Fire Research Note No 1069

HEAT TRANSFER FROM A BUOYANT SMOKE LAYER BENEATH A CEILING TO A SPRINKLER SPRAY:

A TENTATIVE THEORY

by

Howard P Morgan

July 1977

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ABSTRACT

A theory is developed for calculating the heat transferred from a buoyant layer of fire gases and smoke, to a sprinkler spray. The theory involves calculating the heat transfer to a single water drop as it describes its trajectory, and uses experimentally derived information on the nature and structure of such sprays to calculate heat transfer to the whole spray. Because such experimental information is sparse for sprinklers, a very simple model of the ballistic properties of a sprinkler spray is adopted.

Calculations using the theory suggest that the practice of installing sprinklers in the smoke reservoirs of shopping malls would, in some cases at least, reduce the effectiveness of natural venting of smoke by reducing the buoyancy of the hot smoky gases.

Department of the Environment Fire Research Station of the Building Research Establishment

LIST OF MATHEMATICAL VARIABLES

b	Describes the successive iterative steps in local cooling corrections
B	Buoyancy of the layer gases within the spray
C	Parabola constant defining spray envelope
C_d	Drag coefficient
C_p	Specific heat of air (smoky gases) at constant pressure
C_w	Specific heat of water
d	Layer depth
d_λ	Water drop diameter in λ'th interval of size range
D	Downward drag force exerted on the layer by the spray
$\mathcal{D}(\lambda)$	Drop size probability distribution
g	Acceleration under gravity
h	Height of sprinkler head above floor
i	Defines a particular interval in x. $1 < i < I$
I	Number of equal intervals into which d is divided
j	A dummy variable for i
k	Thermal conductivity of air (smoky gases)
m	Water mass flow rate
M	Mass flow rate of layer gases
n	Defines a particular interval in u. $1 < n < N$.
N	Number of equal intervals into which u_N is divided
$\mathcal{N}$	Total number of water drops emitted per second
N_{sp}	Number of sprinklers in a line across the layer flow
Nu_d	Nusselt Number for water drop in air (smoke)
Pr_d	Prandtl Number for water drop in air (smoke)
q	Heat transfer to a water drop
Q	Heat transferred per second, as limited by subscripts
r	Horizontal displacement of water drop
Re_d	Reynolds Number for water drop in air (smoke)
t	Time of fall of a water drop
T	Absolute temperature
ΔT	Difference between two temperatures
δT	Change in temperature (a function of time)
u	Horizontal component of velocity
v	Vertical component of velocity

LIST OF MATHEMATICAL VARIABLES (Continued)

W	Width of mall (or corridor/tunnel)
x	Height below sprinkler head
θ	Defines the accuracy of local cooling calculations
λ	Defines a particular interval of the range of drop sizes $1 < \lambda < \Lambda$
Λ	Number of equal intervals in range of drop diameters
μ	Viscosity of air (smoke)
ν	Number of drops emitted per second as limited by subscripts
ρ	Mass density
ψ	Resultant velocity of water drop

LIST OF SUBSCRIPTS AND SUPERSCRIPTS

b	indicates the b'th iteration in local cooling calculations
f	indicates the mass flow entering the layer due to the fire
i	indicates the i'th interval of height $1 < i < I$
j	indicates the j'th interval of height
l	indicates a layer gas property
m	indicates the value of a layer variable upstream of the m'th line of sprinklers
n	indicates the n'th interval of horizontal velocity. $1 < n < N$
nsp	indicates an overall value for all N_{sp} sprinklers across the layer flow
o	indicates an ambient air property
sp	indicates an average value of the variable over the spray
tot	indicates the overall value for a spray
w	indicates a property of water
λ	indicates the λ'th interval of the range of drop diameters

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1. INTRODUCTION

Smoke from a fire can form a flowing buoyant layer beneath a large area of ceiling in several types of building. Covered shopping complexes (malls) exemplify such behaviour[1,2], and are usually fitted with automatic sprinklers in the malls as well as in the shops where fires are likely to occur. In practice, sprinklers are often fitted in the ceiling smoke-reservoirs of malls. Covered car parks, corridors and tunnels can also show smoke layering in a fire, and are sometimes fitted with sprinklers.

There is a marked shortage of information on the interaction of sprinklers with such layers. The possibility of smoke being dragged down to low level by a sprinkler spray has been examined by Bullen[3], who concluded that most buoyant layers would not be so affected in practice if hot enough to set off the sprinkler. Very little is known about the quantities of heat removed from the layer by the spray; the consequent loss of buoyancy from the layer would reduce the effectiveness of natural ventilation.

The heat transfer from a flame to a spray falling vertically at its terminal velocity was studied by Rasbash[4], with emphasis on the penetration of the water drops into the flame. Other work has been done on the related problems of spray cooling and spray driers (see for example, ref 5),but none is directly applicable to the problem of heat transfer from a buoyant layer to a spray produced by a sprinkler immersed in the layer. Much of such work depends on water evaporation being an important feature, but this is not likely to be the case for relatively cool layers as are found in malls. The considerable body of work on heat transfer to fuel sprays is similar in that the heat transfer mechanism is strongly influenced by evaporation of the fuel itself.

This paper describes an attempt to calculate the heat removed from buoyant layers of the type found in malls. Because of the lack of necessary experimental data, the theory follows ref 3 in using a very simple model for the sprinkler spray. Allowance is made in the theory for the effects of cooling the layer within the volume of the spray, provided that the layer is moving through the spray.

The simplified model of the spray means that this theory is only a first approach to the problem. The numerical results of calculation, some of which are presented below, should serve to indicate the extent of any problems arising from the loss of buoyancy in the layer.

2. A POSSIBLE ALGORITHM

2.1 Principles

Several formulae are available for calculating heat transfer from a fluid to a moving object. For a spherical body, such as a water drop, one can write[6]

$$Nu_d = 0.37\ (Re_d)^{0.6}(Pr)^{\frac{1}{3}} \qquad (1)$$

for Reynolds Numbers between 20 and 150,000

If the initial size and the velocity vector of the drop are known, the ballistic trajectory of the drop can be calculated taking turbulent drag into account. The resultant velocity of the drop can be calculated as a function of its position along its trajectory, and equation (1) can be used to calculate the heat transfer from the surrounding fluid (the buoyant layer) to the drop during its passage through the layer. Where flames are present in the layer, the predominantly low-frequency turbulence associated with the flames will modulate the trajectory of the water drop, as well as providing large variations in layer temperature thus reducing the accuracy of the calculation. Flames will not be present in the majority of smoke layers of practical interest.

If the size distribution of the water drops is known as a function of initial velocity, the heat transferred per second to all the drops in the spray can be calculated.

Ideally, the calculation should also yield the distribution of mass flux of the water as a function of horizontal position, for any height below the sprinkler head.

2.2 Practical Difficulties and Compromises

Falling water drops are, in general not spherical[7]. Their shape depends both on size and velocity of fall, making any analytical expression for heat transfer almost impossible. Departure from a spherical shape is only an important factor for the largest drops, and so the assumption that all drops are spheres should not cause serious errors.

There appears to be no information available on the initial velocity vectors of drops leaving the sprinkler head. Neither is there information on the droplet size distribution as a function of initial velocity vector. This means that any ballistic calculation must ignore the turbulent drag on the drops. There is information available on the average drop size distribution for the whole spray[3,7] (see Fig 1) but only for a limited number of sprinkler types, and of water pressures applied to the sprinkler. It is also known that the water mass distribution at floor level is reasonably uniform across the spray[8]. If, as in ref 3, the drops are assumed to leave the sprinkler head with zero initial vertical velocity and with a range of horizontal velocities, this fact of uniform delivery of water at a known distance below the sprinkler head can be used to calculate the ballistic trajectories of each drop. Because of the lack of experimental data relevant to this model of the spray, and to simplify the analysis, turbulent drag will be ignored in the ballistic analysis below, but will be applied to the vertical component of velocity only, when calculating heat transfer. Furthermore, the appropriate drop size distribution from Fig 1, originally derived from ref 7, is assumed to be the same throughout the spray from one sprinkler, and, for the examples below, are assumed to apply to all types of sprinkler.

The assumptions in the last paragraph are dictated by necessity, and could be replaced in an improved theory when more experimental data become available.

The properties of sprinkler-induced turbulence within the layer are unknown. The layer base has been observed to appear relatively undisturbed in experiments[3], for most conditions wherein smoke is not dragged down by the spray. Hence it is probably a reasonable assumption to ignore internal turbulence in the layer. The effects of cross-flows of layer gases through the spray are difficult to calculate, but are unlikely to be an important influence on the spray for the layer velocities occurring in practice. Hence they, too, will be ignored (ie the bulk velocity of the layer is assumed to be much less than the mean water drop velocity).

The cooling of layer gases within the volume of the spray causes local temperature gradients in the spray volume. The effects of this can be approximated by assuming the layer gases to be at a uniform temperature in the spray, but that this temperature is less than the temperature of the incident layer. This temperature can be calculated using an iterative technique.

It is further assumed that water evaporation is negligible in cases of practical interest. The results of section 4 support this assumption. Water evaporation could easily be incorporated in an improved theory if desired. This would certainly be necessary when the sprinkler is actually located in a fire compartment.

Except for the local cooling correction, the model of a sprinkler spray resulting from the above assumptions and compromises is identical to that used by Bullen[3].

3. CALCULATION OF HEAT EXCHANGE IN A SPRINKLER SPRAY

3.1 Ballistic Variables for a water drop

This section assumes no drag on the water drop in calculating the trajectory of the drop. However, the vertical velocity can be calculated allowing for drag on this component only. The expression for $v_{in\lambda}$ was developed in ref 3, and becomes

$$v^2_{in\lambda} = \frac{g}{\phi} \left(1 - \exp(-2\phi x)\right) \tag{2}$$

using equations (1) and (6) of ref 3

where

$$\phi = \frac{3\rho_a C_d}{4\rho_w d_\lambda} \tag{3}$$

and C_d is related to d_λ by equation (7) of ref 3.

As discussed in the previous section, the water drops must be assumed to leave the sprinkler head (see Fig 2) with no vertical velocity, but with a range of horizontal velocities u. These horizontal velocities can be subdivided into N equal intervals so that a water drop has a horizontal velocity

$$u_n = \frac{n}{N} u_N \tag{4}$$

where u_N is the maximum velocity of any drop, and $1 < n < N$.

Similarly the drop falls under gravity, the distance of fall through the layer (x) being subdivided into I equal intervals.

$$x_i = \frac{i}{I} d \tag{5}$$

where $1 < i < I$

In the absence of turbulent drag, the trajectory of the drop will be a parabola. The resultant velocity at any time (ie after falling through i intervals of height).

$$\psi_{in\lambda} = (u_n^2 + v_{in\lambda}^2)^{\frac{1}{2}} \tag{6}$$

The radius of the wetted circle at the floor is given by

$$r_N = u_N \left(\frac{2h}{g}\right)^{\frac{1}{2}} \tag{7}$$

neglecting the effects of drag on the time of fall.

similarly $$r_n = u_n \left(\frac{2h}{g}\right)^{\frac{1}{2}} = \frac{n}{N} r_N \tag{8}$$

where r_n is the horizontal displacement at the floor of drops having initial velocity u_n.

Hence, from equations (2), (6) and (8)

$$\psi_{in\lambda} = \left(\frac{n^2 r_N^2 g}{N^2 \, 2h} + v_{in\lambda}\right)^{\frac{1}{2}} \tag{9}$$

The value of $v_{in\lambda}$ given by equation (2) can be used in equation (9) to give the value of $\psi_{in\lambda}$ to be used in calculating the heat transfer in the next section. This method of applying turbulent drag to the vertical velocity only is clearly unreal, but is a better first approximation to reality than ignoring drag altogether. In this theory, however, the trajectories are still assumed to be the parabolas found by ignoring drag.

3.2 Number of drops in the spray

The water mass distribution over the wetted circle at the floor is uniform, and the probability distribution of drop sizes is assumed the same everywhere in the spray. Hence the number of drops per unit area of wetted circle is constant.

If the total number of drops emitted per second is $\mathcal{N}$, and the drop size distribution is $\mathcal{D}(\lambda)$,where λ indicates the size of the water drops, which can vary from a diameter d_1 to d_Λ, $\mathcal{D}(\lambda)$ can be defined to have discrete values, one for each value of diameter d_λ. d_λ is then chosen to be the mean value of diameter within interval λ . Hence the number of drops ν_λ of diameter d_λ emitted per second is

$$\nu_\lambda = \mathcal{N} \mathcal{D}(\lambda) \tag{10}$$

Since the number of drops per unit area of wetted circle is constant, the number of drops of diameter d_λ emitted with a velocity between $u_{(n-1)}$ and u_n, is proportional to the area of the annulus of width $r_n - r_{(n-1)}$:

ie $$\nu_{n\lambda} = \frac{\left(r_n^2 - r_{(n-1)}^2\right)}{r_N^2} \mathcal{N} \mathcal{D}(\lambda)$$

using equation (7)

$$\nu_{n\lambda} = \left\{ \frac{n^2 - (n-1)^2}{N^2} \right\} \mathcal{N} \mathcal{D}(\lambda) \tag{11}$$

An expression for $\mathcal{N}$ can be found as follows.
The mass flow of water drops of size d_λ is

$$m_\lambda = \mathcal{N} \mathcal{D}(\lambda) \frac{\pi}{6} \rho_w d_\lambda^3 \tag{12}$$

The total mass flow rate issuing from the sprinkler is

$$m = \sum_{\lambda=1}^{\Lambda} \mathcal{N} \mathcal{D}(\lambda) \frac{\pi}{6} \rho_w d_\lambda^3$$

so the total number of drops per second is

$$\mathcal{N} = \frac{m}{\left[\sum_{\lambda=1}^{\Lambda} \mathcal{D}(\lambda) \frac{\pi}{6} \rho_w d_\lambda^3\right]} \tag{13}$$

m can be related to water pressure by equation (5) of ref 3.

3.3 Heat transfer to one drop falling through the layer

When a drop is falling through the i'th interval of height, we can take the velocity at the end of that interval $\psi_{in\lambda}$, and the temperature difference between drop and layer gases at the start of that interval ΔT_i, as representative of conditions during that interval. To increase the accuracy of this assumption, make I large.

Equation (1) can be expanded into more useful physical terms to give the heat transfer rate to the drop during its travel through the interval i :

$$Q_{in\lambda} = 0{\cdot}37\pi d_\lambda^{1{\cdot}6} k^{2/3} \rho_l^{0{\cdot}6} \mu^{-0{\cdot}267} C_p^{1/3} \psi_{in\lambda}^{0{\cdot}6} \Delta T_i \tag{14}$$

ΔT_i will change in value with changing i, as the drop warms. The heat transferred to the drop during interval j is

$$Q_{jn\lambda}\, \delta t_j$$

where $$\delta t_j = (t_j - t_{(j-1)}) = \frac{d}{I\, v_{jn\lambda}} \tag{15}$$

The temperature rise of the drop during interval j is

$$\delta T_j = \frac{Q_{jn\lambda}\, 6\, \delta t_j}{C_w \pi \rho_w d_\lambda^3} \tag{16}$$

Hence the temperature difference between the drop and the layer gases at the start of the i'th interval, as used in equation (14), is

$$\Delta T_i = T_l - \left(T_w + \sum_{j=0}^{(i-1)} \delta T_j\right) \tag{17}$$

where δT_j is given by equation (16), except that

$$\delta T_j = 0 \qquad \text{for} \qquad j = 0$$

3.4 Heat transfer to the spray

From equation (14), it can be seen that the heat transferred from layer gases to the drop in the i'th interval of height is

$$Q_{in\lambda}\,\delta t_i$$

Hence the heat transferred to the drop during its fall through the layer is

$$q_{n\lambda} = \sum_{i=1}^{I} Q_{in\lambda}\,\delta t_i \tag{18}$$

using equations (14) and (15).

Hence the heat transferred per second to drops of diameter d_λ and initial velocities $u_n > u > u_{(n-1)}$ is

$$Q_{n\lambda} = \nu_{n\lambda}\, q_{n\lambda} \tag{19}$$

The heat transfer rate to drops of diameter d_λ is then

$$Q_\lambda = \sum_{n=1}^{N} \nu_{n\lambda}\, q_{n\lambda} \tag{20}$$

and the heat transfer rate from the layer to the spray is

$$Q_{tot} = \sum_{\lambda=1}^{\Lambda} Q_\lambda \tag{21}$$

Equations (18) to (21) can be combined in one convenient form

$$Q_{tot} = \sum_{\lambda=1}^{\Lambda} \sum_{n=1}^{N} \frac{(n^2-(n-1)^2)}{N^2}\, N\, \mathcal{D}(\lambda) \sum_{i=1}^{I} Q_{in\lambda}\,\delta t_i \tag{22}$$

3.5 To correct for the cooling of gas within the spray volume

This correction will apply to flowing buoyant layers beneath the ceiling of a corridor or shopping mall.

If the corridor has a width W, the heat flux in the uniform layer is evenly distributed across any cross-section of the mall. The maximum vertical cross-section of the sprinkler spray normal to the layer flow is the area of a parabola, such that the area is

$$\frac{4}{3} \; C^{\frac{1}{2}} \, d^{\frac{3}{2}}$$

where the envelope of the spray is the paraboloid

$$r^2 = Cx \tag{23}$$

and

$$C = \frac{r_N^{\,2}}{h}$$

Hence the mass flow rate of layer gases through the sprinkler spray is

$$M_s = \frac{4C^{\frac{1}{2}} \, d^{\frac{1}{2}}}{3W} \; M_f \tag{24}$$

If the initial temperature of the layer is ${}^1T_1$, and the heat transfer rate calculated from equation (22) is ${}^1Q_{tot}$, the change in temperature of the gases actually passing through the spray is

$${}^1\Delta T_i = \frac{{}^1Q_{tot}}{M_s \, C_p} \tag{25}$$

Hence the mean layer temp in the volume of the sprinkler spray can be taken to be

$${}^1T_{sp} = {}^1T_1 - \frac{{}^1\Delta T_1}{2} \tag{26}$$

To allow for local cooling, calculate Q_{tot} several times, each time using a value of T_1 in equation (17) which is successively decreased by a predetermined amount θ. For the b'th iteration, T_1 has the value

$$^{b}T_l = {}^{1}T_l - \frac{^{1}\Delta T_l}{2} \tag{27}$$

This iteration yields $^{b}Q_{tot}$, and $^{b}T_{sp} = {}^{1}T_1 - \frac{^{b}\Delta T_1}{2}$

If the value of $^{b}T_{sp} = {}^{b}T_1$ within acceptable limits, then the mean layer temperature $^{b}T_{sp}$ in the spray calculated from the heat transfer agrees with the mean layer temperature $^{b}T_1$, and the iterative calculation can be ended. The simplest criterion for ending the iteration is then

$$^{b}T_{sp} > {}^{b}T_1 \tag{28}$$

ie $$^{1}T_l - \frac{^{b}\Delta T_l}{2} > {}^{1}T_l - (b-1)\theta$$

ie $$^{b}\Delta T_l < 2(b-1)\theta \tag{29}$$

The values of $^{(b-1)}Q_{tot}$, $^{(b-1)}\Delta T_1$ and $^{(b-1)}T_{sp}$ that were calculated on the penultimate iteration are then taken as the appropriate solutions to the problem.

3.6 Downward drag exerted by the spray

Since the model of the spray is the same as in ref 3, the formulae for the drag-to-buoyancy ratio for the sprinkler and layer, as derived in ref 3, can easily be modified to include the effects of local cooling within the spray, by replacing the layer temperature (T in equation (8) of ref 3) with $^{(b-1)}T_{sp}$ for the above calculation.

3.7 The Calculation

The equations for heat transfer derived above, and for the drag-to-buoyancy ratio (D/B), were incorporated in a computer program. This program is available on request.

A further feature of the program is that the effect of a number (N_{sp}) of sprinklers, side-by-side across the direction of layer flow, can be calculated, since the heat transferred to the line is simply

$$Q_{nsp} = N_{sp} \; Q_{tot} \tag{30}$$

and all other values are as for one sprinkler.

If the gases mix thoroughly before approaching the next line of sprinklers, the layer temperature becomes

$$^{(m=2)}T_l = {}^{(m=1)}T_l - \frac{N_{sp} M_s}{M_f} \, {}^{(b-1)}\Delta T_l \tag{31}$$

Where the superscript on T_l indicates the line of sprinklers being approached by the layer gases.

Hence successive lines of sprinklers can be included in the calculation. This feature is also included in the program.

4. CALCULATED EXAMPLES

This section describes the predictions of the theory for a number of specific examples. Some of the input data is common to all cases below, and can be discussed separately.

Manufacturers' data and experimental observations indicate that a typical sprinkler wets a circle of radius 3 m at a height of 3 m.

ie $\quad r_N = 3.0$

for $\quad h = 3.0$

These values will define the spray envelope, even for layers deeper than 3 m.

The initial water temperature can be assumed to be at the same temperature as ambient air. A reasonable value for this is 15°C, so for the purpose of these examples

$$T_w = T_o = 288°K$$

In the absence of other information, Fig 1 must be assumed to apply to all sprinklers. Hence values of $\mathcal{D}(\lambda)$ and d_λ for each example were obtained from Fig.1

A high but not unlikely water pressure of 552 kN/m^2 (80 psi) has been used as a 'worst-case' for each example. This gives, for a $\frac{1}{2}$ inch diameter sprinkler, a water flow rate of

$$m = 2.45 \text{ kg/s}$$

(i) A single sprinkler operating in a typical single-storey shopping mall, where smoke from a 5 megawatt fire flows along the mall. Suitable values for the smoke layer variables can be obtained from ref 1:

$$M_f = 24 \text{ kg/s}$$
$$W = 10 \text{ m}$$
$$d = 1.5 \text{ m}$$
$$T_1 = 498^\circ K$$

The iteration limits are chosen to be

$$I = N = \Lambda = 10, \quad \Theta = 5.0^\circ C$$

The calculation predicts that this sprinkler will remove 0.32 Megawatts of heat from the layer. The drag to buoyancy ratio will be $\frac{D}{B} = 0.27$, and hence the layer will not be dragged to low level by the spray.

The water in the spray will be warmed by $31^\circ C$, giving a final mean water temperature of $46^\circ C$

(ii) A single sprinkler operating in a typical two-storey shopping mall, where smoke from a 5 Megawatt fire on the lower floor flows along the upper level smoke reservoir. The layer variables can be obtained from ref 2 for a naturally-vented reservoir.

$$M_f = 100 \text{ kg/s}$$
$$W = 14 \text{ m}$$
$$d = 6.0 \text{ m}$$
$$T_1 = 320^\circ K$$

The iteration limits are

$$I = 15, \quad N = \Lambda = 10, \quad \Theta = 1.0^\circ C$$

The calculation predicts that this sprinkler removes 0.25 Megawatts of heat from the layer. $\frac{D}{B} = 0.17$, hence again the layer is undisturbed. The water temperature rises to $39^\circ C$.

(iii) A single sprinkler operating in a typical two-storey mall, as in the previous example, but where the smoke is extracted from the reservoir mechanically. The only differences from the previous example are:

$$d = 2.5 \text{ m}$$
$$I = 10$$

The calculation predicts that this sprinkler removes 0.09 Megawatts of heat.
$\frac{D}{B} = 0.33$, and the layer is undisturbed.

The water is warmed to 24°C.

(iv) A single-storey mall, 10 m wide, having lines of 3 sprinklers across the mall, with successive lines spaced along the mall. Smoke from a 5 Megawatt shop fire travels along the mall, in one direction, setting off line after line of sprinklers until the layer gases are too cool to set off more sprinklers. This is the sort of situation that would be most likely in practice.

Initial values of the layer variables are the same as example (i) above, So too are the iteration limits, except for

$$\theta = 3.0^{\circ}\text{C}$$

The layer depth is assumed to remain constant. The results are presented in Table 1.

The loss of buoyancy due to cooling of the smoky gases will affect the efficiency of operation of any natural venting in the mall. Equation 15 of Ref 9 can be employed to calculate the importance of this effect. To extract the same mass of smoky gases after they have been cooled by six lines of sprinklers, the vent area of the mall would have to be increased by 27% in order to maintain the same layer depth. To remove the same mass of smoky gases through the same vent area, the layer depth beneath the vents must increase by 47%.

5. DISCUSSION OF RESULTS

Despite the simple nature of the spray model, the results of calculation should be qualitatively correct. The figures for $\frac{D}{B}$ illustrate Bullen's conclusion that the layer will be undisturbed when the sprinkler is activated, in most cases of practical interest.

The loss of heat (and hence buoyancy) from the layer due to a single sprinkler operating is not a large proportion of the heat flux in the layer. In none of the examples does the water temperature rise sufficiently to suggest that evaporation would be a significant feature.

Unfortunately, shopping malls usually have arrays of sprinklers, such as that described in example (iv)above. The loss of heat and buoyancy from the layer in such a case can be a very large proportion of the original heat output of the fire,for example, after passing only a few lines of sprinklers in example (iv). Many existing malls have natural smoke ventilation, with vent areas calculated on the assumption that sprinklers will not operate in the mall.

The effect of loss of buoyancy in such cases could be very serious, leading to much deeper smoke layers in the mall than expected. Mechanical extraction systems would be unlikely to suffer from this problem.

When experimental results become available for the water droplet velocity and momentum vector distributions at the sprinkler head, it should be possible to produce an improved version of the theory presented above. Such a version could be based on more realistic trajectory calculations, and the predictions of heat transfer would become more accurate. It is felt, however, that the qualitative conclusions drawn from the examples quoted above are almost certainly valid.

6. CONCLUSIONS

A theory has been developed for calculating the heat transfer from a flowing, buoyant smoke layer to a sprinkler spray. The lack of existing experimental information forces the adoption of a very simple model of the behaviour of the water spray. The results of applying the theory to some practical examples of shopping malls suggest that heat and buoyancy loss from the ceiling layer can seriously reduce the effectiveness of natural venting.

7. REFERENCES

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RESULTS FOR EXAMPLE 4(iv)

Line of Sprinklers (b)	Above-Ambient temperature of layer when approaching line °C	Heat lost from layer Q_{nsp} (MW)	$^D/_B$	Final water temperature (Initial T_W=15°C) (°C)	Cumulative Heat loss (MW)
1	210	1.008	0.09	48	1.008
2	168	0.825	0.11	42	1.833
3	133.6	0.661	0.14	36	2.494
4	106.1	0.531	0.17	32	3.025
5	83.9	0.428	0.22	29	3.456
6	66.1	0.346	0.27	26	3.800
7	51.7	-	-	-	3.800

NOTE: No further sprinklers will be set off after line 6.

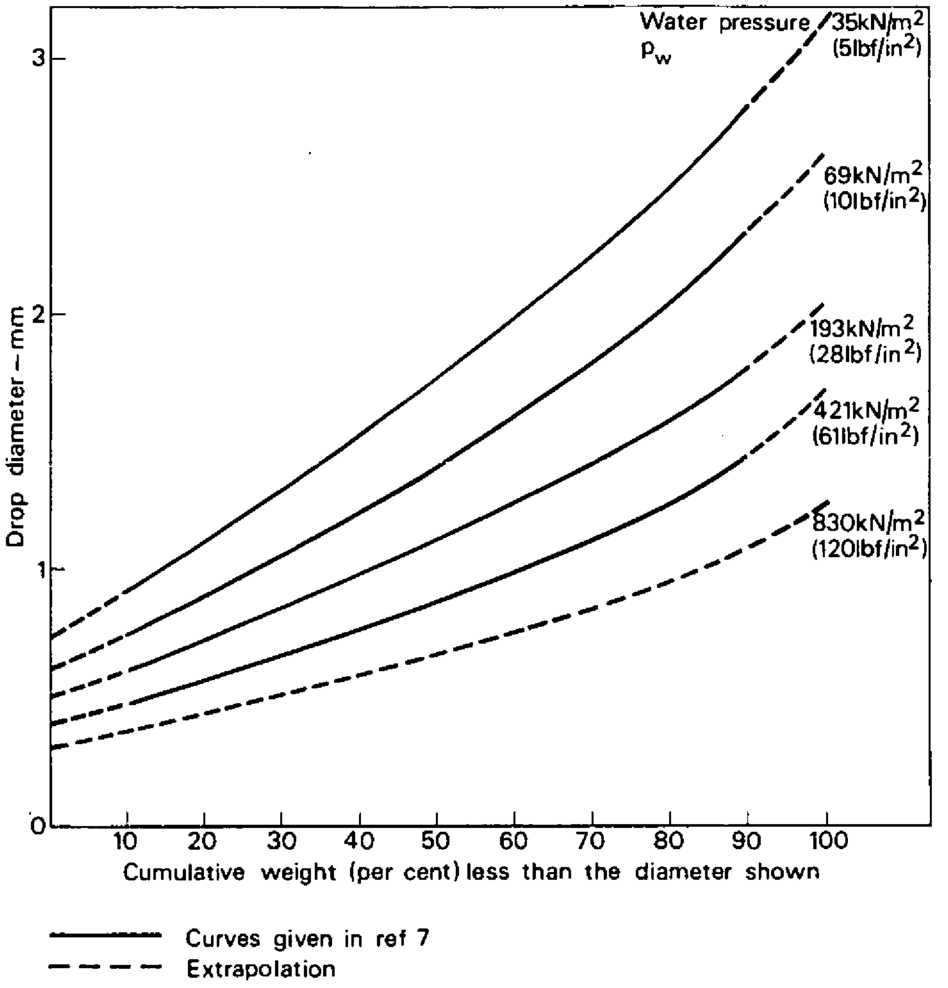

Figure 1 Distribution of drop sizes in a sprinkler spray (from ref 3)

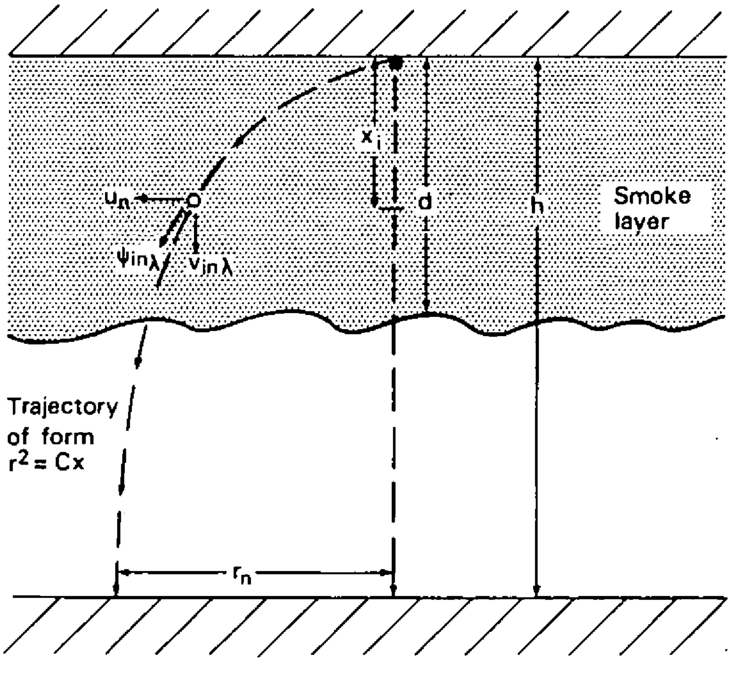

Figure 2 Simple model of a water drop in a sprinkler spray