The Effect of a Sprinkler on the Stability of a Smoke Layer beneath a Ceiling

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A study has been made of the effect of sprinkler sprays on hot buoyant smoke layers with particular reference to covered shopping malls.

THE HAZARDS of smoke spread in enclosed shopping complexes have been considered in previous reports.[1,2,3,4] Experimental and theoretical studies of the behavior of smoke in such complexes have shown that it is not usually practicable to prevent the spread of smoke from a fire in a shop into the adjoining mall. However, this work has also shown that the smoke flowing into the mall almost always forms a stratified layer beneath the ceiling. By subdividing the mall into smoke reservoirs and extracting from them either by natural or mechanical ventilation, it is possible to keep the lower level of the mall relatively smoke-free and to prevent smoke travel over long distances. If the layer is disturbed or allowed to cool too much, mixing with the cooler air beneath may occur. This can produce extensive smoke logging and reduce the effectiveness of the extraction system; escape and fire fighting will be hindered.

It is normal practice in the United Kingdom at present to fit automatic sprinklers to all parts of enclosed shopping complexes, including the malls. Although sprinklers will substantially reduce the hazard if combustible materials are present in the malls, there appears to be a danger that, in some cases, the downward flow of water through the smoke could overcome the stratification of the layer and cause smoke logging. Thus, where malls are kept clear of combustibles and serve only for access so that the sprinklers do not have to contend with a fire originating within the mall, there might be a danger that their installation would increase the hazard to the occupants.

Smoke logging caused by sprinklers has been noted in a number of tests at the Fire Research Station and elsewhere. In some experimental car-park fires in Berne, Basel, and Geneva,[5] conditions in the test areas were fairly clear initially. However, in all the test series, severe smoke logging at low levels occurred rapidly when sprinklers were operated. The value of sprinklers acting on the burning material and reducing the quantity of smoke produced at the seat of the fire was shown in the *Operation School Burning* tests[6] carried out by the Los Angeles Fire Department in schools awaiting demolition. Although the interaction between the sprinkler spray and hot smoke layer away from the fire was not considered in detail, it was noted in Test J4 that "Operation of sprinklers drove smoke to floors and resulted in the generation of steam." In most tests, the corridor became untenable (based on optical density and temperature measurements) before any sprinklers operated or before vents opened, and in these cases, any further deterioration caused by the sprinklers would not necessarily be noted and would not necessarily be relevant to the purpose of the experiments. The report makes it clear that sprinklers in the corridors did not assist in smoke clearance, e.g., in Test C2 "smoke did not clear even though five heads ultimately were operating," and in Test D2 "untenable smoke conditions did not clear even though eight sprinklers were operating."

Preliminary tests in the large-scale experimental mall at the Fire Research Station showed that, under some conditions, the smoke layer could be brought down by a manually operated sprinkler spray, smoke logging then occurring rapidly, with a high smoke density at low level. However, under other conditions, the smoke layer was not disturbed by a sprinkler spray. It is, therefore, important to know what affects the likelihood of smoke logging happening in this situation.

A theory to model the interaction of the sprinkler discharge and hot smoke layer is described in this report and is shown to be in satisfactory agreement with the results of experiments. The practical implications of this work are discussed.

THEORY

Consider the vertical velocity component of a spherical water drop falling in air (Figure 1a). The drop will be subject to a drag force $D(x)$,* given by[7]

$$D(x) = -kv^2 \text{ (assuming turbulent drag)}$$

where $k = C_D \cdot \frac{1}{2} \rho_a A$, C_D being a constant. In practice, C_D is a function of the Reynolds Number based on the drop diameter $\left(\frac{\rho_a d v}{\mu_a}\right)$. In this analysis, C_D is assumed not to vary with displacement x (and hence velocity). The form of the relationship of C_D with Reynolds Number is considered in detail elsewhere.[8] In a turbulent flow situation (which occurs fairly soon after starting from rest for a drop of the size occurring here), C_D becomes insensitive to changes in velocity. The variation of C_D with drop diameter

*See List of Nomenclature on page 34.

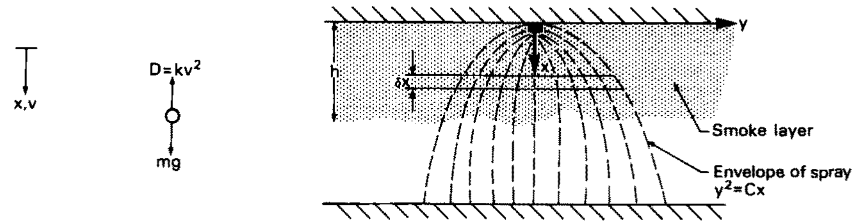

Figure 1. a (left), Motion of a spherical drop falling vertically under gravity, and b (right), sprinkler discharge through the hot layer.

is allowed for in the analysis. The equation of motion of the drop is thus:

$$mg - kv^2 = m\frac{dv}{dt} = mv\frac{dv}{dx}$$

It is assumed that the initial vertical momentum of the water leaving the sprinkler is destroyed by the striker plate, so that the initial vertical velocity component of the drop is zero. This assumption is thought to be reasonable, although the author is unaware of any workers who have investigated this. The solution to the differential equation of motion is thus

$$v^2 = \frac{mg}{k}\left\{1 - \exp\left(\frac{-2kx}{m}\right)\right\} \tag{1}$$

The downthrust on the hot layer is given by the sum of the drag forces on all the drops if all the momentum is assumed to be transferred parallel to the direction of motion of the drops.

The number of drops in an element of the layer (Figure 1b) is equal to

$$\frac{\text{water mass flow rate} \times \delta x}{\text{mass of 1 drop} \times v}$$

$$= \frac{\dot{M}\ \delta x}{mv}$$

The drag exerted on one drop as it falls through the layer is

$$\int_o^h D(x)\,.\,dx$$

and the total drag (D) exerted on all the drops is

$$D = \frac{\dot{M}k}{m}\int_o^h v\,dx,\ \text{for constant } \dot{M},\ k,\ m.$$

Substituting from (1)

$$D = \dot{M}\left(\frac{kg}{m}\right)^{\frac{1}{2}}\int_o^h 1 - \exp\left(-\frac{2kx}{m}\right)^{\frac{1}{2}} dx$$

This can be solved by a substitution of the form:

$$Z^2 = 1 - \exp\left(-\frac{2kx}{m}\right)$$

giving the drag force

$$D = \dot{M}\left(\frac{mg}{k}\right)^{\frac{1}{2}}\left[\frac{1}{2}\, ln\left[\frac{1 + \left\{1 - \exp\left(-\frac{2kh}{m}\right)\right\}^{\frac{1}{2}}}{1 - \left\{1 - \exp\left(-\frac{2kh}{m}\right)\right\}^{\frac{1}{2}}}\right] - \left\{1 - \exp\left(-\frac{2kh}{m}\right)\right\}^{\frac{1}{2}}\right] \quad (2)$$

The downward drag force on the layer will be countered by the upward buoyancy force. Considering the volume of gas through which the discharge of the sprinkler passes and assuming a parabolic envelope containing hot smoke at a constant temperature,

$$\text{Buoyancy force } B = (\rho_o - \rho)g \cdot \text{Volume}$$

The volume of revolution of a parabola is given by (Figure 1b)

$$\text{Volume} = \int_o^h \pi y^2 \, dx$$

and $y^2 = Cx$, where C is a constant

$$\therefore \text{ Volume} = \frac{\pi C h^2}{2}$$

Manufacturers' data and experimental observations indicate that the wetted area at 3 m below the ceiling level is a circle of approximate radius 3 m.

$$\therefore C = 3m$$

and thus

$$\text{Volume} = \frac{3\pi h^2}{2} \qquad \text{m}^3$$

the buoyancy force is

$$B = \frac{3}{2}(\rho_o - \rho)\, g\, \pi\, h^2$$

$$= \frac{3}{2}\pi\, g\, \frac{\rho_o}{T}\, \theta\, h^2 \qquad \text{N} \quad (3)$$

Combining Equations 2 and 3 gives a criterion for the breakup of the hot layer; i.e., the layer will be pulled down if $D > B$

i.e.,
$$\dot{M}\left(\frac{mg}{k}\right)^{\frac{1}{2}}\left[\tfrac{1}{2}\,ln\left[\frac{1+\left\{1-\exp\left(-\frac{2kh}{m}\right)\right\}^{\frac{1}{2}}}{1-\left\{1-\exp\left(-\frac{2kh}{m}\right)\right\}^{\frac{1}{2}}}\right] - \left\{1-\exp\left(-\frac{2kh}{m}\right)\right\}^{\frac{1}{2}}\right] > \frac{3}{2}\pi g\,\frac{\rho_o}{T}\,\theta\,h^2$$

or

$$\frac{D}{B} = \frac{2}{3\,\rho_o\,\pi g^{\frac{1}{2}}}\;\frac{\dot{M}T}{\theta\,h^2}\left(\frac{m}{k}\right)^{\frac{1}{2}}\left[\tfrac{1}{2}\,ln\left[\frac{1+\left\{1-\exp\left(-\frac{2kh}{m}\right)\right\}^{\frac{1}{2}}}{1-\left\{1-\exp\left(-\frac{2kh}{m}\right)\right\}^{\frac{1}{2}}}\right] - \left\{1-\exp\left(-\frac{2kh}{m}\right)\right\}^{\frac{1}{2}}\right] > 1 \qquad (4)$$

RESULTS

In order to obtain values of the drag/buoyancy (D/B) ratio, the discharge characteristics of the sprinkler must be considered.

The mass flow rate through the sprinkler is

$\dot{M}$ = water density × nozzle area × discharge coefficient × ideal velocity

$$= \rho_w \cdot \text{Area} \cdot C_d\left(\frac{2\,p_w}{\rho_w}\right)^{\frac{1}{2}}$$

For the sprinkler used in the large-scale tests (15 mm nominal, spray type)

$$\dot{M} = 3.29 \times 10^{-3}\,p_w^{\frac{1}{2}}\ \text{kg s}^{-1} \qquad (p_w \text{ in Nm}^{-2}) \qquad (5)$$

k/m is given by

$$\frac{k}{m} = \frac{C_D \cdot \tfrac{1}{8}\,\rho_a\,\pi d_w^2}{\frac{1}{6}\,d_w^3\,\rho_w} \qquad (6)$$

$$\frac{3\,\rho_o\,T_o\,C_D}{4\,\rho_w\,d_w\,T}$$

Since the drag coefficient, C_D, is a function of Reynolds Number based on drop diameter, for any given drop size C_D varies with velocity, which itself is a function of height (and of C_D). A mean value of C_D for each drop size was found by successive approximation. For drop sizes in the range 0.3 to 2.6 mm the mean value of C_D in this situation was calculated and found to be given by the approximate empirical relation

$$C_D = \frac{-\ln d_w - 4.6}{3.1} \qquad (d_w \text{ in meters}) \qquad (7)$$

The variation of C_D with temperature is smaller than the variation with drop size and has been neglected here.

The sprinkler produces a range of drop sizes. Information on the drop size distribution for a half-inch upright sprinkler is given in a paper by Yao and Kalelkar,[9] and a weight distribution graph is reproduced in Figure 2.

The D/B ratios were evaluated by dividing the drop distribution into 10 percent weight ranges. The drag contribution of the mean drop size in each of the ten weight ranges was evaluated and added to give the total drag, i.e.,

$$\frac{D}{B} = \frac{0.2\,\dot{M}T}{3\,\rho_o\,g^{\frac{1}{2}}\,\pi\,\theta\,h^2} \sum_{i=1}^{10} \left(\frac{m_i}{k_i}\right)^{\frac{1}{2}} \left[\tfrac{1}{2} \ln \left[\frac{1 + \left\{1 - \exp\left(-\frac{2kh}{m_i}\right)\right\}^{\frac{1}{2}}}{1 - \left\{1 - \exp\left(-\frac{2k_ih}{m_i}\right)\right\}^{\frac{1}{2}}} \right] - \left\{1 - \exp\left(-\frac{2k_ih}{m_i}\right)\right\}^{\frac{1}{2}} \right] \qquad (8)$$

Thus combining Equations 5, 6, 7, and 8, the D/B ratios for different values of p_w, θ, and h were calculated. Ambient temperature was taken as 288° K, and ambient density, 1.25 kg m^{-3}.

Figures 3–6 show the relationship between the drag/buoyancy force ratio and the temperature of the hot layer for various values of layer depth and for four water pressures in the range 70 kN m^{-2} (10 psi) to 830 kN m^{-2} (120 psi). An alternative presentation of the data is given in Figure 7, where the critical temperature θ_c, defined as the layer temperature when the drag and buoyancy forces are equal, is plotted against layer depth for the four values of water pressure. Although the information available from this graph is limited, it gives an indication of whether the drag is greater or less than the buoyancy for given conditions of temperature, layer depth, and water pressure.

If further D/B values are required, a reasonable agreement (D/B within 15 percent of the results given here) is obtained by substituting an average

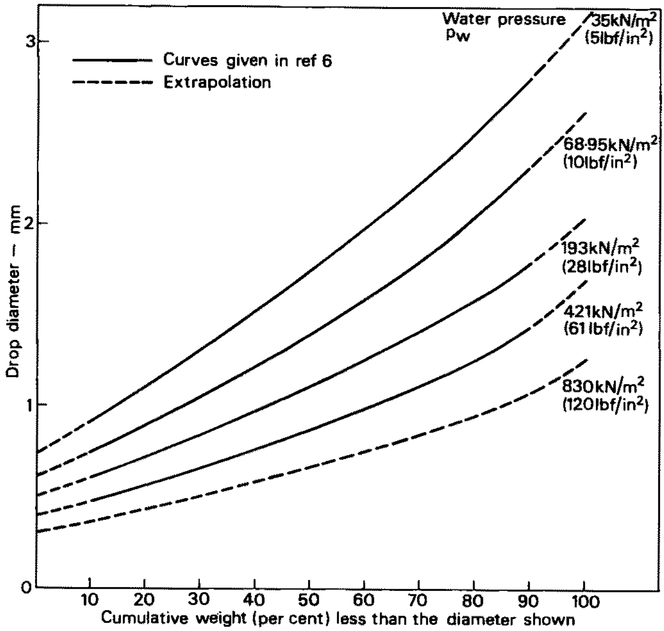

Figure 2. Drop size distribution curves for a half-inch upright sprinkler.[6]

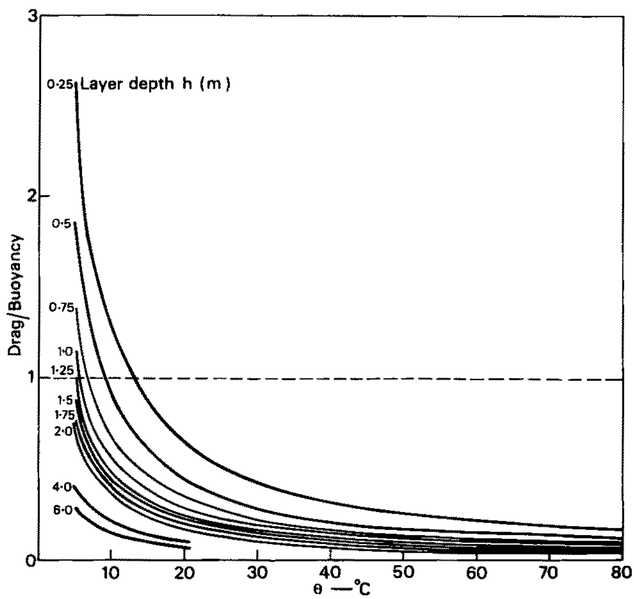

Figure 3. Drag/buoyancy ratio against gas temperature rise, sprinkler pressure 69 kN m $^{-2}$ (10 psi).

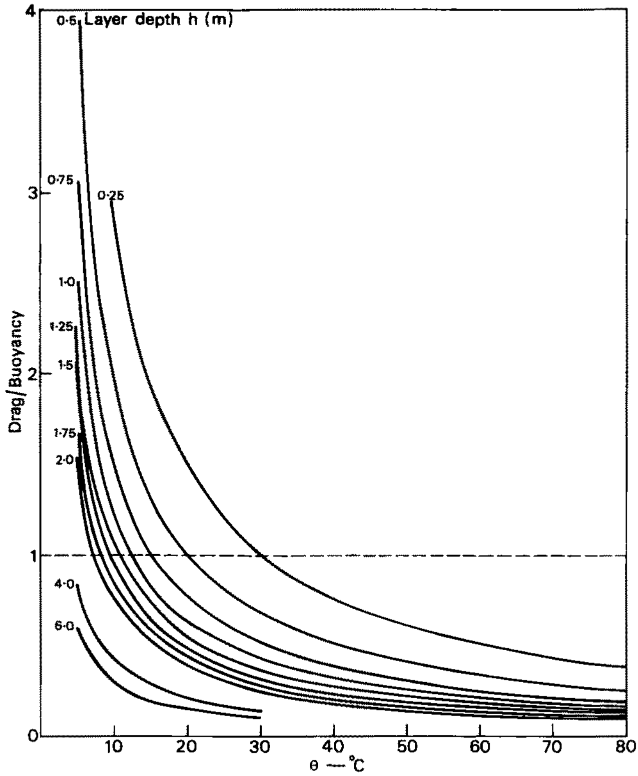

Figure 4. Drag/buoyancy ratio against gas temperature rise, sprinkler pressure 193 kN m $^{-2}$ *(28 psi).*

drop diameter in Equation 4. Since the drop diameters in the spray have a skewed distribution, it is difficult to decide which of the possible average values is most meaningful. Although the mass median diameter is often used in this context, it was found that, in this case, the arithmetic mean of mean drop diameters in each decile of the distribution gave results closest to those given here. For water pressures in the range 70 to 830 kN m^{-2}, the mean drop diameter is a function of the water pressure and from the data in Figure 2 is given approximately by the relation

$$\bar{d}_w = \frac{16 - \ln p_w}{3400} \qquad (p_w \text{ in N m}^{-2},\ \bar{d}_w \text{ in meters}) \qquad (9)$$

Thus Equations 6, 7, and 9 substituted in Equation 4 give the drag/buoyancy ratio for given values of p_w, θ, and h.

COMPARISON WITH EXPERIMENTAL DATA

Three test fires carried out in the experimental mall have given results that can be compared with the theory. In each of the tests, the layer depth

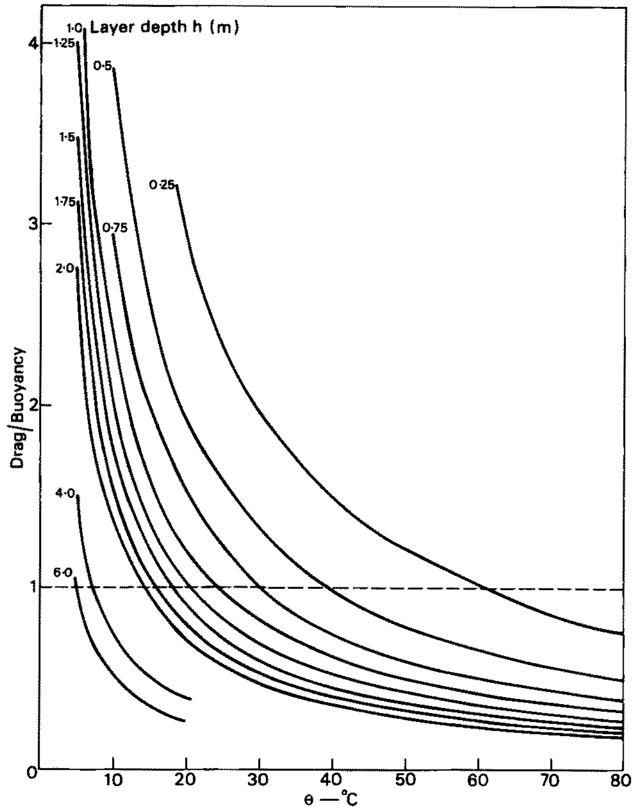

Figure 5. Drag/buoyancy ratio against gas temperature rise, sprinkler pressure 420 kN m^{-2} (61 psi).

and temperature were different, and in each the layer was allowed to stabilize before the sprinkler was operated manually. Although the Swiss car park tests[5] do not provide a great deal of data on the depth and temperature profiles of the smoke layers, in one case it was possible to compute the D/B ratio. A summary of the results from these four tests are given in Table 1.

In all the tests, the drag was greater than the upward buoyancy force when the layer was brought down, and the corresponding θ/θ_c less than 1. In the one case where the layer remained stable, the D/B ratio was less than 1. Whilst these results cannot be said to provide a highly critical test for the accuracy of the theory, the agreement is good enough for design purposes.

DISCUSSION

Because of the complexity of the problem, several of the assumptions made in the analysis only approximately reflect what occurs in practice. In

TABLE 1. *Test Observations*

Test Ref. No.	Observations	Water pressure, bar (psi)	Average layer depth (m) When sprinkler operated	Average layer depth (m) When plume formed	Average layer temperature rise (°C) When sprinkler operated	Average layer temperature rise (°C) When plume formed	D/B	θ/θ_c
150	Downward smoke plume did not form when the sprinkler was operated. A plume was noticed 8 min later after the layer had cooled.	2.8 (40)	0.3	0.45	60	15	0.6 2.0	1.7 0.5
152	The sprinkler was operated later than in 150 and the layer was cooler. A plume formed immediately and smoke was pulled down to floor level.	5.5 (80)	0.75	0.75	12	12	3.0	0.3
153	The layer was deeper than in the above tests and a plume formed immediately.	5.5 (80)	1.25	1.25	25	25	1.1	0.8
—	Experimental car park fire in Berne. Ignition of a simulated petrol spillage under a car. Sprinkler manually set off 30 s after ignition, and severe smoke logging occurred at once.	5.0 (73)	0.5–0.75	0.5–0.75	30	30	1.1–1.5	0.7–0.8

particular, the assumption that the drag force acts over the whole of the area within the envelope of the sprinkler does not correspond accurately to the momentum transfer between individual drops and the surrounding air. Other assumptions, viz. spherical water drops and a uniform constant temperature gas layer, may not occur in practice. However, deviations in these respects from the ideal case assumed should affect the magnitude of the final answer rather than the form of the drag/buoyancy equation. Since the theory gives results that are in agreement with the experimental data at present available, it is thought that, despite these simplifications, the theory gives a viable indication of the likelihood of smoke downflow from a sprinkler.

One aspect of the effect of the sprinkler on the hot layer has not been considered in the analysis. This is the cooling effect of the spray as it passes through the smoke layer. In a relatively stagnant part of the layer — for instance, at a position in a smoke reservoir well away from the fire — local cooling of the layer may cause a downflow even though the temperature in the bulk of the layer is greater than θ_c.* However, if a downflow started in this situation, warmer smoke would flow into the spray envelope to replace that descending; this smoke would have to be cooled before the downflow could restart. Thus the downflow is likely to be much less than if the bulk temperature is below θ_c.

The likely effect of a sprinkler can now be obtained. The Fire Offices' Committee Rules for automatic sprinkler installations[10] state that "for

*But well away from the fire the layer may have cooled so much that sprinklers would not operate.

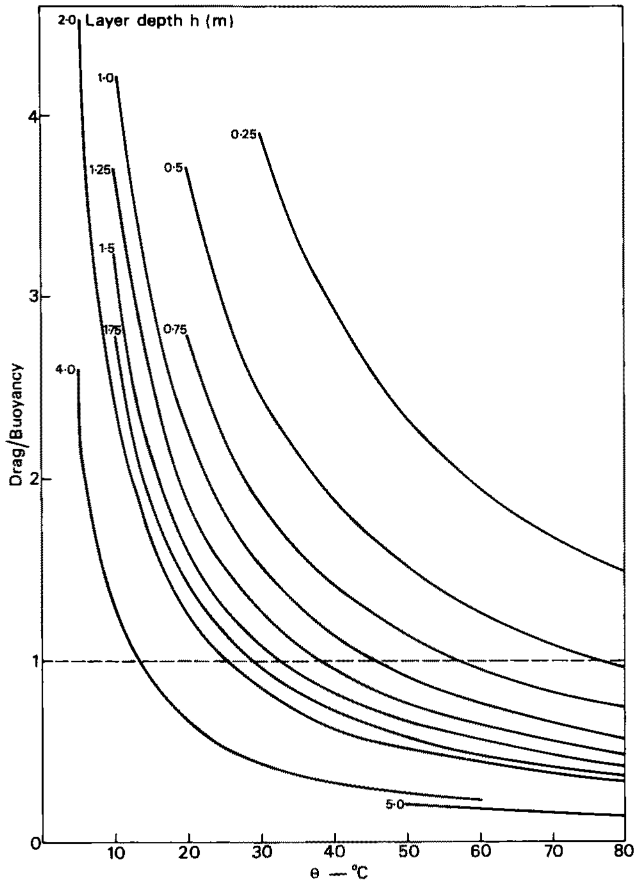

Figure 6. Drag/buoyancy ratio against gas temperature rise, sprinkler pressure 830 kN m $^{-2}$ (120 psi).

normal conditions in temperate climates ratings of 68–74° C will be generally suitable," but in some circumstances higher ratings may be required.

For the rates of fire development in the experiments of O'Dogherty et al,[11] the gas temperature rise at operation of a 68° C rated sprinkler bulb was in the region of 90–115° C because of the thermal inertia of the sprinkler head. Whilst a sprinkler would operate more quickly with a faster developing fire, the gas temperature that would lead to its operation would be even higher.

In single-story shopping complexes, the concern is with smoke layers a meter or more deep. Thus, entering Figure 6 (830 kN m^{-2}, 120 psi) with $\theta = 90°$ C rise and $h = 1$ m, a drag/buoyancy ratio of 0.5 is obtained, much less that would be required to bring smoke down to a low level. This pressure would represent conditions close to the upper pressure limit for

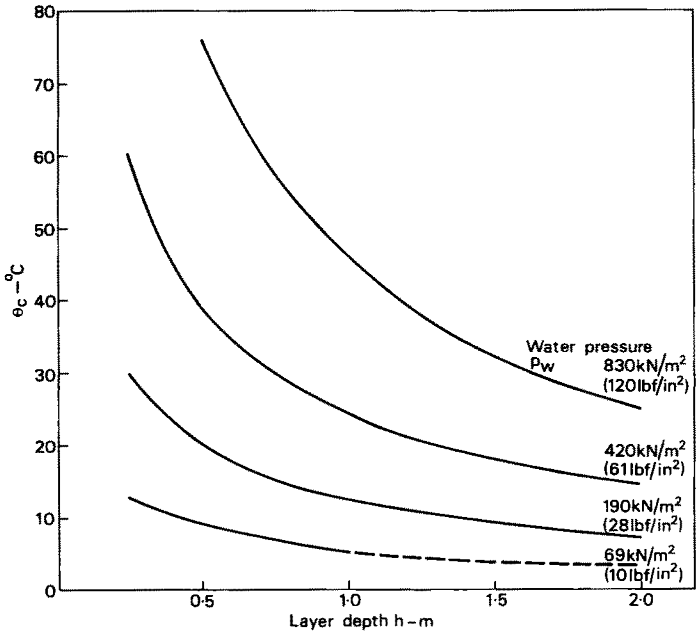

Figure 7. Critical temperature rise against hot layer depth. For a given layer depth, if the temperature is greater than θ_c, the layer will tend to remain stable.

sprinkler installations[10] (10 bar at valve, i.e., 1,000 kN m^{-2}). For lower pressures the drag/buoyancy ratio is lower.

Thus for smoke layers of the thickness likely in shopping complexes, the conclusion is basically that, if the layer is hot enough to set off sprinklers, it will be buoyant enough to remain as a layer. Later on as the thermal and smoke outputs from the fire are reduced by sprinkler action in the shop, the layer in the mall will become cooler, and a point should be reached where those sprinklers which were set off earlier will be able to drag smoke down to a low level. This may happen quite suddenly, but would be a problem mainly during the fire fighting, since the occupants should have been able to escape before this happens.

In any situations (other than shopping complexes) where the smoke layer may be much thinner than a meter or so (i.e., much thinner than may be expected in a covered shopping complex), there is a possibility of smoke logging due to sprinklers. In some circumstances this could possibly create a hazard, but the theory developed indicates the possible solutions. Firstly, the temperature rating of the sprinklers away from the likely seat of the fire (i.e., escape routes and low hazard rating areas) could be raised above that of the sprinklers in the higher risk area. Fewer sprinklers should then operate away from the fire and downflow is less likely to occur with more buoyant gas beneath any sprinkler set off. Secondly, if the effect of water pressure on drop size is neglected in comparison with its effect on the mass flow rate, the drag/buoyancy ratio is proportional to the square root of the water pressure. Thus, sprinklers operating at low pressures are less likely to cause a downflow of smoke. Thirdly, a thick smoke layer will be pulled down less easily than a thin one at the same temperature, so that where the height of the building permits, it is an advantage to have deep smoke reservoirs (smoke extraction is also more efficiently carried out with deeper layers).

Alternatively, if the circulation areas and escape routes contain no materials that would allow fire spread, the use of sprinklers could be restricted to areas where there is a known fire hazard, such as display or exhibition areas and refuse disposal areas. In this way, there would be no loss of coverage in areas of known risk, but there would be less likelihood of smoke logging by the operation of sprinklers distant from the seat of the fire.

Clearly, considerations such as these are far more wide ranging than can be covered by the scope of this report. Other aspects of fire and smoke control in enclosed shopping complexes interact with the problem of preventing smoke logging, and any remedial measures must be made with respect to the total problem.

CONCLUSIONS

- The likelihood of a sprinkler discharge causing a hot smoke layer to break up and form a plume flowing downwards into the clear area beneath is dependent on the operating pressure of the sprinkler and the temperature and depth of the hot smoke layer.
- Where the smoke layer is reasonably thick ($\sim$ 1 m) as in enclosed shopping complexes, a layer that is hot enough to set off a sprinkler will be buoyant enough to remain as a layer at the time of operation of the sprinkler. Downflow will then only occur later as the fire is reduced by sprinklers and would need to be allowed for in fire fighting.
- For thin smoke layers (thinner than may be expected in enclosed shopping complexes), smoke logging can occur, but would be less likely if high temperature rating sprinklers and a medium or low water pressure were used.

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NOMENCLATURE

A = Cross-sectional area of drop, m^2
B = Buoyancy force, N
C_D = Drag coefficient, dimensionless
C_d = Discharge coefficient, dimensionless
D = Drag force, N
d = Drop diameter, m
h = Depth of hot layer, m
k = Drag constant of proportionality, kg m^{-1}
$\dot{M}$ = Mass flow rate of water, kg s^{-1}
m = Mass of drop, kg
p = Pressure, N m^{-2}
T = Absolute temperature, ° K
v = Velocity of drop, m s^{-1}
μ = Absolute coefficient of viscosity, Ns m^{-2}
ρ = Density, kg m^{-3}
θ = Temperature difference, ° C

SUFFIXES

$_a$ = Referring to air.
$_r$ = Referring to the condition when drag and buoyancy forces are equal.
$_o$ = Referring to ambient datum conditions.
$_w$ = Referring to water.

ACKNOWLEDGMENTS: The theoretical analysis is based on an idea by H. P. Morgan. The experiments quoted are part of a study of fire problems in pedestrian precincts being undertaken by the Fire in Buildings Section of the Fire Research Station.