HOT SMOKE TESTS: TESTING THE DESIGN PERFORMANCE OF SMOKE AND HEAT VENTILATION SYSTEMS AND OF IMPULSE VENTILATION SYSTEMS

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ABSTRACT

Fire Engineered smoke control systems cannot usually be fully tested in the design condition without causing damage to the building. Where the design performance is sufficiently important to merit an acceptance test of that performance, it is possible to set up a hot smoke test based on scaling relationships, such that the smoke depth (usually the critical parameter on a Smoke and Heat Exhaust Ventilation System (SHEVS)) and the distance traveled by smoke against an opposed airflow (the critical parameter in an Impulse Ventilation System) are the same in the test as for the design condition. Hot smoke tests not based on scaling can give potentially rests misleading results on these parameters.

The paper also describes a simplified outline of the design procedure for Impulse Ventilation Systems and shows that these systems conform to the same scaling relationships as for a SHEVS.

The alternative to these scaling methods is where design and test conditions are predicted by the same calculation method and where the test prediction is confirmed by observation.

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1. INTRODUCTION

1.1 Performance-based Smoke Control Systems – Objectives and Achievements

Many large and/or complex buildings have fire safety strategies depending on performance based design calculations. This is especially the case where smoke control systems are intended to permit relaxation of other requirements. An essential part of the performance-based design process is to identify the key objectives of the system, for example whether the system is intended to keep smoke away from people using escape routes, or whether the system is intended to provide clear access for firefighters to approach the fire in safety.

Installation of the system must correctly implement the design. Experience in many countries has shown that the final system as actually installed often differs from the original design. This may be due to late changes to the building or to simple misunderstandings. This presents the Approving Authority (and the building owner/management) with a double question: a) was the original design satisfactory for achieving the desired objective and b) does the actually installed system, perhaps influenced by any late detail changes to the building, achieve the desired objectives. Put simply – does this part of the fire safety strategy work?

1.2 The Principle of On-site Performance Testing

Where doubt may exist in the mind of the building's owner and/or management; or where doubt may exist in the mind of the Approving Authority, it becomes desirable to find a way to test the performance of the smoke control system, as actually installed in-situ. Smoke control using pressure differentials can be tested easily without any input of heat, by measuring pressure differences across the protected door, and (where specified by appropriate Codes [e.g. 1]) air velocities induced at specified open doorways.

This "cold" approach is not appropriate for smoke control systems where the objective is to control the movement of thermally-buoyant gases in the same undivided volume as the fire. Heat must be generated to create buoyancy, even when testing the performance of the system.

Unfortunately, the design fire size appropriate for protection of people or for assisting firefighting, is usually large enough to damage the fabric of the building to some degree. The largest fire size acceptable for in-situ testing of actual smoke control systems, on the other hand, must not permit damage as a direct result of the test. It follows that a hot smoke test must use a fire smaller than the fire safety strategy's design size in most cases. This creates the question: how good is the hot smoke test in simulating the intended performance of the smoke control system? The present paper discusses methods for ensuring relevance between hot smoke tests and design performance.

2. A BRIEF HISTORY OF HOT SMOKE TESTS

The key distinguishing characteristics of a hot smoke test is the use of heat to generate buoyancy. This has been done in various ways.

One early ad-hoc method was to raise the air temperature in a room (e.g. a retail unit) adjacent to the space protected by the smoke control system, and then suddenly to remove the partition between room and space [2]. Because this method allows only limited input of heat (to avoid damage to the room) and creates a transient buoyant flow rather than a sustained flow, it may not be a fully relevant representation of a realistic design fire.

Another method was the use of a space heater emitting a fast jet of hot air. This jet can be directed against a baffle to destroy the horizontal momentum of the jet, allowing the gases to rise as a buoyant thermal plume [3,4]. The disadvantages of this approach are principally the difficulty of calculating entrainment into the jet; of identifying the dimensions of the "virtual source" of the thermal plume; and the practical difficulty of generating more than a few hundred kilowatts of heat.

The most realistic method is to burn fuel as an actual fire. An early ad-hoc exercise at Preston (UK) [5] in 1989 used builders' dry scrap wood as the fire. This showed that appreciable heat generation rates could be used safely in buildings – it also proved useful in identifying unsuspected leakage paths for smoke. One major drawback was the shortage of visible particulates in the smoke.

Subsequent hot smoke tests have mostly used ethyl alcohol, usually in the form of Industrial Methylated Spirits (IMS). This is convenient, virtually free of particulates in the fire gases and is of relatively low toxicity. Synthetic smoke is used to make the combustion products visible.

Work in Australia from 1989 using pyrotechnic smoke generators and IMS [e.g. 6,7] led to the publication of an Australian Standard for hot smoke tests [8] (originally published in 1996, now including 1999 revision). This only applies where the fire is directly below the final smoke reservoir of a smoke and heat exhaust ventilation system (SHEVS), which restricts its range of application.

In the UK, also through the 1990's, the Fire Research Station developed a similar method but using an oil-mist smoke to render visible the hot gases. FRS & IFSET together used this method in several major buildings [9,10].

3. ENSURING RELEVANCE OF THE HOT SMOKE TEST TO THE DESIGN CONDITION

Some hot smoke tests are done primarily to ensure that the equipment operates, and in the proper sequence. The Australian Standard [8], for example, is explicit in stating this as the objective of a hot smoke test. It does add, in clause C 1.2, that "where practical" it can be used to verify specified layer depths. It does not, however, tell the reader how to verify layer depths using test fires significantly smaller than the design fire.

Where there is a clearly applicable theoretical model underpinning the smoke control system's design (as is often the case with SHEVS), having a different smoke condition to the design case may not matter. The same theoretical model as was used for design can be used to predict the performance in the test. If there is a good match between observed performance and prediction in the test, there is increased confidence in the design.

Unfortunately there are some buildings where theoretical models are not clearly applicable. Even where CFD models are used for design, it is rare to find them used for predicting the test condition – often for reasons of cost.

It can be desirable to confirm whether the design, or its implementation by the installer(s), can achieve the design performance even where there is no theoretical model applied to both test and to design. In the case of a SHEVS, this will mean checking whether the smoke layer base stabilizes at the specified height. In the case of an impulse ventilation system, it would mean checking whether the hot layer is prevented from advancing too far against the air movements induced by the jetfans. It is important under such circumstances that the smoke movements conform to the design condition in the key parameters (usually depth and/or distance traveled) despite a much smaller fire having been used in the test.

4. SCALING

4.1 Background to Scaling

Scaling laws, where fundamental relationships are used to extrapolate from one condition to another, have been known for many years. Froude number scaling has been central to much experimental work over the years [11-13] especially in the use of small-scale physical models to study buoyant smoke flows. The same relationships can be used [e.g. 14] to convert between different sized fires at the same linear scale.

It is the purpose of the present paper to present a simple formulation of the conventional "scaling laws" and to propose how they can be used to create test fires, which will achieve very similar smoke depth and travel as in the design condition. It will also be shown how fan velocities (SHEVS exhaust fans; or impulse system jetfans) need to be modified to achieve the same objectives.

4.2 Simplified Froude Number Scaling

It is conventional in Froude number scaling to apply scaling only to fully-turbulent flow regimes. This means in practice that the Reynold's number must be large enough for D'Arcy's formula to hold, that is:

$$\Delta p \propto \rho u^2 \tag{1}$$

where Δp is a pressure difference (Pa) driving a gas flow (air and/or smoke) of density ρ (kgm^{-3}) at a velocity u (ms^{-1}).

Where flows are driven by buoyant pressures, we can write for the buoyant pressure:

$$\Delta p = \Delta \rho g h = \rho_o \frac{\theta}{T} g h \tag{2}$$

where ρ_o is ambient air density (kgm^{-3}), θ is the temperature above ambient (°C), T is ($T_o + \theta$) (K), T_o is the absolute ambient temperature (K), g is acceleration under gravity (ms^{-2}) and h is a characteristic height (m).

If we combine equations (1) and (2) and treating changes in T_o as being small, we get (in dimensional terms):

$$u^2 \propto \theta L \tag{3}$$

where L represents a characteristic length scale.

The volume flow rate across a surface of area S (m²) normal to the direction of flow (e.g. a cross-sectional area):

$$V = Su \propto \theta^{1/2} L^{5/2} \tag{4}$$

The mass flow rate (M) of gases is:

$$M = \rho V = \rho_o \frac{T_o V}{T} \tag{5}$$

Using equation (4):

$$M \propto \frac{\theta^{1/2}}{T} L^{5/2} \tag{6}$$

The convective heat flux Q is:

$$Q = M c \theta$$

where c is the specific heat of air at constant pressure.

Using equation (6):

$$Q \propto \frac{\theta^{3/2}}{T} L^{5/2} \tag{7}$$

The time for a given flow process to occur (τ) is related to length scale and velocity by:

$$\tau = \frac{L}{u} \propto L u^{-1} \propto \theta^{-1/2} L^{1/2} \tag{8}$$

using equation (3).

In a hot smoke test in the actual building, the linear scale is 1:1, i.e. L = 1 in the above formulae.

Hence we can summarize the scaling relationships relevant to the test as:

$$u \propto \theta^{1/2} \tag{9-1}$$

$$V \propto \theta^{1/2} \tag{9-2}$$

$$M \propto \frac{\theta^{1/2}}{T} \tag{9-3}$$

$$Q \propto \frac{\theta^{3/2}}{T} \tag{9-4}$$

$$\tau \propto \theta^{-\frac{1}{2}} \qquad (9\text{-}5)$$

These relationships apply within the bulk of the smoky gases. They do not apply in the same way to the fires, or to fans. If the overall system is to behave in the expected manner, it is necessary to specify test fires and to specify changes to the fan exhaust speeds, which mimic the relationships inherent in the main smoky gas flows.

Provided that a design smoke temperature can be identified in or close to the initial fire plume, and that a maximum acceptable test smoke temperature can be specified in the same location, we can expect the remainder of the flow pattern, even if it is a complicated pattern of further entrainment and flows, to conform to the same scaling relationships. This assumes that heat losses from the smoke have relatively little effect on the flows – usually a reasonable approximation in practice. Hence if a suitable scaling can be established early in the flow, we can expect subsequent layer depths and travel to be closely similar in the test as in the design.

5. APPLICATION OF SCALING TO A SHEVS

5.1 Theory

SHEVS in particular are especially relevant to the development of Hot Smoke Tests, as this method of smoke control is particularly suited to protect escape routes in the same space as the fire. The design principles are simple (see Fig. 1):

- Provide some method to limit the fire size to a practicable value. This commonly implies the use of sprinklers as part of the SHEVS "package".
- Identify an appropriate size of fire on which to base the design, appropriate to the building and its occupancy.
- Create a smoke reservoir beneath the ceiling to contain thermally buoyant smoky gases, at a height safely above the people or contents being protected.
- Exhaust smoky gasses from the smoke reservoir at a rate to match or exceed the rate of entry of smoke from the fire into the smoke reservoir.
- Provide for sufficient cool, clean air to enter the building below the smoke reservoir to replace the gasses being removed.

The quantitative design of such systems is more complicated, and is described, for example, by Morgan et al. [15].

Typical design fires for a SHEVS can be several MegaWatts in size. Unfortunately, normal buildings are not designed to survive such fires undamaged. This creates a problem for the enforcer of safety regulations, who needs to be sure that the system designed for the building, and actually installed in that building, will actually fulfill its purpose in the event of a real fire.

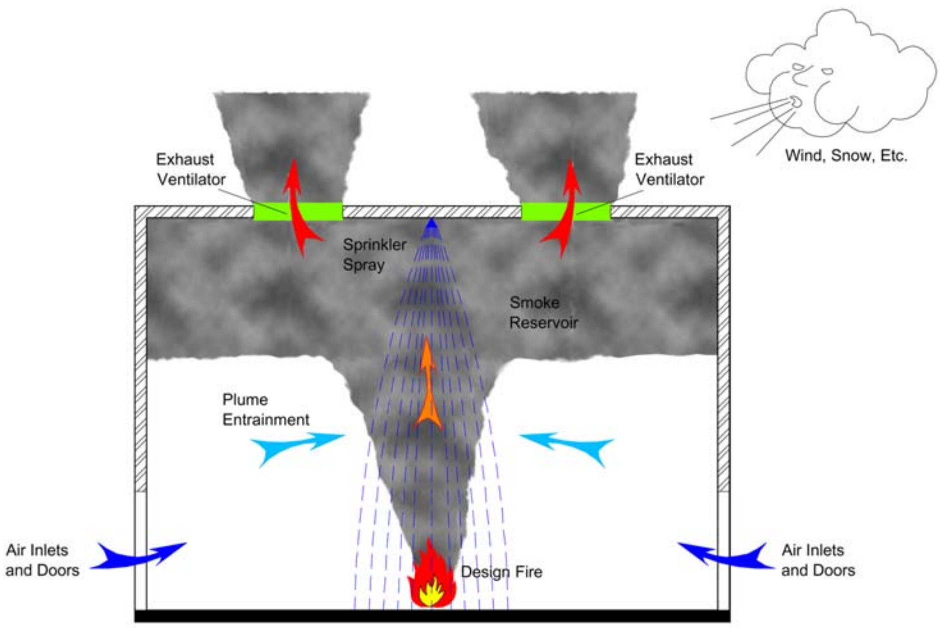

Fig. 1: The principles of smoke and heat exhaust ventilation

It will usually be possible to identify a predicted design temperature above ambient θ_1 close to the initial fire – for example where the initial plume reaches a smoke layer above (not necessarily in a smoke reservoir). In general, it will be possible to specify a maximum acceptable gas temperature at the same location during the hot smoke test θ_2 based on the need to keep a safety margin between this temperature and the lowest temperature likely to cause damage.

We can immediately use equations (9) to write:

$$u_2 = u_1\left(\frac{\theta_2}{\theta_1}\right)^{0.5} \qquad (10\text{-}1)$$

$$V_2 = V_1\left(\frac{\theta_2}{\theta_1}\right)^{0.5} \qquad (10\text{-}2)$$

$$M_2 = M_1\left(\frac{\theta_2^{1/2}}{T_2}\right)\left(\frac{T_1}{\theta_1^{1/2}}\right) \qquad (10\text{-}3)$$

$$Q_2 = Q_1\left(\frac{\theta_2^{3/2}}{T_2}\right)\left(\frac{T_1}{\theta_1^{3/2}}\right) \qquad (10\text{-}4)$$

$$\tau_2 = \tau_1\left(\frac{\theta_1}{\theta_2}\right)^{0.5} \qquad (10\text{-}5)$$

We can see immediately that any exhaust fan must have its exhaust capacity (velocity at the fan's exhaust orifice) reduced in the same proportion as equation (10-1) if we are to keep a constant linear scale, i.e. to expect the layer depth in the test to be the same as for the design condition. This could either be done using a variable-speed fan or, more practically, with a temporary mask reducing the fan intake area for the test.

Where we are defining θ_1 and θ_2 as applying close to the initial plume, we can use the "large fire plume equation" to deduce a test fire.

For the large-fire plume formula [15]:

$$M = C_e P Y^{3/2} \qquad (11)$$

where C_e is an entrainment constant which takes the value 1.9 for large-area rooms where the smoke layer's base is high above the fire; or the value 0.21 for large area rooms where the smoke layer's base is close above the fire (Morgan et al. [15] suggest that this value should be used where $Y \leq 3A_f^{0.5}$ and A_f is the area of the fire); or the value 0.34 for small rooms with an opening to one side of the fire such that the fire will "lean" away from the opening. C_e has the dimensions $kgs^{-1}m^{-5/2}$. P is the total fire perimeter (m), and Y is the clear height around the plume (m).

If we require Y to be the same for both fire sizes, we then see that

$$M \propto P$$

and from equation (10-3) we see

$$P_2 = P_1\left(\frac{\theta_2^{1/2}}{T_2}\right)\left(\frac{T_1}{\theta_1^{1/2}}\right) \qquad (12)$$

5.2 An Example

Assume a design fire of convective heat release rate Q_1 = 2500 kW, fire perimeter P_1 = 8.8 m, initial clear height Y_1 = 3.0 m.

Using equation (11), and following ref. [15] for a relatively low ceiling:

$C_e = 0.21$

From which,

$M = 9.60\ kgs^{-1}$

$\therefore\ \theta_1 = Q/Mc = 2500/9.60 \times 1.01 = 258°C$.

Assume for the purposes of this example that the largest acceptable value of θ_2 = 40°C and ambient = 15°C above ice point.

We then obtain from equation (10-4) that the total convective heat flux from the fire:

$$Q_2 = 2500\left(\frac{40^{3/2}}{328}\right)\left(\frac{546}{258^{3/2}}\right) = 254 \text{ kW}$$

The total fire perimeter, using equation (12), is

$$P_2 = 8.8\left(\frac{40^{1/2}}{328}\right)\left(\frac{546}{258^{1/2}}\right) = 5.77 \text{ m}$$

Assume N square fire trays having these total values of Q_2 and P_2, a total area of A_2, and where each tray has side W. Further assume alcohol (IMS) with a burning rate of approximately 700 kWm^{-2} [8].

$$Q_2 = 700\ A_2 = 700\ N.W^2 \qquad (13)$$

$$P_2 = N.4W \qquad (14)$$

From equation (13),

$$W^2 = \frac{254}{700N} \quad (15)$$

From equation (14),

$$W = \frac{5.77}{4N} \quad (16)$$

Divide equation (15) by equation (16),

W = 254/700 x 4/5.77 = 0.25 m

Substitute back into equation (14) and N = 5.77.

Therefore, to a reasonable approximation, 6 trays, each 0.25 m by 0.25 m, arranged in a well dispersed pattern within the "footprint" of the design fire (5 m^2, 2.2 m x 2.2 m) should ensure that layer depths observed in the test should correspond to those specified in the design. See for example Fig. 2. If there is a significant discrepancy, the design and/or installation need to be reviewed.

6. APPLICATION OF SCALING TO AN IMPULSE VENTILATION SYSTEM

6.1 Principle of Impulse Ventilation

Impulse, or Jetfan, ventilation systems are becoming increasingly popular as a form of smoke and fume ventilation in tunnels [16]. This technique has been developed as a means of providing fume ventilation for car parks. It is also claimed that they provide smoke ventilation in the event of a fire, with the purpose of providing smoke-free fire-fighting access to the burning car from one side, although at the expense of smoke-logging the car park on the other side of the fire.

While there is a growing feeling that jetfan ventilation needs to be tailored to the circumstances of each building, usually using CFD to confirm its effectiveness, there is no publicly available guidance on how these systems should be designed for optimum performance.

Hot, thermally buoyant smoky gases from a burning car will flow outwards beneath the ceiling as a ceiling jet. This jet floats on top of the colder, cleaner bulk air beneath. The speed of advance of such ceiling jets can typically be up to 5 ms^{-1}, depending on temperature and depth of the hot gases. The airspeed of the cold air beneath needed to overcome the advance of this ceiling jet needs to be at least equal, and in the opposite direction, to the speed of advance of the ceiling jet.

If an array of jet fans is to prevent the advance of the smoky ceiling jet, it must either induce a generally opposed bulk airflow at these high velocities, or it must disrupt the ceiling jet, creating turbulent mixing of colder air into the smoke to the extent that a slower and more practical bulk airspeed will remove the smoke in the desired direction. This implies that the jetfan exhausts ought to be optimised to oppose a ceiling jet, which may not be the same as for optimum fume ventilation (see Fig. 3). In practice this implies that all the jetfans can be directed towards the ceiling jet, wherever the fire may occur, suggesting the use of a large number of small fans. The consequence of this is that it is often impractical to direct fans to disrupt the ceiling jet, and reliance has to be placed on accelerating the bulk airflow instead.

For reasons of conservation of mass, the bulk airflow in an enclosed car park cannot be greater than is induced by the final exhaust fan, whatever the capacities of the jetfans.

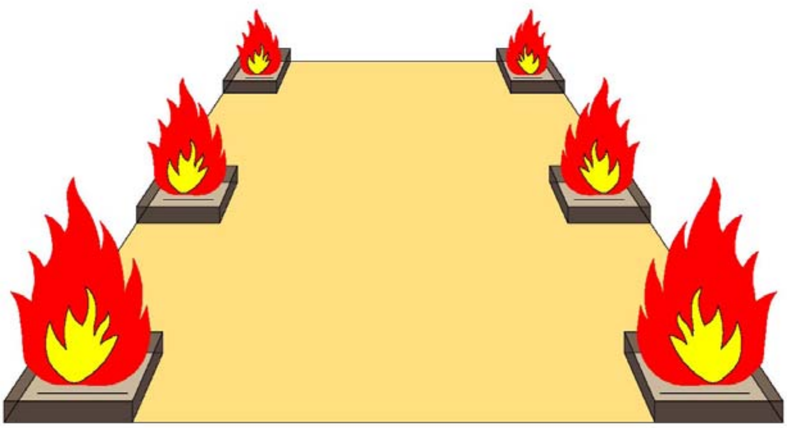

Fig. 2: Fire tray layout for the SHEVS example cited in Section 5.2

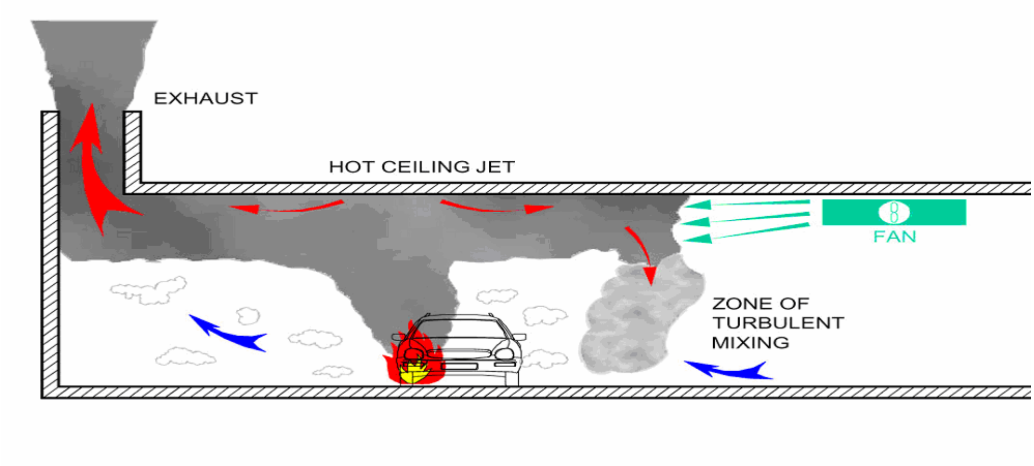

Fig. 3: Impulse (or Jetfan) smoke ventilation
Section view: Jet directly opposed to ceiling jet

These ideas lead to the following concerns:

- If the jetfans are too far apart in the direction at right angles to their exhaust direction, the smoky ceiling jet will advance between adjacent jetfans leading to eventual smokelogging of the fire-fighting approach (see Fig. 4).

- If downstand beams are parallel to the jetfan exhausts, they will channel both the ceiling jet (tending to maintain a higher speed in the ceiling jet) and the jetfan exhaust jet (due to the Coanda effect in the channel). This could allow smoke to advance past a line of jetfans (see Fig. 5) unless there is a jetfan in each and every channel, or the bulk air velocity is sufficient to oppose the channeled smoke flow.

- If downstand beams run at a right angle to the jetfan exhausts, they will deflect both the smoky ceiling jet and the jetfan exhaust jet downwards (see Fig. 6), enhancing the turbulent mixing and disruption of the ceiling jet.

The design of an impulse smoke control system first requires an assessment of the speed of advance of the ceiling jet traveling outwards from the fire – in the absence of an imposed airflow.

Hinkley [17] has discussed the speed of advance of the leading edge of a smoke layer (i.e. a ceiling jet) in a corridor or tunnel. This is explained in more detail in Section 6.2 below.

Others have discussed the velocity of a channeled ceiling jet (e.g. between downstand beams parallel to the flow) as an established or steady flow [e.g. 18].

Morgan et al. in Annex E of ref. [15] give formulae for characteristic layer velocities below transverse beams as well as between parallel beams.

Velocities in radial ceiling jets (under smooth ceilings) are given by ref. [18]. All of these formulae (except ref. [17]) will omit the resistance to flow of the air being displaced as the "nose" advances. Hence they will tend to overestimate the velocity of a "nose", thus erring on the side of caution when calculating the number of jetfans required.

All of these formulae require an initial calculation of the mass flow rate and convective heat flux reaching the ceiling from a design fire (e.g. a 3 MW, 12 m perimeter car fire if the design follows BR 368 [15]. Applying equation (11) for example can do this. It can usually be assumed to a reasonable approximation that Y in equation (11) (the clear height) can be set equal to the ceiling height, although more precise calculations are possible whereby the layer depth is calculated and is then used to modify Y, often as an iterative process.

The designer will now have calculated a velocity of advance of smoke appropriate to the circumstance. Let this be v_{crit}. If the advance of the smoke is to be halted, an opposing airflow of at least the same speed should be created by the jetfans.

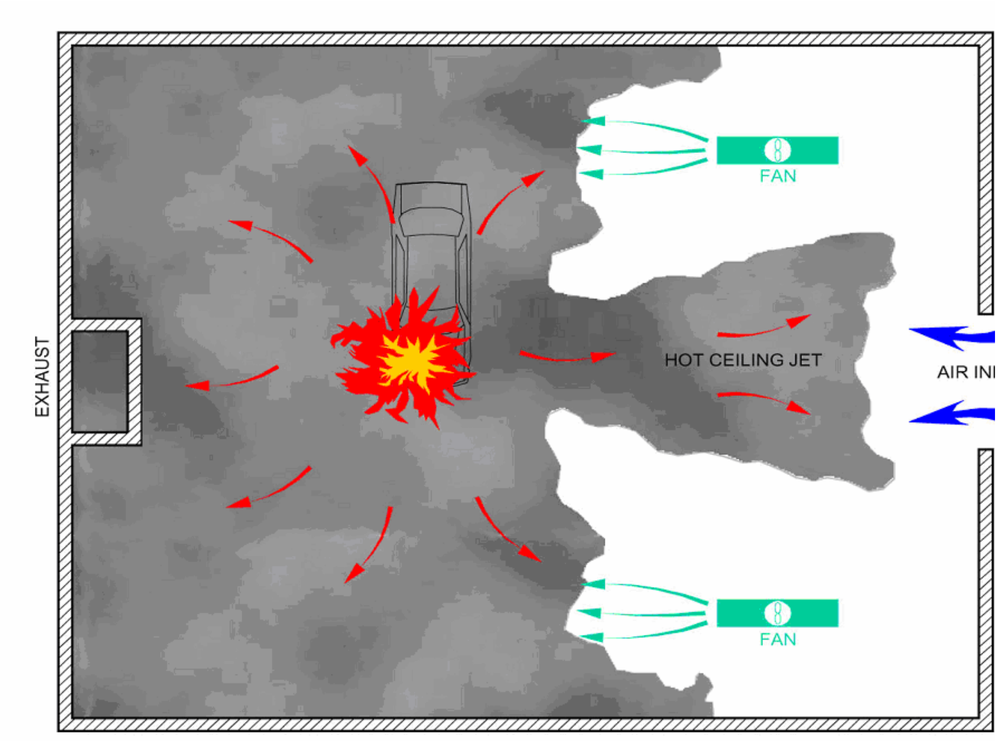

Fig. 4: Impulse (or Jetfan) smoke ventilation
Plan View: Possible effect of excessive fan separation

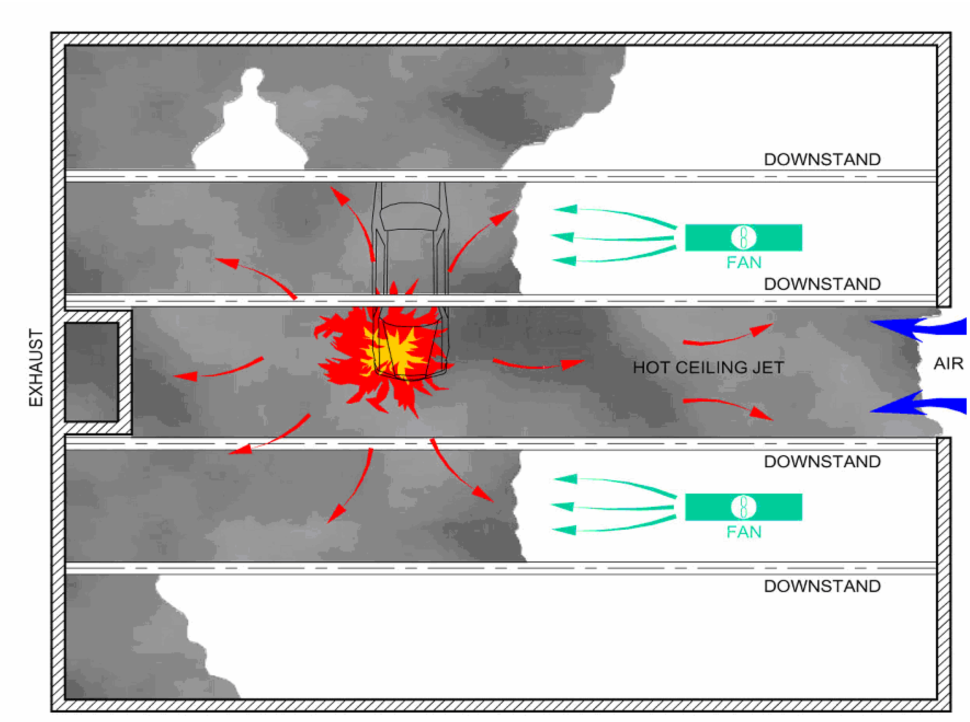

Fig. 5: Impulse (or Jetfan) smoke ventilation
Plan view: Possible effect of downstand beams parallel to fan jets

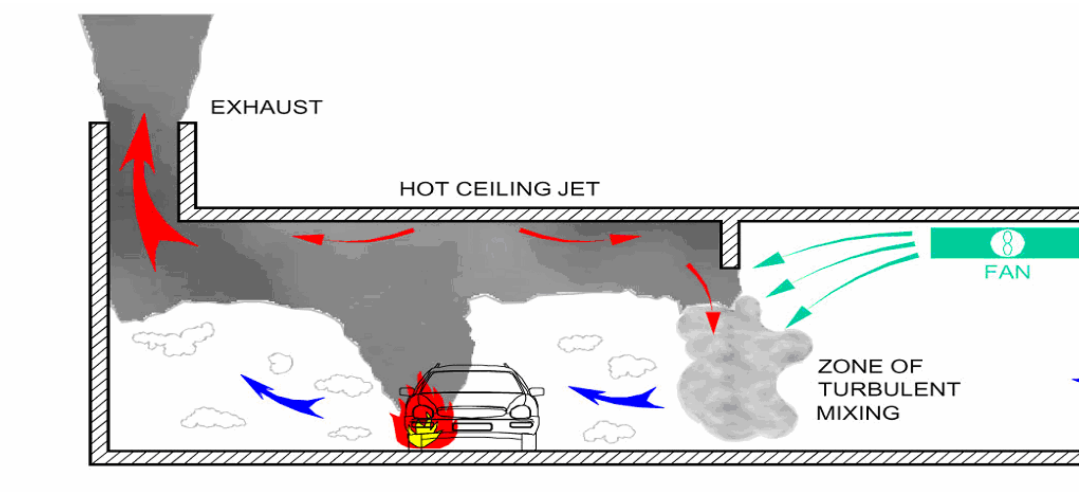

Fig. 6: Impulse (or Jetfan) smoke ventilation
Section View: Possible effect of downstand beams at right angles to fan jets

If we have N fans, each having an exhaust area A_{fan} and an exhaust velocity v_{fan}, (see Fig. 7 for an illustration of a jetfan in situ) the momentum in each jet at its exhaust is $\rho_o A_{fan} v^2_{fan}$. These jets will entrain air, eventually transferring all their momentum to the bulk airflow. If that airflow has a minimum velocity v_{crit} to stop the advance of the smoke layer, we have:

$$N\rho_0 A_{fan} v_{fan}^2 \geq \rho_0 A_x v_{crit}^2 \qquad (17)$$

where A_x is the cross sectional area of the car park (or tunnel) normal to the airflow.

For a specified jetfan characteristic, this allows N to be calculated. Note, however, that in practice some momentum is lost as the air exerts force on pillars, vehicles, and on obstacles in general. This phenomenon can be allowed for in the relatively simple case of a tunnel, but is extremely difficult to assess for a car park – especially one of large area. The effect is to increase the number of jetfans required for the system to work effectively. It is usual, even for tunnels, to adopt CFD modeling to confirm the effectiveness of a proposed design. It is unusual, however, to find that a hot smoke test condition has also been modeled using CFD.

6.2 Theory of Scaling "Nose" Flows

The fundamental equations governing smoke flows will be the same as in Sections 4 and 5 above, although the design objective is to prevent smoke spreading against the fan exhausts.

Thermally buoyant smoke layers advance beneath a ceiling by displacing the air in front of the "nose" of the smoke layer. This air is effectively pushed downwards by the layer. The energy required to do this comes from the smoke layer and so displacing this air can be regarded as a resistance to the "nose" of the layer flow – an effect absent in a flowing established smoke layer.

Hinkley [17] has shown (see his equation (16), modified for higher temperature by setting $u' = u(T/T_o)^{1/3}$) that the velocity of advance of the "nose" takes the form:

$$\frac{v_{nose}}{u'C} = \left(\frac{(h-d)(2h-d)}{h(h+d)}\right)^{1/3} \qquad (18)$$

where h is the height of a tunnel or channel, d is the buoyant layer depth and

$$u' = \left(\frac{gQT}{c\rho_o T_o^2 W}\right)^{1/3} \qquad (19)$$

where W is the width of the tunnel or channel.

C is an empirical constant found by Hinkley [17] to be approximately 0.5. Note that Hinkley speculated that C would tend to 1.0 as the advance of the nose was slowed by an opposing bulk airflow, due to a reduction in friction at the ceiling. We should recognize, however, that flow resistances due to friction at a smooth ceiling are likely to be smaller than those due to displacement of air in front of the "nose" – which would depend on the relative speed of the buoyant layer to the bulk air. Hence C is more likely to be near the empirical value even when the "nose" has zero net speed relative to the ceiling.

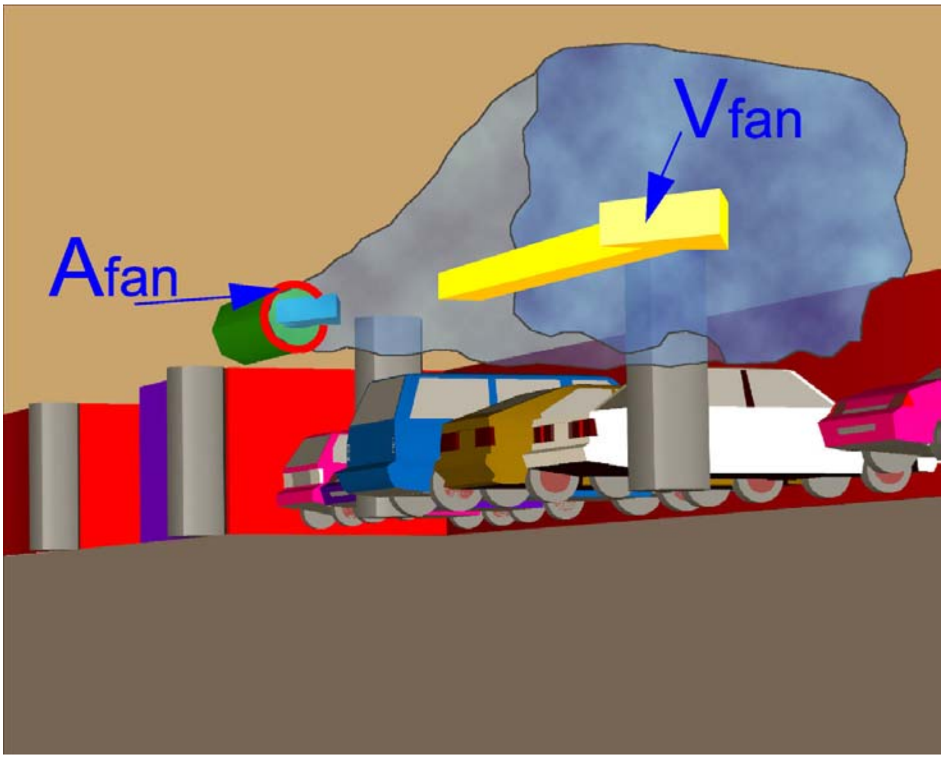

Fig. 7: The exhaust jet from a jetfan mounted close beneath a car park ceiling

Hence:

$$v_{nose} = C\left(\frac{gQT}{c\rho_0 T_o^2 W}\right)^{1/3}\left(\frac{(h-d)(2h-d)}{h(h+d)}\right)^{1/3} \quad (20)$$

If we want one-to-one linear scaling, we can substitute equation (9-4) into equation (20), leaving us with:

$$v_{nose} \propto \left(\frac{\theta^{3/2}}{T}T\right)^{1/3} \propto \theta^{1/2} \quad (21)$$

As equation (21) is the same as equation (9-1), we conclude that the speed of advance of the "nose" of the layer, which is the crucial parameter for success of an "impulse" smoke control system, obeys the same scaling rules as the rest of the smoke flow.

It follows that for smoke depths and distances reached by the smoke against opposing flows to be the same in the hot smoke test as for the design fire, all fans including both jetfans and smoke exhaust fans should be adapted, as for the SHEVS case discussed in Section 5 above, so that their exhaust velocities comply with equation (9-1).

In practice, this will mean that whenever the test temperature θ_2 takes a lower value than the design temperature θ_1, the jetfan volume flow rates as well as the exhaust fan volume flow rates should be reduced according to equation (10-2). It also follows that the hot smoke test fire should be established using equations (10-4) and (12) in the same way as discussed for SHEVS in Section 5.

6.3 An Example of Scaling Applied to a Hypothetical Car Park

Consider a hypothetical car park fitted with an impulse ventilation system. It is desired to carry out a Hot Smoke Test in order to establish the limits of smoke travel for the design fire (which in turn was chosen to be a 3 MW, 12 m perimeter fire as suggested by Morgan et al. [15]).

For the purposes of this example, we can take the height of the ceiling above the floor as being 2.45 m. This is typical of many car parks.

We need to establish the design gas temperature at the ceiling, close to the point where the fire plume impinges on the ceiling. We can approximate by noting that the depth of a ceiling jet is approximately one-tenth the ceiling height. We can now apply equation (11) to the fire plume with a clear height of 2.25 m. This yields the result that the mass flow rate entering the ceiling layer is 8.5 kgs^{-1}.

Similarly to the SHEVS example, we can take

$$\theta_1 = \frac{Q}{Mc} = \frac{3000}{8.5x1.01} = 350^o C$$

The maximum allowable gas temperature at the same location in the Hot Smoke Test will depend on the materials present and the extent of thermal protection introduced specifically for the test. Let us assume for this example that we will limit the test temperature rise above ambient at this location to 40^{o}C. We can now apply the scaling relationships derived earlier.

Using equation (10-4), we see that the convective heat flux from the test fire becomes 225 kW.

Using equation (12), we see that the total fire perimeter in the test should be 7.9 m.

For Industrial Methylated Spirit (burning at 700 kWm^{-2}), the simultaneous requirements of 225 kW and 7.9 m perimeter can be satisfied using 12 trays, of 0.16 m x 0.16 m each. These should be placed within the "footprint"of a design fire (see for example Fig. 8).

Using equation (10-2), the volume flow rates of both the jetfans and the smoke exhaust fans during the test need to be 0.34 times the design flow rates i.e. effectively one-third.

7. PRACTICAL IMPLICATION FOR HOT SMOKE TESTING

a) Without adopting a fire tray pattern which corresponds to the scaling relationships in the gas flows, the observed smoke depths and/or distances traveled by smoke will not correspond to the design predictions.

b) Where fans are present, their exhaust velocities need to be altered to conform to the scaling relationships in the gas flows, otherwise the observed smoke depths and/or distances traveled by smoke will not correspond to the design predictions.

c) Unless scaling is taken into account when specifying the hot smoke test fire and any fans involved, the full design performance of a smoke control system cannot be properly assessed.

d) The exception to a) to c) above is when the same calculation procedures have been used for both the design condition and for the hot smoke test, and is fully appropriate to both conditions. In this case, a good match between prediction and observation for the hot smoke test gives confidence in the application of the calculation procedure to the design condition.

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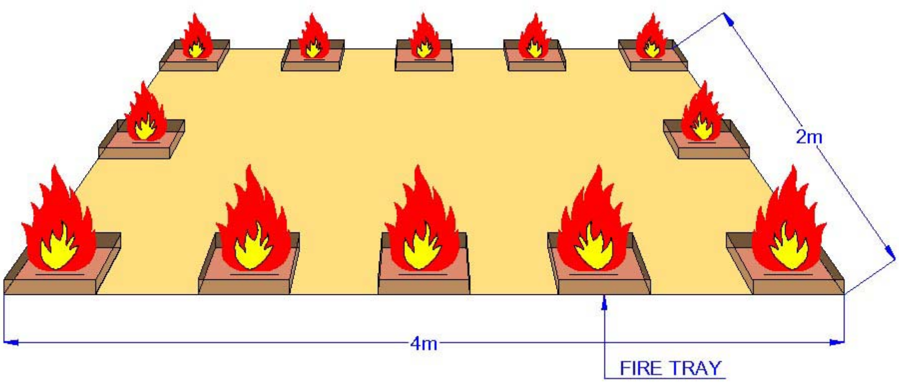

Fig. 8: Fire tray layout for the Car Park example of section 6.4

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