{0.4})$ term with four additional terms related to the spread of plumes in building wakes, and has been demonstrated to agree with wind tunnel observations. © 1998 Elsevier Science B.V.

Keywords: Lift-off; Buoyant plumes; Atmospheric dispersion; Building wakes

1. Background

A buoyant plume blowing along the ground may 'lift-off' if the inward velocity at its base generated by buoyant forces exceeds the diffusive velocity generated by ambient

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PII S0304-3894(97)00094-0

turbulence [1]. The lift-off tendency is expected to be inhibited for plumes with large width-to-depth ratios and/or large horizontal homogeneities, which tend to undergo convective instabilities which break up the plume. The few previous analyses [1–5] of this problem all dealt with plumes with width-to-depth ratios of order unity and which tend to conserve their initial buoyancy flux, F_o, defined in the standard way,

$$F_o = (V_o/\pi) g(\rho_a - \rho_o)/\rho_a. \quad (1)$$

Subscript 'o' refers to the initial plume, subscript 'a' refers to the ambient environment, V is the plume volume flux, g is the acceleration of gravity (9.8 m/s^2), and ρ is the density. Note that a positively buoyant plume is one whose density, ρ_o, is less than that of the ambient air.

In the case of the accidental release of some chemicals (e.g., pressurized liquid NH_3, pressurized gaseous or liquid UF_6, pressurized liquid HF, or pressurized and refrigerated liquid H_2), the plume does not conserve its initial buoyancy flux, F_o. In fact, the relative plume density $(\rho_a - \rho)/\rho_a$ may change sign from positive (i.e. the plume is less dense than air) to negative (i.e. the plume is denser than air) and back again, depending on the relative influence of several chemical and thermodynamic effects. These processes are especially critical for UF_6, the chemical that was the subject of the model development research reported by Hanna et al. [6] and Hanna and Chang [7], and led to the development of the lift-off model described in the current paper. The following five processes are the major contributors to changes in the buoyancy flux in UF_6 plumes.

- The molecular weights of the plume gases (including polymers) may change from being greater than the molecular weight of air to being less.
- The temperature differences between the plume, the ambient air, and the substrate (land or water) may change sign.
- The effective plume density may be strongly affected by aerosols carried by the plume, especially for flashing liquid releases.
- Heat may be added by exothermic reactions and by condensation of liquids.
- Heat may be removed by endothermic reactions, depolymerization, and evaporation of liquids.

For example, consider a system where about 10 kg/s of pressurized liquid anhydrous HF is released and subsequently reacts with ambient water vapor. The plume may first be very dense due to the presence of aerosols and polymers, but may eventually become buoyant because the molecular weight of HF monomer is less than that of air, because most of the aerosols have evaporated, and because of the additions of heat due to chemical reactions. These effects can prevail over other effects which are acting to decrease the plume's buoyancy, such as the cooling of the plume due to the depolymerization process and due to the evaporation of aerosols. All during these processes, the plume will be growing in the vertical (depth H) and the horizontal (width W), due to turbulent dispersion. We define a *local* buoyancy flux, F, using Eq. (1), but substituting the *local* values of the volume flux, V, and the plume density. For a plume of dimensions H and W that is travelling downwind at effective speed u, the volume flux V can be assumed to equal uHW, where H and W are not necessarily equal.

Most previous analyses of this problem have made use of the 'lift-off' parameter, L_p, originally defined by Briggs [1]. L_p is intended to represent the ratio of the inward velocity at the plume base due to buoyancy forces to the outward mixing velocity due to the ambient turbulence. L_p is defined by the following expression,

$$L_p = \frac{gH(\rho_a - \rho)/\rho_a}{u*^2} \tag{2}$$

where the friction velocity, $u*$, can either be measured directly by turbulence instruments or can be calculated using boundary layer profile equations. In Eq. (2), Briggs [1] made the standard assumption that the ambient turbulent energy is proportional to $u*^2$. This lift-off parameter, L_p, is defined in nearly the same way as the plume bulk Richardson number, and applies only for positively buoyant plumes. Observations of plume lift-off in laboratory studies [2–5] suggest that the ground-based plume will lift off the ground when $L_p > 20$; this number has an uncertainty of at least a factor of two. For values of L_p slightly less than 20, the plume may stretch vertically without lifting completely off the ground, leaving a residual concentration at the ground. Briggs [1] and others have employed the L_p criterion of Eq. (2), along with assumptions for the growth of plume volume flux V with time, to derive formulas for calculating the distance at which $L_p = 20$ for plumes where buoyancy flux, F_o, is conserved. These formulae are very useful for many applications, but are more difficult to apply to reactive plumes or aerosol plumes, where F_o is not conserved.

2. A revised lift-off model

The simple concept described above, that a buoyant plume will lift-off when its local L_p exceeds 20, had been incorporated in an earlier version of a dispersion model for the reactive chemical, UF_6 [6]. However, since the $L_p > 20$ criterion describes an 'all-or-nothing' phenomenon, it does not properly account for the smooth transition in the structure of the plume as its buoyancy gradually increases. Consequently, one of the authors (G.A. Briggs) of the current paper reanalyzed the Hall and Waters wind tunnel data [3], which demonstrated the smooth transition associated with the lift-off phenomenon, and proposed a revised formula in an unpublished memo in 1995. The primary emphasis of that wind tunnel study was on releases of positively-buoyant plumes that were initially uniformly spread across rectangular-shaped building faces. As we were studying and testing Briggs' revised formula, a new report from the same wind tunnel researchers [8] arrived which was concerned with positively-buoyant plumes released from various configurations of vents on buildings. We considered these new data in deriving the lift-off formula described in the paragraphs below, which is now incorporated in the HGSYSTEM/UF_6 hazardous gas dispersion code [7].

On the basis of our analysis of the two sets of wind tunnel data, plus consideration of fundamental physics, we propose a revised definition of the lift-off parameter, L_p. We prefer to define a new lift-off parameter which can be considered to be a dimensionless buoyancy flux, $F** = F/u^3W$. F is the buoyancy flux defined in Eq. (1), but using local values of plume volume flux and density, and is treated as a local parameter (to account for possible changes in buoyancy due to chemical reactions and other processes).

The wind speed, u, is defined as the effective wind speed over the depth of the plume. The plume width, W, is used as a scaling length rather than plume depth, H, since the inward velocities induced by hydrostatic pressure forces are proportional to $(F/uW)^{1/2}$ when local volume flux, V, equals uWH [1]. Thus lift-off is inhibited for broad flat plumes. Using the identity $F=(V/\pi)g(\rho_a-\rho)/\rho_a=(uWH/\pi)g(\rho_a-\rho)/\rho_a$, it can be shown that the two alternate lift-off parameters are related by $L_p=\pi(u^2/u*^2)F**$, or $L_p=300F**$, if the common approximation is used that $u/u*=10$. It must be noted that, in the reports [3,8] describing the wind tunnel experiments, an alternate dimensionless buoyancy parameter was defined using H rather than W. However, we prefer to use W because it is consistent with known physical relations and because $F**$ is then equal to a simple multiple of L_p.

Because the new model has been derived from wind tunnel data [3,8] involving positively-buoyant releases from buildings, the initial dilution of the wind tunnel plumes was strongly affected by aerodynamic effects around the buildings (i.e. downwash). It is assumed that the lift-off effect, as characterized by $F**$, can be distinguished from building downwash, wake growth, and other dilution processes if F, u, and W are appropriately evaluated. Thus, the proposed 'lift-off term' is assumed to be applicable to plumes in the presence or absence of building effects.

Most of the wind tunnel scenarios reported in Refs. [3,8] were used in the data analysis leading to the lift-off equation given below. The main criterion for the inclusion of data from specific sets of wind tunnel scenarios in this analysis was that a significant number of cases should be available that they could be combined and compared in plots of dimensionless concentration versus either $F**$ (at fixed values of x/H_B) or x/H_B (at fixed values of $F**$). Here, H_B and W_B are building height and width perpendicular to the wind and x is the distance measured from the downwind building face. We used CuR^2/Q as the dimensionless concentration, where C is the plume centerline ground-level concentration, u is the upstream wind speed at height H_B, Q is the release rate, and $R=H_B^{2/3}W_B^{1/3}$. The latter is a building scaling length defined by Wilson and Britter [9]; in cases of large W_B/H_B, the building scaling length R is not allowed to exceed $2H_B$.

The analysis included nearly all of the cases shown in Figs. 9, 13, 16, and 19 of Hall and Waters [3] and the $F**=0$ and 0.03 or 0.033 cases shown in Figs. 46, 47, 50, 53, and 54 of Hall et al. [8]. Specifically, the analysis included the following components.

(1) Plots were made of CuR^2/Q versus $F**$ at: (a) $x/H_B=1.2$, 12, and 40 for releases from three different faces of buildings with $W_B/H_B=2$, with two different surface roughnesses; and (b) $x/H_B=1.2$ and 12 for releases from the lee-face of buildings with $W_B/H_B=1$, 2, and 3.

(2) Plots were made of CuR^2/Q versus x/H_B at $F**=0.0$ and 0.1 for buildings with $W_B/H_B=2$ at wind directions of 0, 45, 60, 90, and 135° from the releasing face and at 0° with half- or quarter-face releases.

(3) Plots were made of CuR^2/Q versus x/H_B at $F**=0$ and 0.03 or 0.033 for releases from a door or from 1 to 15 roof vents on warehouse-shaped buildings with width to height and width to length ratios of either 3 or 10.

An example of these plots is shown in Fig. 1 for the data described in number (1) above, where the data are derived from Fig. 9 of Hall and Waters [3]. The analysis of the

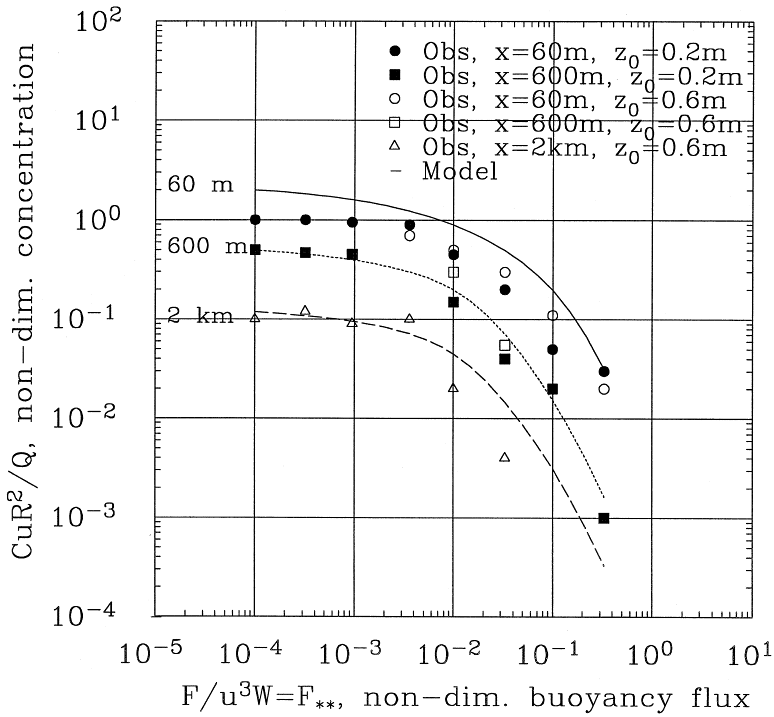

Fig. 1. Predictions of the lift-off model expressed by Eq. (3) at downwind distances of 60 m, 600 m, and 2000 m, compared with observations of positively-buoyant plumes in Hall and Waters' wind tunnel study [3]. C is maximum (i.e. plume centerline) ground level concentration. Two different surface roughnesses ($z_0 = 0.2$ m and 0.6 m) were tested. Building height is 50 m, building width is 100 m, and neutral (class D) ambient stability is assumed. Winds are perpendicular to the building face.

three types of plots described above led to the development of Eq. (3), which is also shown on Fig. 1 for each of three downwind distances ($x = 60$, 600, and 2000 m). Its four adjustable coefficients were manipulated until visual inspections of the plots showed that it provided a moderately conservative fit to the bulk of all the above-mentioned wind tunnel observations.

$$\frac{CuR^2}{Q} = \frac{\exp(-6F**^{0.4})}{\left[0.037 + 0.03\left(\frac{x}{H_B}\right)^2 + F**^2\left(\frac{x}{H_B}\right)^4 + \left(\pi\frac{\sigma_y\sigma_z}{R^2}\right)^3\right]^{1/3}} \tag{3}$$

The numerator in Eq. (3) is the 'lift-off' term, which describes the decrease in ground-level concentration, C, due to buoyant stretching or lifting of a positively-buoyant plume. The exponential term was chosen because it has the proper asymptotic behavior at small and large $F**$, and the numerical parameters, 6.0 and 0.4, were selected because they provide good fits to all of the data described above.

The denominator of Eq. (3) is assumed to be proportional to the cross-wind area of the plume. Each of the terms in the denominator is consistent with fundamental physical relations for the dispersion of positively- or neutrally-buoyant plumes that have been developed and verified over the past two decades. For example, note that in the limit as x approaches zero for zero plume buoyancy $(F** = 0)$, the solution reduces to $CuR^2/Q = 3$, which is the relation used in current regulatory models for passive plumes well-mixed across the recirculation cavity just downwind of a building [10–12]. The wind tunnel experiments showed little change in the ground-level concentrations at downwind distances, x/H_B, of 1.2, 12, and 40, whether the plume was released from the upwind face, the downwind face, or the roof of the building [3]. Also, in the limit of very large x, the solution reduces to $Cu/Q = (\pi\sigma_y\sigma_z)^{-1}$, which is the familiar Gaussian plume model (where the concentration, C, is the maximum value at ground level on the plume centerline and the release is at ground-level). The σ_y and σ_z formulas in the last term are based on Briggs' analytical equations [13].

The second term in the brackets in the denominator of Eq. (3) describes the growth of the recirculation cavity; we assume that the cavity growth should be capped at a distance of $50H_B$, which is commonly considered to be the distance where the effects of the cavity are dissipated [14]. The third term in the brackets describes the growth of the plume due to buoyancy, and its value should be capped at the distance to final rise. As assumed in US regulatory models such as ISC [15], the distance to final rise is assumed in Refs. [6,7] to be $49F_o^{5/8}$, in m, when F_o is in units m^4/s^3. However, this 30-yr old equation is highly empirical and is based only on data from elevated stacks, not ground sources. Improved formulae appropriate to ground sources do exist, such as $x = 0.8F_o/u*^3$ (from Eqs. 8.58 and 8.97 in Ref. [16]), and could be tested in future improvements to the lift-off equation. Some uncertainties may arise because the equations in Refs. [15,16] assume conservation of buoyancy flux, F, whereas Eq. (3) is intended to be generally valid for plumes where buoyancy flux, F, may vary with distance. It should be noted that the above-prescribed limits to the second and third terms in the brackets of Eq. (3) were not evident in the wind tunnel data [3,8], but have been included to make the equation consistent with known relations for buoyant plumes.

It is important to note that the initial buoyancy flux, F_o, was conserved in the wind tunnel experiments [3,8] from which Eq. (3) was derived. However, it may be assumed that the $\exp(-6F**^{0.4})$ term in Eq. (3) is valid *locally* for plumes where the buoyancy flux, F, varies with distance, due to chemical reactions, phase changes, or the presence of aerosols. In this case, $F**$ would be defined using the local plume width, W.

In the absence of a building (or as the building dimensions approach zero), Eq. (3) reduces to the following equation, which is applicable to an initially ground-based plume from a point source or from a small line, area, or volume source,

$$\text{No building: } \frac{Cu}{Q} = \frac{\exp(-6F**^{0.4})}{\left[\left(F^{2/3}x^{4/3}u^{-2}\right)^3 + \left(\pi\sigma_y\sigma_z\right)^3\right]^{1/3}} \tag{4}$$

The expression in the denominator of Eq. (4) represents the effective cross-sectional area of the plume and is simply a summation of the buoyancy component and the turbulent dispersion component. The 'lift-off' is parameterized by the term in the numerator. As before, F and W are defined locally (i.e. at the downwind distance, x, of interest) and the method is valid only for plumes that are positively-buoyant (i.e., $F > 0$). It is also important to note that the value of the first term in the denominator is uncertain when F changes strongly with x. In its current form, the first term in the denominator implies rapid adjustment of the plume cross-sectional area to the size that would be obtained if the plume had the current F value from the start.

It follows from the rationale used to derive Eqs. (3) and (4) that the lift-off term (i.e., the numerator in both equations) can be applied to any mathematical expression for the ground-level concentration in a positively-buoyant, initially ground-based plume In very general terms, the following equation is assumed to be valid,

$$C(\text{with lift}-\text{off}) = C(\text{in absence of lift}-\text{off}) * \exp(-6F**^{0.4}), \tag{5}$$

where C is maximum ground level concentration on the plume centerline. The lift-off term should be thoroughly tested for a wide range of source scenarios and meteorological conditions. As further wind tunnel and field observations are collected, it will be possible to further refine these modeling procedures and recommendations.

Acknowledgements

This research was supported by the US Department of Energy through subcontract 1AKXJ947C with Lockheed–Martin Energy Systems (LMES). Dr. Briggs' research was supported by the National Oceanic and Atmospheric Administration (NOAA), under an agreement with the EPA. The authors thank Mr. Douglas Lombardi, Dr. Sanford Bloom, Mr. W. Douglas Goode, and Mr. Kenneth Keith, Jr. of LMES for their contributions to the model development. Dr. Rex Britter of Cambridge University and Dr. Ian Sykes of ARAP Group/CRTD/Titan. provided technical comments on an earlier version of the lift-off model.

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