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THE RATE OF TEMPERATURE RISE IN A COMPARTMENT FIRE

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SUMMARY

The behaviour of the growing hot layer caused by a fire under a ceiling is discussed theoretically for an idealised situation. The calculations show the value of compartmentation in hastening the operation of fire detectors and provide a meaningful reference standard for the rate of rise characteristic of a detector.

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1. Introduction

Fires can be detected by a temperature sensitive device and these are often designed so that they operate when the air temperature reaches a certain predetermined value or, at a lower temperature when the air temperature rises at a fast enough rate.

This note discusses the rise and rate of rise in the air temperature in an idealised fire situation. The theoretical treatment follows that given for small fires by Thomas, Hinkley et al[1] in connexion with roof venting and it is intended to provide data to assist in relating performance standards of detectors to practical fire conditions. The use of the theory for small fires is used because we are concerned with relatively small temperature rises at the ceiling, in other words with flames which are not tall in comparison with the building.

2. Theoretical calculations

We shall consider two stages in the growth of a fire. The first is mainly relevant to the development of fire below an extended and undivided roof space.

Here hot gases spread sideways under the roof and there is no layer formed before the detector operates. For this condition any progressive rise in the temperature is a result of the fire spreading and the gradual reduction in the rise of heat loss to the ceiling.

When the spreading gases reach the sides enclosing the compartment, or a part of it, a layer will develop and even if the fire does not grow the temperature of the gases near the ceiling will rise because as the layer deepens there is a shorter vertical distance through which the hot gases pass and are diluted by cool air.

A simple criterion will be given to distinguish between the two situations.

2.1. A Steady fire

The mean temperature rise θ a distance above the effective point source of a fire as calculated from the equations given by Yih[2] is

$$\frac{\theta}{T_0} = \frac{6.5}{g}\left(\frac{gQ}{\rho c T_0}\right)^{2/3} Z^{-5/3} \qquad (1)$$

where g is the acceleration due to gravity

T_0 is the absolute ambient temperature

ρ is the density of the surrounding air

c is the specific heat of the surrounding air

and Q is the rate of heat release.

(In view of the difference between the mean and the maximum temperature rise, which immediately above the fire is some 60 per cent higher than the mean, the following theory may overestimate the operating time of detectors immediately over the fire.)

The corresponding mass of rising air is

$$M = 0.15_3 \rho \left(\frac{gQ}{\rho c T_0} \right)^{1/3} z^{5/3} \qquad (2)$$

We shall neglect differences between the density of the rising air and the surroundings except for the buoyancy effect. This is permissible since detectors operate at about 69°C.

The time for hot gases to reach the ceiling is a few seconds and so it is sufficiently accurate to treat equations (1) and (2) as instantaneously valid even when the fire is growing i.e. when Q is not constant so long as the relative change in Q in a few seconds is negligible.

An estimate of the time at which a layer begins to form may be made provided some assumptions can be made about

(a) the mixing between the hot gases forming under the layer and the air beneath them once the plume bends over under the ceiling, and

(b) the depth of the spreading layer.

Mixing within the hot layer will be assumed to be perfect but we shall neglect any mixing with the cold air beneath. The depth of the spreading layer is not readily estimated. We shall assume it to be half the diameter of the plume in order to obtain an order of magnitude approximation for the time. The plume radius is approximately $z/5$ and so the time to fill the space of this depth is

$$t_1 \doteq \frac{Az}{5 \times 0.15 \left(\frac{gQ}{\rho c T_0} \right)^{\frac{1}{3}} z^{5/3}} \qquad (3)$$

where A is the area of undivided ceiling space

The maximum value of t_1 is determined mainly by the height of the building which is denoted by h.

The depth of the point source below the floor is taken as

$$z_0 \doteq 1.5 \sqrt{A_f} \qquad (4)$$

where A_f is the area of floor covered by fire and so the height of the building h is related to H the height above the effective point source by

$$h + 1.5\sqrt{A_f} = H \qquad (5)$$

and from eqn. (3)

$$t_1 = \frac{1.3 A}{\left(\frac{gQ}{\rho c T_0} \right)^{\frac{1}{3}} H^{\frac{2}{3}}} \qquad (6)$$

After time t_1 the layer begins to grow, and in order to perform simple calculations which indicate the main features of the behaviour we shall assume that during this growth the layer can be regarded as being uniform in temperature and composition i.e. mixing within the layer is instantaneous.

The change in mass of the layer at time 't' is given by

$$-\rho A \frac{dz}{dt} = M \qquad (7)$$

Integrating this with M given by equation (2) and with $z = H$ when $t = o$ gives

$$\left(\frac{H}{z}\right)^{\frac{2}{3}} = 1 + 0{\cdot}1\left(\frac{gQ}{\rho c T_0}\right)^{1/3}\frac{Ht}{A}$$

$$= 1 + \frac{t}{t_2}$$

where

$$t_2 = \frac{15}{2}t_1 = \frac{10A}{H^{2/3}}\left(\frac{\rho c T}{gQ}\right)^{1/3} \qquad (8)$$

The initial condition given above is not strictly correct since according to the previous calculation we should take $Z = 4/5$ when $t = t_1$ but the accuracy of this feature is doubtful and it is omitted in this approximate treatment.

The temperature rise is readily evaluated for a steady fire. Neglecting any heat loss to the ceiling we have

$$\theta = \frac{Qt}{\rho cA\,(H - z)} \qquad (9)$$

When the fire has been burning some time the fraction of heat lost to the ceiling approaches a constant which is proportional to the area of the ceiling that is heated. Initially heat loss may be a dominant influence on the temperatures especially at some distance from the fire. We shall however neglect heat loss. It is not thought that this will seriously affect the main features of the rise in temperature under the ceiling; particularly not where the building is high and the interest is centred on deep layers and long operating times.

From equation (9) we have

$$\theta = \frac{Qt_2}{\rho cAH}\left(\frac{t/t_2}{1 - \dfrac{1}{(1 + t/t_2)^{3/2}}}\right) \qquad (10)$$

$\frac{Qt_2}{\rho cAH}$ will be denoted by θ^*

The rate of temperature rise is obtained from equation (10)

$$\frac{d\theta}{dt} = \frac{Q}{\rho c A H} \frac{\left(1 - \frac{1 + (5/2)y}{(1+y)^{5/2}}\right)}{\left\{1 - \frac{1}{(1+y)^{3/2}}\right\}^2} \qquad (11)$$

where $y = {}^{t}/t_2$

Fig. 1 shows θ, ${}^{Z}/H$ and $\frac{d\theta}{dt}$ as functions of ${}^{t}/t_2$. We have taken the time to be zero when the hot gases first reach the ceiling. At this instant the temperature rises from ambient to the value given in equation (1) viz. $\frac{2}{3}\ \theta^{x}$. At the moment the hot gases first reach the ceiling the rate of temperature rise is mathematically infinite but immediately after the value for small fires tends to 0.835 $\frac{Q}{\rho cAH}$. The quantity $\frac{Q}{\rho cAH}$ is the rate of temperature rise which would obtain if all the heat output of the fire were perfectly mixed in the volume of air below the area of ceiling compartmented of height H. Because equation (11) gives a nearly constant value of $\frac{d\theta}{dt}$ which differs by less than 17 per cent from $\frac{Q}{\rho cAH}$ this quantity is a useful characteristic for rate of rise detectors. The temperature at the ceiling however, remains in excess of what would be calculated from perfect mixing by roughly $\frac{2}{3}\ \theta^{*}$

The dotted line in Equation 1 shows the temperature behaviour for such perfect mixing without layering.

It should be noted how $\frac{d\theta}{dt}$ falls inversely with H and is proportional to Q.

2.2. A spreading fire

We shall neglect the effect of the varying size of the fire on Zo. The justification for this is that equation (4) probably over estimates Zo by an increasing larger amount when there are no flames present. Indeed Zo may become negative i.e. the effective point source is within the flame zone.

The time t_1 at which a complete layer has been formed by a spreading fire is given

$$\frac{A}{5} = 0.15 \left(\frac{g}{\rho c T_0}\right)^{\frac{1}{3}} H^{\frac{2}{3}} \int_0^{t_1} Q^{1/3}\, dt \qquad (12)$$

during which time the rate of temperature rise from equation (1) is

$$\frac{d\theta}{dt} = \frac{13}{3}\ \frac{To}{g} \left(\frac{gQ}{\rho c T_0}\right)^{\frac{2}{3}} \frac{1}{H^{5/3}}\ \frac{dQ}{Q\,dt} \qquad (13)$$

At this stage of the fire $\frac{d\theta}{dt}$, like Q, is independent of A but proportional to $H^{5/3}$.

If the development of fires in their early stages if regarded as being between a linear and a square law dependance on time, equation (12) can be replaced by

$$t_1 = \frac{2A}{H^{2/3}} \left(\frac{\rho c T_0}{g Q} \right)^{\frac{1}{3}} \pm 25\% \qquad (14)$$

where Q_1 is the value of Q at t_1. The rate of temperature rise can then be expressed as

$$\rho \frac{cAH}{Q} \frac{d\theta}{dt} = \frac{13}{6} t_1 \quad \frac{1}{Q} \frac{d\theta}{dt} \qquad (15)$$

Once a layer has formed the left hand side is approximately unity.

3. Discussion and worked examples

Consider a fire in which Q is a prescribed function of time. For a time which is long when A is large (an undivided ceiling) the temperature and its rate of rise vary inversely as $H^{5/3}$. Increasing H reduces the time t_1 and the value of Q at which the layer is established and begins to deepen. It follows that as H increases it is less likely that a detector will operate before a layer is established over the whole ceiling area. Compartmenting the ceiling and reducing A reduces t_1 and so hastens the development of a layer.

Once a layer is established the rate of rise of temperature is larger, the smaller is A and the sooner the ceiling compartment is filled. It may be noted too that the smaller is A the lower is the heat loss to the ceiling. This helps to operate the detectors sooner and makes the calculations numerically better. After the gases have spilled into the surrounding compartments the temperature in the filled compartments remains typical of a building of a height up to the bottom edge of the screen, increasing only as the fire extends in area.

If A is taken as 93 sq m (10,000 sq ft), ρ as 1.3×10^{-3} g/cm^3 c as 0.24 cal g^{-1} deg C^{-1}, H as 6 m (20 ft) and Q_1 as a 0.56 sq m (6 sq.ft) fire producing 30 cal cm^{-2}s^{-1}, equation (14) gives

$$t_1 = 220 \text{ secs.}$$

and equation (1) give θ as 65°C.

A 6 sq ft. fire in a crib of bulk density 0.1g cm^{-3} will increase its diameter by about 25 cm, about doubling the area, in 220 secs. This means that $t_1 \frac{d\theta}{Q dt}$ is of order unity and $\rho \frac{cAH}{Q} \frac{d\theta}{dt}$ is about 2. This is significantly larger than the value due to the subsequently deepening layer. For such a fire therefore we expect the detector to operate as a result of the increasing temperature due to the spread of the fire. The temperature rise of 65°C is a little higher than the minimum that will operate a fixed temperature detector. If, however, the compartmented area was reduced to (465 sqm) 5,000 sq. ft and the ceiling 12 m (40 ft) high the value of t_1 for the same fire is 70 sec. but $\rho \frac{cAH}{Q}$ is the same. The value of $\rho \frac{cAH}{Q} \frac{d\theta}{dt}$ will be rather less than unity. For this example both factors will be of importance since $\rho \frac{cAH}{Q} \frac{d\theta}{dt}$ is not negligible but the major role in operating the detector is the deepening of the layer.

In both examples quoted above the value of $\frac{Q}{\rho cAH}$ is $^{1}/_{10}$ deg C/s. or 60°C per minute. This is well within the range of 1 - 30 deg C/min for various thermal detectors, so that if the building is too large or the fire too small to operate the detector before the layer deepens it is in theory practicable to detect a 6 sq. ft fire if the ceiling is subdivided.

Consider a slowly developing fire. If we insert equation (1) into equation (14) we obtain

$$t_1 \doteq \frac{2A}{H} \left(\frac{6.5 \ To}{g \ \theta H}\right)^{\frac{1}{2}} = \frac{5A}{H} \left(\frac{To}{g \ \theta H}\right)^{\frac{1}{2}} \qquad (16)$$

As noted earlier the fire of 6 sq. ft will operate a detector (having negligible thermal capacity) about when the ceiling space is filled horizontally and begins to deepen. We put θ in equation (16) equal to the operating temperature viz. 50°C above ambient, and obtain

$$t_1 \doteq \frac{12A}{H\sqrt{gH}}$$

This implies that if a fire in the building has not operated the detector within a time $\frac{12A}{H\sqrt{gH}}$ there will be a deepening layer of hot gas within a screened area A below the ceiling.

This time is not very sensitive to the rate of growth of the fire up to the time at which it is just large enough to operate the detector. In practice of course for such a marginal fire the thermal capacity of the detector will introduce a long delay. Nevertheless, this time which is accurately enough written $\frac{10A}{H\sqrt{gh}}$ will serve as a useful definition of the critical operating condition. That is, if a thermal detector is to operate before the ceiling space is filled and the hot gas begins to descend the operating time must be less than $\frac{10A}{H\sqrt{gH}}$.

Knowing the operating time for a given type of developing fire under a large undivided ceiling we can deduce whether it is worthwhile compartmenting the ceiling to hasten operation.

For example if for a certain fire the operation under a large undivided ceiling at a height of 6 m (20 ft) is 3 min (180 sec) we find that

$$\frac{H\sqrt{gH}}{10} \times 180 = 9{,}100 \text{ sq. ft.}$$

Compartment the ceiling into areas of less than 9000 sq. ft should hasten operation.

For a smaller fire with a longer operating time such compartmentation would be even more valuable.

It is not always practicable to construct screens descending low enough. A minimum size for the screen can be obtained by considering the height to its bottom edge. Unless the fire under consideration can be detected in a building of this height installing the screens may not be of much value unless the detector is capable of responding to a rate of rise in temperature even when the ambient temperature is relatively low.

The maximum benefit that can be derived in providing ceiling screens is to reduce the effective height of the building to the level of the bottom edge of the screens. The spacing of the screen determines the time taken for the building to attain the "effective height".

4. Conclusions

A rate of temperature rise has been evaluated which is characteristic of the fire and the compartment and provides a practical reference standard for detectors.

The calculations and the examples show the value of compartmenting the ceiling in raising the rate of temperature rise for large buildings where an undivided ceiling may be several hundred thousand sq. ft in area. This is particularly so when the height to the ceiling is large and when the fire is slow in developing in the phase prior to detection.

Reference

(1) THOMAS, P. H., HINKLEY, P. et al "Investigations into the flow of hot gases in roof venting" Fire Research Technical Note No. 7. H.M.S.O. London 1963.

(2) YIH, C. S. Proc 1st Ins. Nat. Congr. Appl. Mech. 1952. 941-7.

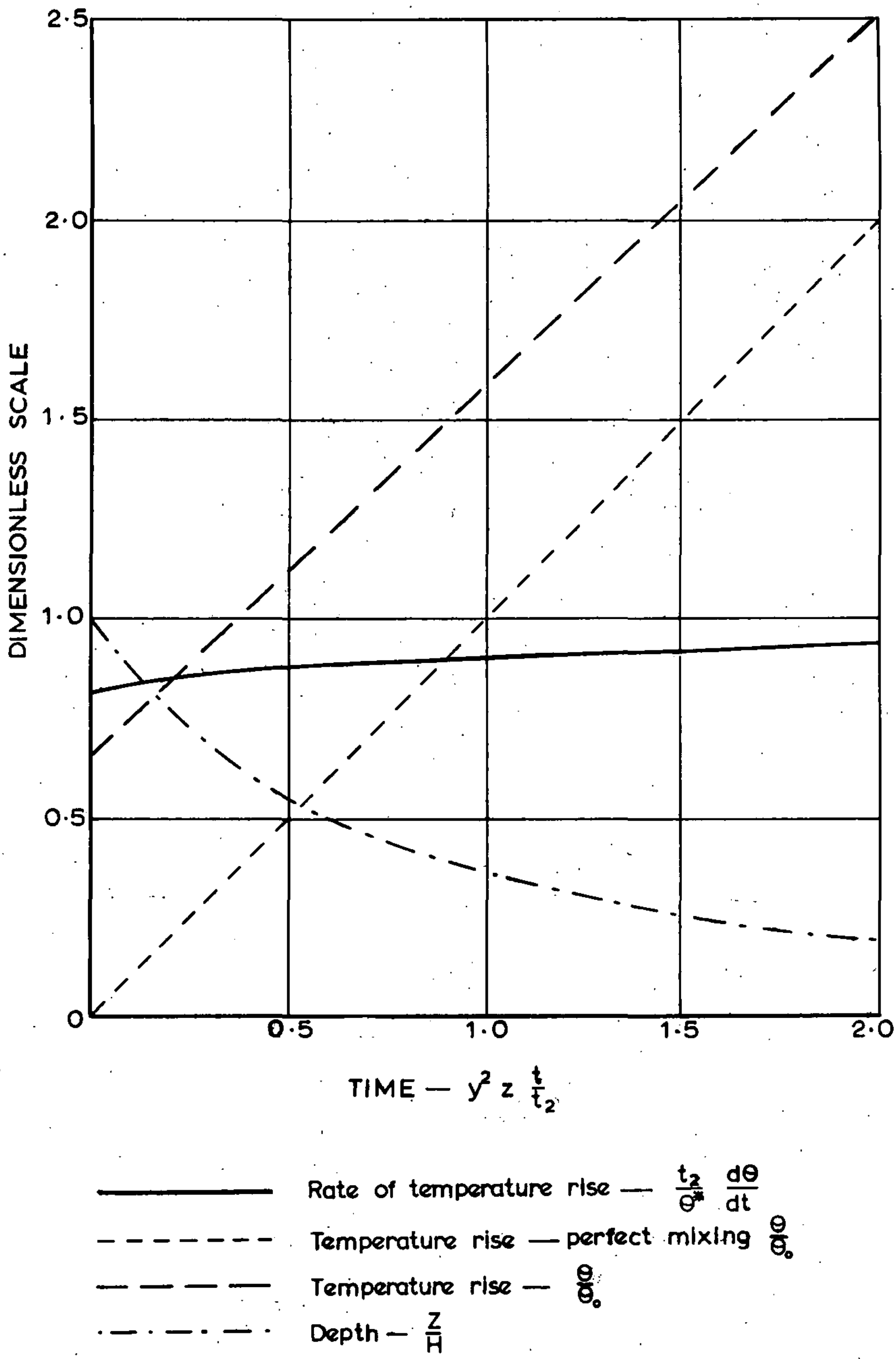

FIG.1. CALCULATED TEMPERATURES AND DEPTH OF HOT LAYER

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