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P.H. THOMAS

SOME PROBLEMS OF PLUME THEORY SMOKE MOVEMENT AND THE ONSET OF FLASHOVER

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SOME PROBLEMS
OF PLUME THEORY SMOKE MOVEMENT
AND THE ONSET OF FLASHOVER

P.H. Thomas
Department of Fire Safety Engineering
Lund University,
Sweden

PREFACE

The three papers comprising this report are each concerned with various aspects of the application of scaling, plume theory in the assessment of the hazards from smoke and flashover, the design of smoke control in buildings and the interpretation of experiments.

Philip Thomas
Lund, December 1989

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SOME OF THE BASIC PRACTICAL CONSIDERATIONS IN ANALYSING THE BEHAVIOUR OF PLUMES AND FLOW FROM OPENINGS

Contents

Summary

Attention is drawn to some of the limitations of conventional plume theory, some differences between axi–symmetric and line plumes, and some rationalisation which is possible in correlating data for the flow from wide vertical openings.

The paper is more a summary and a series of notes than a lengthy exercise in the subject.

1. Introduction and Background

A number of topics relevant to conventional plume theory need examination before discussing details of its application to design, if only to demonstrate the limitations of theory beyond which resolution of detail is not possible.

1.1 Conventional plume theory

Plume theories such as those used by Thomas, et al. (1) Heskestad (2), Zukoski et al. (3), Hinkley (4) and Morgan and Marshall (5) are partly theoretical and partly empirical.[1] There is an empirical content even in basic numerical modelling since turbulent flow is based on statistical theories of turbulence. Conventional plume theory is based on time averaged quantities and this distorts the descriptions of momentum and kinetic energy. This however does not have a primary effect on the theory of plumes so long as similarity can be assumed, for then the fluctuating component is proportional to the mean and the form of the resulting relationships between dimensionless variables is affected only in the empirical coefficients which are derived from experiments.

1.2 Basic ideas and similarity

The theoretical part of plume theory is based on the continuity of the vertical mass flow expressed in terms of the concept of entrainment, the conservation of convected heat or buoyancy, and the vertical buoyancy producing a rate of change of momentum. The idea of an entrainment coefficient "α" was introduced by Morton, Taylor and Turner (6). Its constancy depends on the conservation of the horizontal distributions of vertical velocity and temperature rise (or of density difference). The nature of the distribution defines the value of "α";

for example α for a "top hat" plume is $\sqrt{2}$ greater than that for a Gaussian distribution (7) when mass and momentum are both equal for the two types of distribution.

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[1]Hinkley's application to plumes of a formula derived for flames is virtually wholly empirical.

1.3 The classical axi–symmetric weak plume

If, conventionally, we assume α is constant and "ρ" is assumed constant $(= \rho_o)$ except in the buoyancy term we obtain for the conservation of mass

$$c_1 \frac{d}{dz} \left[b^2 \rho \omega\right] = \alpha b \omega \rho_o \qquad (1)$$

where c_1 is a constant dependent on the choice of horizontal distribution, "top hat", Gaussian etc, b is the effective radius of the plume and "ω" is the vertical velocity..

The momentum equation is

$$c_2 \frac{d}{dz} (b^2 \rho \omega^2) = g b^2 \Delta\rho \qquad (2)$$

where $\Delta\rho = \rho_o - \rho$, g is the acceleration due to gravity and c_2 is another constant. The conservation of heat is

$$c_3 c_p \theta \rho b^2 = Q \qquad (3)$$

where c_3 is a third constant.

c_1, c_2 and c_3 are obtained from various integrals of the Gaussian or "top hat" distributions. Allowance can be made for a different scale for velocity "ω" and temperature rise θ. These equations lead, for the flow a long way from the source, to

$$\frac{g\theta}{T_o} = c_5 \left[\frac{gQ}{\rho_o c_p T_o}\right]^{2/3} \cdot \frac{1}{z^{5/3}}, \qquad (4)$$

and

$$\omega = c_6 \left[\frac{gQ}{\rho_o c_p T_o}\right]^{1/3} \frac{1}{z^{1/3}} \qquad (5)$$

where g is the acceleration due to gravity

T_o is the ambient absolute temperature

ρ_o the uniform density

c_p is the specific heat of the fluid at constant pressure

Q is the rate of heat release
z is the height above the virtual source.

The constants of proportionality depend on the choice of distribution and on α. In practice they are used to define "α".

The question arises as to what is the correction for "strong" plumes i.e. where one allows for the different density in all terms.

Thomas et al. (1) used ρ instead of ρ_0 in the denominator of $\frac{gQ}{\rho_0 c_p T_0}$ and in the term for mass $m' = \frac{Q'}{c_p \theta}$. This leads to terms in $\left[1 + \theta/T_0\right]^{1/3}$ or $\left[1 + \theta/T_0\right]^{2/3}$ but more recent considerations suggest other forms with a better theoretical basis.

1.4 The weak and strong axi–symmetrical plume

Morton (8) considered both strong and weak axi–symmetric plumes in terms of the simplification of the "top hat" profile and, following Thomas (9) using Ricou and Spalding's (10) analysis (see below), proposed

$$\alpha = \alpha_0 \sqrt{\rho/\rho_0} \qquad (6)$$

With this equation and the substitution of $B = b\sqrt{\rho/\rho_0}$ and values of c_1, c_2 and c_3 appropriate to a "top hat" profile, equations (1), (2) and (3) become

$$c_1 \frac{d}{dz}(B^2 \rho_0 \omega) = \alpha_0 B \omega \rho_0 \qquad (7)$$

$$c_2 \frac{d}{dz}(B^2 \rho_0 \omega^2) = gB^2 \frac{\Delta\rho}{\rho} = gB^2 \theta/T_0 \qquad (8)$$

$$c_4 c_p \theta \rho_0 \omega B^2 = Q \qquad (9)$$

and $\rho\theta = \rho_0 T_0$

These are the equations for the weak plume with "b" replaced by $b\sqrt{\rho/\rho_0}$.

The conventional assumptions are made, viz. no effective pressure differences and negligible vertical diffusion[1].

Workers at the Factory Mutual Research Corporation have published three papers (11), (12) and (13) claiming θ/T_0 gives a better correlation of data[2] than does θ/T.

1.5 Some problems

We note that the mathematical transformation is not possible if the distribution is not the simple "top hat" form. The assumption of Gaussian distribution is however arbitrary, based on an empirical description of a bell shaped distribution which is clearly nearly Gaussian, but only a more detailed analysis can discuss this aspect of plumes.

We now need to consider line plumes and further problems arise. We first reconsider the derivation of equation (6). Ricou and Spalding (10) correlated experiments on jets where there were significant density differences between ρ of the injected fluid and ρ_0 of its ambient surroundings. They gave the following equation

$$\frac{dm}{dz} = K(M\rho_0)^{1/2} \qquad (10)$$

where m is the mass flux, M the momentum flux and K is dimensionless.

Thomas wrote dm/dz as proportional to $\alpha b\omega\rho_0$ *and M as proportional to* $\rho\omega^2 b^2$ and deduced equation (6). However similar experiments have not been done for 2–dimensional plumes and jets for which m and M cannot be the relevant quantities; these are the values for unit length i.e. m', M' respectively. It is not clear how to adapt equation (10) to include m' and M' and retain a

---

[1]This is in effect the "free boundary layer" approximation and depends on the flow being predominantly vertical. It begins to fail when there is significant necking or expansion near a finite source.

[2]With no doubt an additional comment by the Bellman.

dimensionless quantity! Perhaps equation (6) is the more fundamental. But if it is there are further problems with line plumes.

One is that in principle, the inflow into an ideal (infinite) plume is constant at all distances from the plume to infinity and presumably subject to disturbances a long way from the plume. A second is as follows.

Recasting equations (1), (2) and (3) with b instead of b^2 (and different but constant values for c_1, c_2 etc and Q replaced by Q' i.e. the rate of thermal energy release per unit length of line), cannot exploit any variation of Morton's transformation with $\alpha = \alpha_0\sqrt{\rho/\rho_0}$. Only if α = constant can such a transformation be made, viz

$$b' = b\rho/\rho_0 \tag{11}$$

However, as yet, line plumes have only been discussed in terms of a constant α and we are now forced to examine the theory of line plumes in the light of above comments.

1.6 The Lee and Emmons line and strip plume theory

Lee and Emmons, (11) on whose work Morgan and Marshall (5) based their analysis, wrote their equations in term of buoyancy deficiency, not convected heat. This leads to their results being given in terms of $\frac{\Delta\gamma}{\gamma_0} = \frac{\Delta\rho}{\rho_0}$ (γ being specific weight = $g\rho$) which Morgan and Marshall replaced by $\frac{\theta}{T_0+\theta}$. Treating the denominator T as different from T_0 may be a better approximation than earlier ones but is not justified by appeal to Lee and Emmons because they assumed $\rho=\rho_0$ in all terms other than in buoyancy, the driving force for line plume. Consider a "top hat" strong line plume with constant α.

$$2\frac{d}{dz}(b\omega\rho) = 2\alpha_0\omega\rho_0 \tag{12}$$

$$2\frac{d}{dz}(b\omega^2\rho) = 2g\Delta\rho b \tag{13}$$

and $$2c_p\rho\theta\omega b = Q' \tag{14}$$

The use of equation (11) gives

$$\frac{d}{dz}(b'\omega) = \alpha_0 \omega \quad (15)$$

$$\frac{d}{dz}(b'\omega^2 \rho_0) = g\frac{\Delta\rho}{\rho} \cdot \rho_0 b' \quad (16)$$

and $$c_p \cdot \theta \rho_0 \omega b' = Q' \quad (17)$$

where $\Delta\rho$ appears as $\frac{\Delta\rho}{\rho} = \frac{\theta}{T_0}$

The Gaussian distribution can be accommodated by <u>assuming</u> ω and θ are Gaussian in a transformed horizontal scale $\psi = \int_0^r \rho dr/\rho_0$.

$$\text{viz.}\ \theta \ \alpha \ \exp \left[- \int_0^r \rho dr\right]^2 / b^2 \lambda \rho_0 \quad (18i)$$

$$\text{and} \ \ \omega \ \alpha \ \exp \left[- \int_0^r \rho dr\right]^2 / b^2 \rho_0 \quad (18ii)$$

Attempting to allow for the distinction between ρ and ρ_0 requires an analysis beyond that of simple plume theory and the assumptions as to the nature of the profile which may be related to a transformed horizontal scale. Clearly one must appeal to experiments or perhaps numerical modelling.

2 <u>Flow out of openings.</u>

2.1 The use of plume and hydraulic theory for enclosure fires.

We use "weak" plume theory and allow for the flow into and out of an opening in ways appropriate to shallow layers or deep layers; intermediate layers must be dealt with by the method of Prahl and Emmons (15). We also write

$$Q'_e = m' c_p \theta \quad (19)$$

when Q'_e refers to the flow of convected heat leaving unit width of opening at a temperature rise of θ and mass flow m' for unit width.

The results are shown in Fig.1 for the three configurations shown in Fig.2. In addition Thomas (16) has shown that the power law formulae of McCaffrey and Quintiere (17) can be written, within the limits of data as

$$\frac{m'}{H\left[\frac{gQ'_e}{\rho_o c_p T_o}\right]^{1/3}} = 0.15 \pm 0.04$$

Note we have removed the dependence on heat transfer but Q' is here Q'_e the net energy leaving the opening (see also 2.3).

2.2 Numerical Modelling

The above "zone" modelling of flows ought to be subject to computational analysis (by "field" modelling). That it has not been is perhaps one reason for the present difficulties. One relevant analysis has however been made by Blay, Turhault and Jourbert (18) allowing for temperature dependent density (in all terms). They analysed the two-dimensional system shown in Fig.3.

and studied 3 conditions without heat loss ($\dot{Q}' = \dot{Q}'_e$)

1. $Q' = 10$ kW/m, $H = 0.25$ m
2. $Q' = 200$ kW/m, $H = 2.5$ m
3. $Q' = 400$ kW/m, $H = 2.5$ m

and wrote that the results followed scaling laws

(a) $\theta \; \alpha \; (Q'^4 H^{-6})^{1/5}$

(The $-1/5$ in their paper is clearly a misprint.)

b) $V \; \alpha \; Q'^{2/5} H^{-1/10}$ in the hot zone

and c) $V \; \alpha \; (Q'H)^{1/5}$ in the cold zone

where V is velocity.

The "expected" θ (for weak plumes) scales as $\left[\frac{Q'^4}{H^6}\right]^{1/6}$ so the larger this is the greater the ratio of the θ calculated by Blay et al. to the conventional θ.

In the expression $\dfrac{m'}{H\left[\frac{gQ'}{\rho_o c_p T_o}\right]^{1/3}}$

we substitute $\frac{Q'}{c_p\theta}$ for m' and θ is proportional to $\left[\frac{Q'}{H^{3/2}}\right]^{4/5}$. The expression is then proportional to $\theta^{-1/6}$ and curves of this form, matched to others at $\theta/T_o = 1$ are shown in Fig. 1.

2.3 Summary of Comments on Enclosure fires.

The flow out of wide openings can be described by

$$\frac{m'}{H\left[\frac{gQ'}{\rho_o c_p T_o}\right]^{1/3}} = \frac{m}{HL^{2/3}\left[\frac{gQ}{\rho_o c_p T_o}\right]^{1/3}} = \kappa \qquad (26)$$

where κ is a weak decreasing function of temperature. The approximate method of interpreting the McCaffrey–Quintiere regression makes "κ" a weak increasing one but this is probably due to the limitations imposed on the treatment of the heat loss term, which is described elsewhere (16). The treatments given of the various equations for enclosure flows, supported by the numerical analysis of Blay, Turhault and Jourbert suggest that data should be examined by evaluating "κ" and examining its variation with window and compartment geometry, and perhaps the geometry of the position and size of the fire, and the hot layer temperature.

The relation above is the basis for combining a 2 and 3 dimensional plume (19) avoiding calculation of edge effects. Thus:

$$m = \gamma \cdot Q^{1/3}(L+\mu z)^{2/3} z \qquad (27)$$

reduces to the axi–symmetric plume equation for $\frac{z}{L} >> 1$ and for the line plume when $\frac{z}{L} << 1$. The two constants γ and μ are determined by these limits which are correctly described and so can be used as a first approximation for intermediate situations (z can be adjusted to accommodate a virtual source if so desired).

3. The Equivalent Gaussian Source

For a plume with velocity decreasing asymptotically to infinity away from the axis the term "b" is characteristic of its width. However there is a real average temperature defined by flow and heat. For a "top hat" profile the average and maximum temperatures are the same but for the Gaussian distribution they are not. Since a plume maximum temperature cannot rise when the distribution changes from a "top hat" to a Gaussian distribution as it must when emerging from a nozzle or slit or from a layer burning around a corner there must be a drop in the average temperature and if thermal energy is to be conserved in the model of the flow the mass must be increased. The ratio of average to maximum temperature in the Gaussian flow of Lee and Emmons is about 2/3 so there must be an apparent entrainment of about 50% when the "top hat" profile becomes a Gaussian flow.

An Equivalent Gaussian Source can be provided which matches a "top hat" profile in mass as well as heat and momentum but then its peak temperature must be presumed to be higher and it is in effect "fictitious". The real temperatures will necessarily be less. This is clearly an area where experimental study and numerical analysis are overdue.

4. A Paradox

Lastly we consider what might happen if a plume is disturbed along its vertical axis. Conventional plume theory treats the local horizontal velocity as proportional to the local vertical velocity which for a line source is constant in the far field. If such a plume were interrupted by, say, a horizontal insulated wire grid which did not deflect the central axis there would necessarily be a loss of vertical momentum and velocity and so of entrainment. The lesser dilution implies that the temperature at some level above the disturbance in the new far field would be raised! Does this happen? Are the conventional assumptions governing mean values, similarity, neglect of pressure etc sufficiently robust to describe this relatively simple effect?

5. Conclusion

Several details concerning the application of plume theory have been discussed though some have more relevance to the interpretation and correlation of validating experimental data. Perhaps the most important points concern the distortion of simple scaling by the secondary effects of rises in temperature.

The calculation by Blay et al. confirms that the discrepancy between actual temperature and temperature rise predicted from conventional scaling laws rises as temperature rises. So does the use of $\theta/(T_0+\theta)$ instead of θ/T_0, but whether the latter is a fortuitous expression of the first effect is not clear. If it is, it should be recognized as such (requiring further numerical calculations) and not treated as a corollary of the Lee and Emmons theory which it is not.

Little has been written here about the conditions for finite sources where mass and momentum flows do not match as in the far field so that the plume initially necks or expands. The remarks about similarity however are apposite since a flame is not Gaussian near its base but has a biomodal distribution. The remarks about the fluctuating component of energy and momentum are also apposite, especially in connection with the interface between a plume and a layer. It is hoped that in these notes there has been enough comment and exposition to demonstrate some of the limitations within which engineering analyses for plumes applies.

There is clearly scope for some more experimental work and numerical analysis.

6. Acknowledgement.

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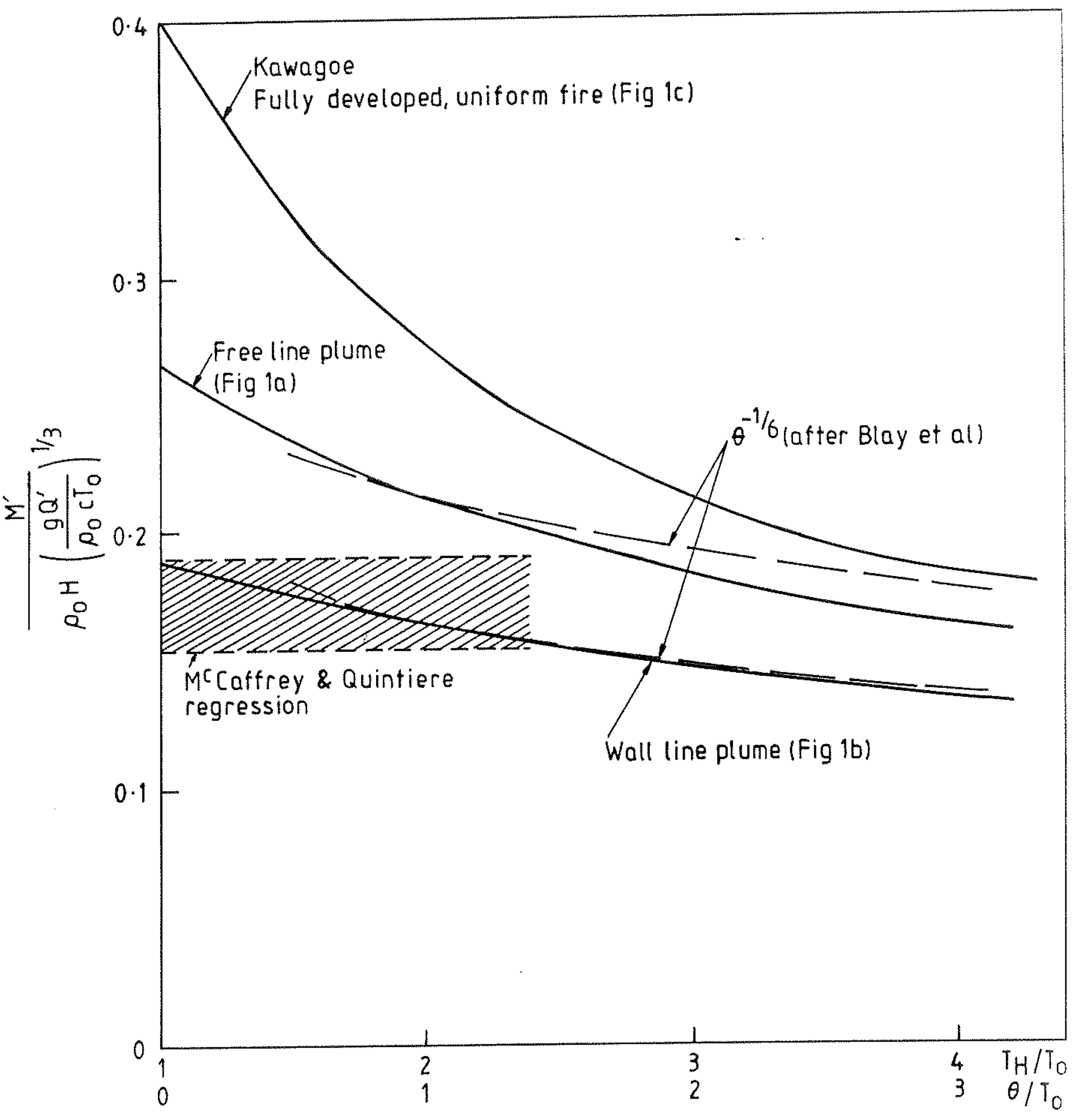
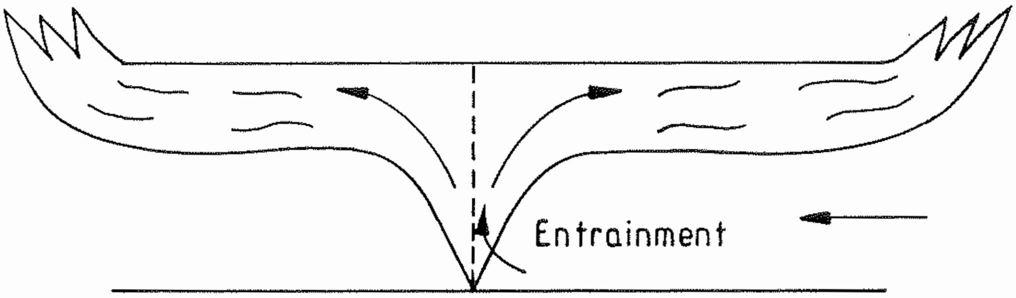
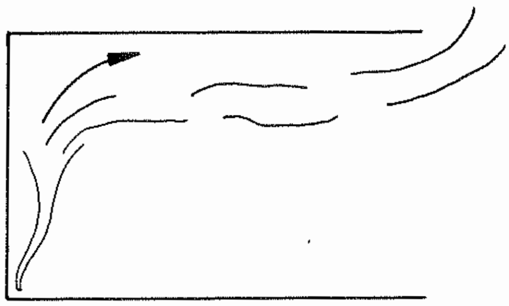


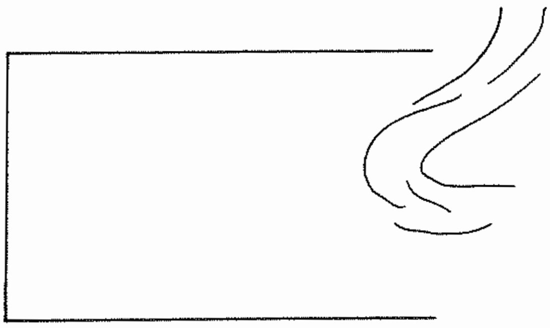
Figure 1 Comparison of types of flow out of compartments



(a) Line plume at plane of symmetry



(b) Line source at base of wall



(c) Fully developed fire (following Kawagoe's model)

Fig 2 Configurations of flow from openings

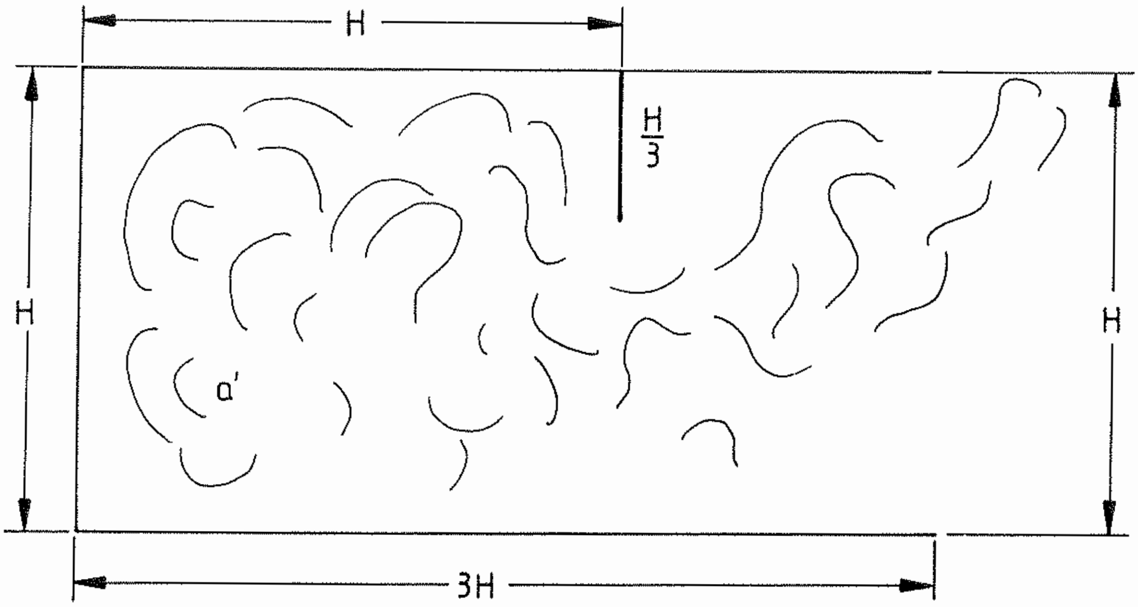


Figure 3 The scenario of Blay, Turhault & Joubert

FURTHER COMMENTS ON THE FLOW OF GASES FROM VERTICAL OPENINGS WITHIN SHOPPING MALLS.

Morgan and Hansell (1) conclude their April comment on Law's (2) February comment on Gardner's (3) paper with the result that the fire power Q_f necessary to produce flashover in a room of height "H" (with wide openings) depends on H as

$$Q_f \; \alpha \; H^{2.4}$$

They say the result for an "ideal" case is $Q_f \; \alpha \; H^3$.

McCaffrey et at. (4) employ 600°C temperature rise as a criterion of flashover. This is not far in excess of temperature rises typical of flames reaching the smoke layer in the upper part of the space so if one recalls correlations of vertical flame heigth "L" with firepower Q these results are easily understood. Thus McCaffrey (5) derived

$$L \; \alpha \; Q^{0.4} \qquad (1)$$

so for $\frac{L}{H} \approx 0(1)$ at flashover

$$Q_f \; \alpha \; H^{2.5}$$

Thomas's (6) correlation can be rewritten as

$$\frac{L}{P} \; \alpha \; \left[\frac{Q^2}{P^5}\right]^{0.3} \qquad (2)$$

where the original D – a linear dimension characteristic of fire area – is here replaced by P the perimeter to which it is proportional for a given shape of flame base.

For $\frac{L}{H} \approx 0(1)$ we have[1]

$$Q_f \ \alpha \ P^{0.85} \ H^{1.65} \qquad (3)$$

and if one were to write $P \alpha Q^{1/2}$ one would obtain

$$Q_f \ \alpha \ H^{2.9}$$

These relationships are independent of compartment dimension or window width provided the size of the flames is determined by entrainment unimpeded by the window. The criterion of flames reaching half way, or all the way, up to the ceiling is on the safe side of a flashover criterion and expresses conditions near to it.

Morgan and Hansell (1) contrast in detail McCaffrey et al.'s regression equation, which Law (2) pointed out as more appropriate for narrow openings, with Babrauskas's (7) equation based on much of the same data[2].

A comparison between those equations and others has been made by Thomas (8) from which it appears that not too much significance should be attached to their different forms. There are reservations to the use of all such equations, inside as well as outside the range of the experimental data, many of them mentioned by Morgan and Hansell. There is rather less significance to their phrase "a quite different function" than might be inferred especially in view on the restriction or $Aw/A\sqrt{H}$ to less than 2000, as will be seen from Thomas's graphical representation in reference (8).

It should be noted generally that two equations

$$y = Ax_1^n x_2^m$$

and $$y = C + Dx_1 + Ex_2$$

---

[1]The indices 1.65 and 0.85 add up to 2.5 because the origin of equations (1) and (2) is dimensionless. The index in equation (2) was obtained from statistical analysis as 0.31. Had it been 0.33 equation (3) would have been the familiar $Q \alpha PH^{3/2}$.

[2]There are some misprints in the form quoted. If Q is in kw both coefficients are too small by 1000.

both have three disposable constants and can fit the same data in limited ranges of x_1 and x_2 according to how much scatter one accepts in the representations of the data.

It is possible to rewrite the regression of McCaffrey et al. in terms appropriate to wide openings. If, then, Q'_{ex} the convected energy emerging per unit width is used instead of the energy Q' emitted inside per unit width of openings, one can show that the heat loss term has little influence on the expression

$$\frac{m'}{\rho_o H \left[\dfrac{g Q'_{ex}}{\rho_o c_p T_o} \right]^{1/3}}$$

The heat loss referred to and expressed in the McCaffrey et al. regression refers to a uniform temperature. One needs simple procedures for dealing with the horizontal temperature gradiants due to loss to the ceiling in three dimensional flow and one would have to lean heavily on the criterion of flashover as a criterion of hazard and on the assumptions of a uniform depth of layer and of motion predominately in one direction.

Perhaps, in view of these problems, one could regard the decisive condition for the outset of the hazards of flashover as flames reaching the smoke layer, or say H/2 because it is likely to be a necessary condition for flashover (and a conservative one). For small compartments it is little different from the criterion of flashover itself. For large compartments it introduces – as it perhaps should – a factor of safety.

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SOME COMMENTS ON RECENT CALCULATIONS AND DATA ON VOID-SCREEN DEPTHS

The data presented by Morgan and Marshall (1) in the March issue of the Journal supplement those published earlier by Marshall (2) and have attracted comment by Hansell (3): they deserve further comments. Their Fig (5) shows the variation of Δd_w – the difference between the hot gas layer depths "d_w" and "d_m", respectively near and farther from the fire – and "d_m" itself. Standard deviations are quoted but it is not clear whether the statistical analysis accommodates the special features of such a presentation in which the variations in the two quantities themselves are likely to be correlated. The same uncertainty also applies to Hansell's (3) analysis. In Marshall's correlation the mall width W and the exit width W_{ex} were the same but they are different for the new data.

Fig (1) shows the original measured quantities "d_w" and "d_m" against "W_{ex}". The small negligible difference in "d_w" between data for shop widths "W_{sh}" equal to 7.5 and 5 m (scaled up size) is 0.08 m but, allowing for this reduces the scatter in the data for "d_w" and makes the departure of the data for Test 13 more obvious. There is a smaller effect on "d_m" but data from Test 13 and Test 14 depart noticeably from the general trend.

The scaling requires equality of $Q/S^{5/2}$ where Q is fire power and S a dimension characterizing the scale eg. mall height "H". In the range considered Q (i.e. $Q/S^{5/2}$) did not significantly affect the relationship between "d_w" and "d_m". So the scaling presumably takes the simplified form

$$\frac{\Delta d_w}{S} = F\left[\frac{d_m}{S} \cdot \frac{W}{S} \cdot \frac{W_{ex}}{S} \cdot \frac{W_{sh}}{S} \ldots\right] \qquad (1)$$

where F means "a function of".

Any other geometric ratios would also be included in F. Following Morgan and Marshall's implication that "d_m" incorporates all the effect of W_{ex} and treating the small effect of W_{sh} as negligible, we have

1. $$\frac{\Delta d_w}{S} = F_2 \left[\frac{d_m}{S} \cdot \frac{W}{S}\right] \qquad (2)$$

where F_2 is another functional relationship.

It is such a relation which has presumably been used to scale up the small scale experimental data to a 5 m high mall. Morgan and Marshall observe "that it is not generally true that Δd_w is independent of the mall width ... but only that it is true for one particular geometry". This is correct so long as "geometry" includes size as well as shape; but the data are presented without reference to the 5 m height and this it would seem needs to be explicit. Whilst d_w and d_m may be independent of height "H" for shallow layers one must entertain the possibility that there is a physical dependence for thick layers approaching half the mall height.

Hansell describes the data by

$$\Delta d_w = \frac{2}{\mathrm{Ln} W}(1 - \mathrm{Ln} d_m) \qquad (3)$$

which we rewrite as

$$N = \frac{(\mathrm{Ln}\frac{W}{S} + \mathrm{Ln}\,S)S}{1 - \mathrm{Ln}\frac{d_m}{S} - \mathrm{Ln}S} \cdot \frac{\Delta d_w}{S} \qquad (4)$$

where in equation (3) N is 2, but here must be regarded as possibly depending on S. For given values of $\frac{\Delta d_w}{S}$, $\frac{W}{S}$ and $\frac{d_m}{S}$ we obtain from equation (4)

$$\frac{dN}{dS} = \frac{N}{S}\left[1 + \frac{1}{\mathrm{Ln}W} + \frac{1}{1 - \mathrm{Ln}d_m}\right]$$

So for W ~ 7.5 m and δ_m ~ 5 m (roughly mid–values of the data)

$$\frac{dN}{N} \approx 3.1 \frac{dS}{S}$$

i.e. a small change in S produces a three times larger change in N for given dimensionless ratios. The constant 2 is not independent scale and maybe rather sensitive to it.

A general equation of the type of equation (2) above can express relationships between d_w and d_m which are independent of scale but for that they would need to be proportional to each other. This they are not and one must treat extrapolation with caution.

REFERENCES

(1) MORGAN H.P. and MARSHALL N.R., The Depth of Void Edge Screens in Shopping Malls, Fire Engineers Journal 48 (152), 1989, p.7

(2) MARSHALL N.R., Smoke Control in Shopping Malls, Fire Surveyor 14 (1), 1985, p.15

(3) HANSELL G.O., Comment on reference (1) above, idem, p.9.

Fig.1 d_w and d_m against independant variable W_{exit}

[Three points raised by 0.05 to normalize effect of shop width]