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THE ROYAL SOCIETY

Fires in tunnels

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The problem of fires in tunnels is reviewed and new experimental data are presented which show for possibly the first time that the established correlations between fire size and critical ventilation velocity appear to be incorrect at large fire sizes; the dependence of these data upon the particular tunnel geometry is also evident. The departure from previous expectations is attributed to non-Boussinesq effects and tilting of the fire plume in the downstream direction. The Boussinesq approximation, implicit in standard correlations, is considered to be inappropriate for a study of the dynamics of hot smoke layers due to the significant effects of large density gradients on the horizontal momentum equation.

Keywords: fire; tunnel; ventilation; critical velocity; tunnel geometry experiments; fire modelling

1. Introduction

Unlike the domestic compartment fires considered earlier (Bishop & Drysdale, this issue), serious fires underground are rare. Such incidents do occur, however, and in the case of long vehicle tunnels these events pose a potential threat to tunnel occupants if a safe evacuation route is not available; in the particular case of the Channel Tunnel, the Service Tunnel is designed to be a 'safe haven' during such emergencies: a concept which proved successful during the fire which occurred in November 1996 (figure 1; Winney 1997). The confinement afforded by a tunnel increases the severity of problems faced by the emergency services. These were discussed by Fuller (1985), following the Summit Tunnel fire in December 1984 (Jones 1985, figure 2), and include the provision of adequate communications, access to the site, the optimum duration for breathing apparatus and the physiological and psychological stresses induced by working in hot dense smoke. The presence of adequate ventilation was considered by Fuller to provide a significant tactical advantage when tackling such fires, by increasing the visibility and diluting toxic and flammable fumes. Eisner & Smith (1954) contrasted the relative ease of fighting well-developed fires in the open compared with smaller underground mine fires which often required sealing-off following unsuccessful attempts at fire-fighting. They concluded that it was essential for fire-fighters to be able to approach to within 11–14 m of a fire in order to effectively attack the fire. Evidently, the ability to fight an underground fire at relatively close range is assisted by the provision of forced ventilation which enables the fire to be attacked from the upstream side. However, progress can be impeded if smoke

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Figure 1. Aftermath of the Channel Tunnel fire in November 1996 (Photo courtesy of Eurotunnel/QA Photos Ltd).

moves against the ventilation stream due to buoyancy effects; a phenomenon known as *back-layering* (figure 3). These effects were modelled by Eisner & Smith (1954) using both a laboratory-scale hydraulic analogue and a full-scale experimental mine gallery. A quantitative explanation of the phenomenon was not advanced; however, an effective and simple method of counteracting an existing reverse smoke flow was demonstrated. It was shown that if a transverse screen was introduced in the lower half of the tunnel, the local blockage resulted in an increased ventilation velocity in the upper half of the tunnel which forced the smoke layer back towards the fire.

Ventilation systems are installed in long vehicle tunnels primarily to provide acceptable conditions during normal operation; excessive temperatures must be prevented and adequate fresh air must be supplied to the tunnel occupants. Three main configurations of mechanical ventilation are common; these are *semitransverse*, *fully transverse* and *longitudinal*. Semitransverse systems encompass those which supply fresh air only and those which extract vitiated air only; air is supplied or extracted continuously along the tunnel length through numerous adjustable apertures in the ventilation plenum which runs parallel to the tunnel axis (usually either above a

Figure 2. Flames over 120 m high burning above one of the Summit Tunnel's vent shafts in December 1984 (Yorkshire Television news footage).

false ceiling or below floor level). Fully transverse systems permit the independent regulation of both air supply and extraction along the tunnel length via two separate plenums. Transverse systems are common in road tunnels but for rail tunnels they become prohibitively expensive, and longitudinal systems dominate this area. The advantage of the longitudinal system is that the running bore also acts as the ventilation duct, thus obviating the need for either a separate ventilation bore, or an increase in the size of the running bore (fans are usually mounted in shafts off the tunnel, and not in the traffic space itself). The limitations of longitudinal systems become apparent during fire emergency conditions, especially in the severe case of a burning train with a fire in its centre and immobilized in the middle of the tunnel. The question then arises as to 'which fan configuration is best?' and indeed the whole issue of fire emergency procedures is complex (Vardy 1988; Winney 1997).

With a transverse system it is possible to extract smoke from the vicinity of a blaze into the exhaust plenum (Chan *et al*. 1988), but the operator of a longitudinal system does not have the option of local pollutant extraction. Longitudinal ventilation can, however, be employed to provide clear air upstream of the fire, creating a smoke-

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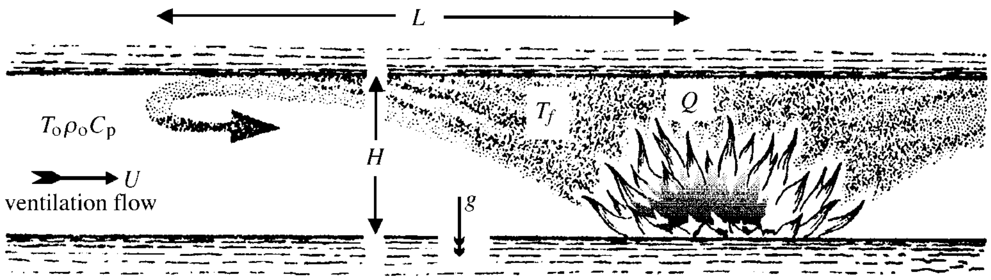

Figure 3. Smoke back-layering in a ventilated tunnel (after Eisner & Smith 1954).

free escape route and allowing the fire services to attend the fire in the manner proposed by Fuller (1985) and Eisner & Smith (1954). The obvious drawback of this strategy is the possibility that it may lead to a deterioration of the environment downstream of the fire where people may still be trapped. Notwithstanding this important consideration, the ability to provide positive smoke control remains a key element in the design of tunnel ventilation systems, the need for which is confirmed by experience. Several major vehicle tunnel fires have been well documented over the last 50 years (see, for example, Donato 1972, 1975; Egilsrud 1984; Jones 1985; Chan *et al*. 1988); the full range of forced ventilation configurations, including none at all, is represented in these incidents. An analysis of these events (see, for example, Egilsrud 1984) reveals a consistent need for positive smoke control to allow the fire to be attacked quickly and effectively; many of the incidents where this was not possible resulted in the abandonment of fire-fighting efforts with the fire being left to burn out.

Given this argument, two obvious questions require answers at the design stage; what is the maximum size of any possible fire (i.e. the *design fire*), and what corresponding magnitude of ventilation velocity is required to prevent backflow? The latter is often referred to as the *critical velocity* (U_{cr}), though there is some confusion over the exact definition of this quantity. Here it is taken to mean that bulk flow velocity which will prevent any backflow, rather than that which will arrest a ceiling smoke layer of finite length, L (figure 3). Design fire sizes relating to road tunnels were first suggested by Heselden (1976) and more recently the EUREKA-EU 499 'Firtun' project has produced some excellent quantitative data on the heat-release rates from large fires in tunnels (see, for example, French 1994). The critical velocity U_{cr} has conventionally been calculated using simple formulae (Heselden 1976; Bendelius & Hettinger 1988), derived from a consideration of the balance between inertial and buoyancy forces and backed by the results of small-scale experiments (§ 2 *c*) and validated against relatively sparse large-scale test data (§ 2 *b*). Recently there has been a great increase in tunnelling activity, largely as a result of environmental concerns, and thus the topic of smoke control by ventilation has been revisited. The EUREKA programme is one of many contemporary studies; another notable set of experiments has just been completed at the Memorial site (Luchian 1992). The construction of the Channel Tunnel acted as an initial stimulus to work in the United Kingdom. Aware of the arguments for positive smoke control as a procedural option, the Channel Tunnel operators and regulators commissioned a series of experiments in a large facility at the Health and Safety Laboratory, Buxton, UK (Bettis *et al*. 1993, 1994*a*). The aim was to investigate the quality of the tunnel environment both up- and downstream of a severe fire in both an empty tunnel and one occupied by a HGV Shuttle Train. It was also intended that the experimental data would be used to test the predictions of mathematical models.

This paper reviews some of the experimental and modelling techniques available for assessing tunnel conditions in the event of a fire and presents some new large-scale data on the backflow of smoke against a longitudinal ventilation system modelled on the Channel Tunnel geometry; it is shown that established empirical relationships of the types reported by Heselden (1976) and Bendelius & Hettinger (1988), and used widely by tunnel designers, become unreliable in the case of large fires. The new data underline the implicit dangers associated with the extrapolation of empirical relationships outside their valid domain.

2. Experiments

(*a*) *General considerations*

Experimental data can be applied directly to practical situations, providing the tests are *similar* to real fires in tunnels, both in geometry and scale. Using dimensional analysis, scaling rules can be devised to extrapolate experimental conditions to those in 'similar' situations with different dimensions (Spalding 1963; Williams 1969; Quintiere 1989). Clearly, this introduces uncertainty, since it is not possible to 'scale' faithfully all the processes occurring in a fire, but only those considered the most important; this 'partial modelling' approach has been discussed by Spalding (1963). Two major assumptions are common when modelling buoyant smoke propagation, namely that the geometry is reproduced accurately and that the Froude number best represents the dynamics of the problem (and hence must remain numerically equal at model- and full-scale). This approach maintains the balance of inertial to buoyancy forces, but does not correctly scale many other aspects of the fire. Thus it violates correct scaling of parameters and processes such as radiation, fuel bed geometry and heat transfer rates. The latter occurs because Reynolds number similarity is not preserved.

In such experiments, the fire is regarded throughout as a source of heat and buoyant flow only. On this basis the heat output varies as $l^{5/2}$, where l is the ratio of the length-scale of the model to that of the prototype. It is comforting to note that, since the particular fire sources used in the recent HSL Buxton experiments exhibited some elements of ventilation control, there is some evidence (Drysdale 1985) that such fires do scale in this manner. Removing an interest in the details of near-fire phenomena, e.g. flame geometry and flame spread processes, removes many of the problems inherent in Froude scaling. Providing the Reynolds number is sufficiently high that the flow is fully developed and turbulent, such that Reynolds number effects are unimportant, then the interaction between the buoyant flows and the ventilation should be modelled accurately. The only aspect of the upstream flow not modelled correctly will be the heat transfer.

If, for example, the heat transfer surfaces are assumed to be flat and undergoing forced convection, typical heat transfer correlations are of the form

$$Nu \propto Re^{0.8} Pr^{0.3}, \tag{2.1}$$

where Nu, Re and Pr are the non-dimensional Nusselt, Reynolds and Prandtl numbers, respectively. For a Prandtl number near unity, the Stanton number is defined as

$$St = \frac{h}{\rho c_p U} = \tfrac{1}{2} C_{\mathrm{f}}, \tag{2.2}$$

where h is the heat transfer coefficient, c_p is the specific heat capacity of the fluid (at constant pressure), ρ and U are the density and velocity of the fluid, respectively, and C_{f} is the skin-friction coefficient (again dimensionless). However, the skin-friction coefficient is only a weak function of the Reynolds number (it is proportional to $Re^{0.3}$) and might be neglected. Note that C_{f} will be constant for a rough wall, but $St = \frac{1}{2} C_{\mathrm{f}}$ is not strictly valid for rough-wall flow. Thus, pragmatically, we expect the Stanton number to be about the same at both model and prototype scale, particularly if the scale reduction is modest. Froude modelling requires that velocity be proportional to $l^{1/2}$, and consequently the heat transfer coefficient will scale as $l^{1/2}$. In Froude modelling the temperature will be scaled directly and therefore the heat transfer per unit time per unit area will also scale as $l^{1/2}$.

The heat transfer within the prototype tunnel walls may also differ from the model, but, providing the lining is constructed of the same material and is thermally thick, the differences are probably minor. The implication for a real heat transfer rate scaling as $l^{1/2}$ is that the hot layer will cool more rapidly at the larger scale and thus the distance at which any backflow is arrested will be shorter than that observed in the model. However, the difference is likely to be small due to the probable dominance of turbulent mixing as a cooling mechanism. Froude modelling does also introduce a different time scale for heat transfer and flow dynamics. In this case it produces no great problem since the scale for solid and gas phase processes are substantially different. It is not possible to model radiative heat transfer; radiation will be smaller in the model than at full scale and in any event will only dominate heat transfer in the proximity of the fire. In the upstream region, where gas temperatures less than 250 °C are found, radiation will be unimportant compared to other heat transfer mechanisms. The utility of such an approach has yet to be tested rigorously. Oka *et al*. (1996) have reported the first attempt to reproduce fires on a one-tenth scale; the intention was to simulate the experimental configuration of Bettis *et al*. (1994*a*). Initial evidence, for the upstream region, where one would expect Froude modelling to apply, shows that the technique can be used with some success.

More typically, experiments are used for the assessment and development of empirical, analytical or numerical models which describe various aspects of fires in tunnels. However, to achieve this the available data must contain all the input parameters required by the models. Models of fires in tunnels typically require information on the fuel type and disposition, the flow of ventilation air and measurements which can be interpreted to give the heat output from the fire, probably as a time-history. To model this time-history, information is required on the geometry of the system and the materials of construction. Calorimetric, fuel mass loss or oxygen depletion techniques are used to calculate heat output. In the first of these it is important to measure all the temperature rises due to the fire, including those of the structure as well as the temperature and flow-rate of the exhaust air containing combustion products. In order to assess the performance of these models, experimental data on the tunnel environment are required. These may include physical (and/or chemical) information describing the spatial and temporal distribution of gaseous combustion products, radiation from the fire and possibly heat transfer to the tunnel walls, the latter particularly if longer term behaviour is important.

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The open literature contains a number of reported tests on fires in tunnels. These have been at a variety of scales, ranging from small laboratory rigs to full size tunnels, have used a number of different heat sources, and have been instrumented to a greater or lesser extent. In a recent review (Lea *et al*. 1995), a total of 35 papers have been identified as representing this work, although this list is by no means exhaustive. Unfortunately, however, most authors have reported in scant detail on heat output and ventilation flow rate. Most of the work which includes quantitative data on these parameters has tended to be at a small scale, totally divorced from that typical of operations, and presented little guidance as to how the results may be scaled. Only six of the 35 authors have presented sufficient data to allow any direct comparison with theoretical predictions.

(*b*) *Large-scale tests*

Large-scale tests are expensive and this factor tends to prohibit the installation of a comprehensive array of instrumentation and limit the total number of experiments which can be undertaken; such tests have historically provided 'tantalizing snapshots' of the tunnel fire phenomenon, but have always fallen short of providing sufficient data to completely validate the functional relationships derived at laboratory scale. Examples of well-known full-scale tunnel fire tests are the early Glasgow series (Heselden 1976), those at Zwenberg (Feizlmayr 1976) and some 'blind head' tunnel fires at Offeneg (Haerter 1994). Despite their renown, these tests fall into the 'tantalizing snapshot' category, primarily due to their inadequate heat output data. In contrast, the recent EUREKA 499 project has provided many useful data on tunnel fires. These tests were performed in a disused Norwegian mine tunnel, nominally 5.5 m high, 6.5 m wide and 2.3 km in length. Unfortunately the walls were rough and the cross-sectional area was highly variable. There was, however, comprehensive instrumentation of some large fires, involving many full-sized vehicles typically found in modern vehicle tunnels. One fire test involved an articulated lorry full of furniture which produced a maximum heat output of *ca.* 100 MW (French 1994). Assuming that the technique of oxygen consumption calorimetry proves reliable in these experimental configurations, this programme will add significantly to the available data, particularly in defining design basis fires.

The Memorial programme represents another large-scale test series which has just been carried out in a disused two-lane highway tunnel in Virginia, USA (Luchian 1992). The facility comprised a tunnel 850 m long with a 3.2% slope. Tests have included transverse, semitransverse and longitudinal ventilation regimes with fires of nominally 20, 50 and 100 MW provided by liquid pools and wooden cribs; the fire mitigation of foam and sprinklers was also examined. A programme of over 100 trials was required to cover the range of fire sizes, ventilation systems and rates, etc. The tunnel was comprehensively instrumented in both up- and downstream directions and it is anticipated that, again, provided the measurements taken to assess heat output are adequate, this programme should produce useful data for both model development and validation. Apte *et al*. (1991) have also presented a detailed study of fires at larger scale. These experiments have been used for developing a computational fluid dynamics (CFD) approach to modelling tunnel fires. A total of 23 experiments were conducted using longitudinal ventilation in a simulated mine gallery some 2.4 m high, 5.4 m wide and 130 m (*ca.* 55 tunnel heights) long. Temperature contours were

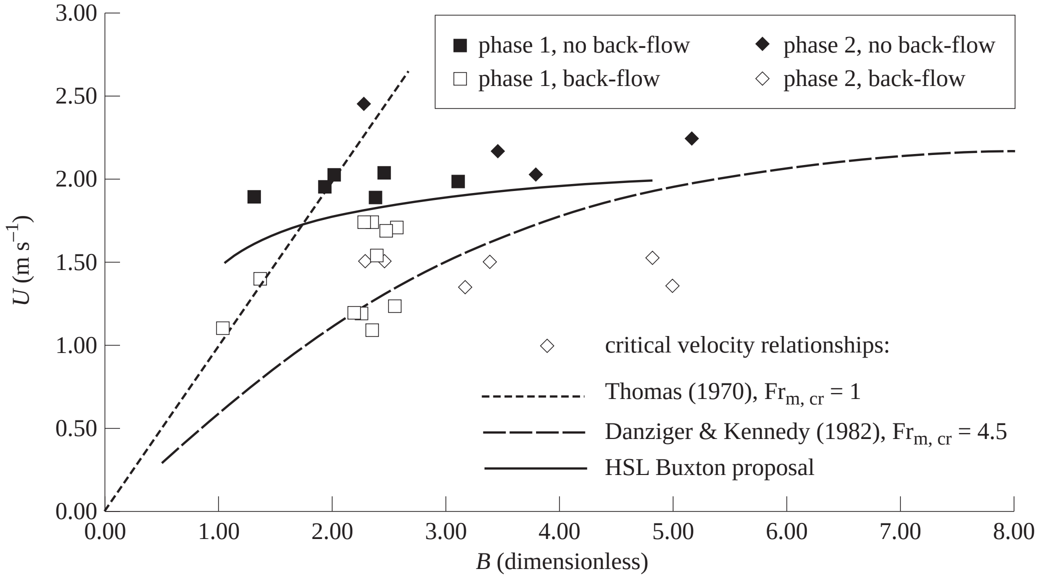

Figure 4. Correlation of large-scale HSL data on smoke backflow (adapted form Lea 1995).

presented for eight of the tests with octane pool fires ranging from 0.5 to 12 MW and mean ventilation velocities from 0.2 to 2 m s^{-1}.

An extensive series of experiments has recently been conducted at the HSL, Buxton (Bettis *et al*. 1993). These were carried out in a 366 m long, 2.56 m high tunnel with a cross-section of 5.4 m^2, shaped to a BS 229 standard colliery arch profile. Both obstructed- and open-tunnel situations were considered. The former involved one-third scale models of part of a heavy goods vehicle (HGV) shuttle train for the Channel Tunnel. The objective of the experiments was to provide data suitable for the validation of a CFD simulation of the interaction between the tunnel's longitudinal supplementary ventilation system (SVS) and a back-layering smoke flow. In the event, nine tests were carried out, using kerosene pools as the principal fire source generating between 2 and 18.6 MW heat output (equivalent to 31–290 MW at full scale), though the ventilation velocity was varied in the range 0.5–3.7 m s^{-1} during individual tests. A comprehensive data-set was obtained from up to *ca.* 150 sensors measuring temperatures, heat fluxes, gas concentrations and fluid velocities at locations from 50 m upstream to 200 m downstream of the fire. The heat output from the experimental fires was determined using oxygen consumption calorimetry at the tunnel cross-section 100 m downstream of the fire; mean values of the longitudinal velocity and oxygen concentration were obtained from between 10 and 15 discrete measurements at various points in this plane. A significant source of error is the relatively low magnitude of the air velocity during such experiments; therefore Q was also calculated from the measured rate of fuel mass loss combined with a value for combustion efficiency (χ) and here the expected error was of the order of 10%.

The results from these tests suggested that the value of critical velocity tended to some near constant value with increasing heat output and thus did not conform to the simple theory developed by Thomas (1970) and others, where $U_{cr} \propto Q$. Consequently, a further set of experiments in an unobstructed tunnel, initially intended to validate a phenomenological model of the downstream region, was modified to fulfil a dual purpose and further examine the movement of combustion products against the longitudinal ventilation (Bettis *et al*. 1994*a*). This series comprised 11 kerosene pool fires plus one wooden crib fire, during which the ventilation flow was adjusted to produce 'steady-state' combinations of heat output and ventilation rate for periods in excess of 4 min duration. The heat output and ventilation rate were varied within the ranges 0.3–4.0 MW and 1.1–2.1 m s^{-1}, respectively. The extent of any backflow was determined within *ca.* ±2.25 m using a combination of video cameras and near-ceiling temperature measurements. Figure 4, adapted from Lea (1995), summarizes the data from these large-scale experiments and compares them with the predictions of simple relationships which have been used for the design of tunnel ventilation systems.

The terms 'phase 1' and 'phase 2' refer, respectively, to the unobstructed and obstructed geometries. The velocities in the latter have been corrected for the presence of the obstacles which amounted to some 25% of the unobstructed tunnel area; therefore the velocity reported is the mean value in the annular space upstream of the fire. In addition, the radiative component has been removed from all heat outputs so that the convective part only (Q) is considered. The independent variable B, known as the 'buoyancy factor', is defined as

$$B = \left(\frac{gQH}{\rho_0 c_p A T_0} \right)^{1/3}, \tag{2.3}$$

where A is the tunnel area and the other quantities are shown in figure 3. The trend at high heat outputs and the divergence from current theories is clear. It should be noted that the ordinate U does not represent a 'critical velocity' as such, but is merely indicative of a period of steady-state conditions which may or may not be associated with smoke back-layering; in the context of figure 4, critical velocities will exist somewhere between the open symbols (smoke back-flow observed) and the solid symbols (no observed back-flow of smoke). The weak dependence of critical velocity with heat output was observed during the tests, particularly when the flaming extended up to and along the tunnel ceiling. In the downstream region it was observed that the growth of the stratified ceiling layer was in reasonable agreement with a simple predictive model based on mixing of a gravity current (Daish & Linden 1994); however, the distribution of smoke was observed not to follow that of temperature so that at large downstream distances the highest smoke densities were seen near to the ground.

(*c*) *Laboratory experiments*

The experiments of Bettis *et al*. (1993, 1994*a*) represent the most closely controlled and scrutinized set of large-scale tunnel fires reported to date. However, they still leave many questions unanswered. Small-scale investigations are attractive because they allow more control over the experimental conditions and are generally more economic, allowing parametric studies to be performed. Their use depends on the accuracy of the scaling model employed and care is required in the design of the experiment to ensure that the most important processes are scaled correctly and that dynamic similarity is retained. The US Bureau of Mines has carried out extensive research in this area and is typical of small-scale work in this area. Lee *et al*. (1979)

conducted laboratory-scale experiments using a 13.6 m long wind tunnel of 0.27 m^2 cross-section with an oak-lined burning working section of length 7.1 m. The wooden lining was confined to the roof plus the two side walls only, and was of variable length. The measured data included flame spread rate, ventilation flow characteristics, heat fluxes, gas temperatures and gas composition. Their results showed that the airflow induced by a given fan in the presence of a tunnel fire could be less than half the value attained in the same system in the absence of the fire. They further demonstrated how this 'throttling' phenomenon could lead to flow reversal of the type observed by Eisner & Smith (1954). A simple criterion was developed to ascertain whether or not backflow would occur, based on correlations of the reversed layer velocity, a density-modified Froude number (just upstream of the fire), and a Froude number based on far upstream conditions.

Similar experiments, using a coal-lined working section, were carried out by Chaiken *et al*. (1979) to investigate the same parameters as above, and also the response of fires to sealing, a form of 'passive' fire-fighting often undertaken in mines when 'active' measures are not feasible. Again, considerable reverse flow was observed in the upper level of the duct upstream of the fire, and again a Froude number argument was used to estimate the critical velocity required to prevent backflow. The results suggested that the ratio of the fire zone length to the duct diameter should be included as a non-dimensional scaling parameter. However, this conclusion is probably specific to similar experimental and prototype configurations where the length of the fire zone represents a significant proportion of the total tunnel length; in this case between $\frac{1}{26}$ and $\frac{3}{26}$. In addition, the entry length leading to the fire zone was only *ca.* $14H$.

An analogous reverse-flow phenomenon is also common in coal mines and occurs when methane gas escapes into the mine gallery at roof level. Being less dense than air, a stably stratified roof layer can form, and persist against a ventilating air flow. Since methane is flammable in concentrations between 5 and 15% in air, it is essential to dilute any outflow to less than 5%, and this is the main reason for ventilating coal mines. Heselden (1976) referred to research in this area in his discussion of road tunnel fires, and evolved an expression relating the velocity required to halt backflow to the thermal output of the fire. He also considered the effect of a longitudinally ventilated fire upon the tunnel environment downstream of the fire site. Vantelon *et al*. (1991) reported a programme of work carried out in a 0.15 m radius semicircular tunnel 3 m (only 20 tunnel heights) long. The work was specifically designed to study 'back-layering'. Using a flat gas burner, a test matrix with five fire sizes and five velocities was completed, although only a subset of these data were presented. The data are of dubious use principally due to the scale of the experiment and the small tunnel length.

Kwack *et al*. (1990) reported a test programme designed to study the flow of smoke through aircraft bodies, using a one-third scale model. The model facility was 0.76 m high and 0.52 m wide, although it is nor clear from the paper whether the cross-section was rectangular (which could be implied from the presentation of simple dimensions) or had a curved edge (more appropriate to a study of aircraft). The 'tunnel' was 9.2 m (i.e. 12 tunnel heights) long and four tests were reported, in varying detail, with fire sizes ranging from 246 to 335 kW and ventilation velocities from 0.58 to 0.87 m s^{-1}. Steady-state temperature distributions were presented for each test, together with some transient temperature data and some multipoint velocity data. Again, the influence of the short tunnel length is of concern. Xue *et al.* (1993) have carried out experiments to obtain data for model validation. The tests were performed in a circular duct of 0.25 m radius, fitted with a floor at *ca.* 0.1 m above the lowest point, and in a test section 8.45 m (21 tunnel heights) long. A premixed gas burner was employed, producing a heat output of 3 kW and two tests at velocities of 0.46 and 0.92 $\mathrm{m\,s^{-1}}$ were reported. In each case, two downstream temperature profiles were presented at each of four discrete times during each test. Also of note is the work by Hwang & Wargo (1986) who have made the most detailed study to date of the effects of slope on hot layer movement. Their work was on a small scale ($H \sim 0.3$ m) and covered a range of slopes up to 1 in 4. Fire sizes were quoted on the basis of flow rate to the gas burner used, so any estimates of heat output would require assumptions concerning the fuel and associated combustion efficiency during the tests. The work concentrated on the greater slopes, with 5° (1 in 11) being the smallest angle used. This is less useful for transport tunnels, where the inclines are generally less steep.

Oka *et al.* (1996) have reported the first attempt to reproduce tests from a large-scale programme in the laboratory. They have taken the experiments of Bettis *et al.* (1994*a*) and built a model of their facility at one-tenth scale in the laboratory, faithfully reproducing the geometry. Fire sizes and ventilating flows were then scaled by the application of Froude modelling and the flows upstream of the fire. The correlation of results with the large scale was extremely close with variations of critical velocity taking a one-third power-law dependence on heat output for small fires but tending to a near constant value when flaming extended over the height of the tunnel. Figure 5 shows some typical results for non-dimensionalized critical velocity against normalized heat release and compares large- and small-scale experiments. The trend of critical velocity and agreement of both sets of experiments is clearly seen. Thus for the first time the potential for laboratory modelling for this situation was demonstrated.

3. Tunnel fire models

(*a*) *Introductory comments*

To assess the hazards arising from tunnel fires and to plan effective mitigation strategies, it is necessary to have a prior understanding of the behaviour of fire and smoke movement in tunnel environments. It is not practicable to investigate every individual construction experimentally, hence predictive models are required. These models range from simple empirical relationships, through phenomenological or integral/zone models, to complex three-dimensional CFD simulations. All model types are potentially useful. Thus the simpler models are ideal for repeated applications, such as would be required in a risk assessment, where cost and practicality are also important. CFD is expensive to apply repeatedly and so is used primarily as a research tool. Ideally, the requirement is for a well-validated, yet accessible, model for use in ventilation system design and emergency procedure development.

The simulation of fires in longitudinally ventilated tunnels has received the greatest attention in the literature and is the focus of the present section; however, applications to transverse or semitransverse ventilation systems are also briefly noted. Close to the fire, the primary aim has been to predict the critical longitudinal ventilation velocity required to halt the upstream movement of combustion products, U_{cr}. The

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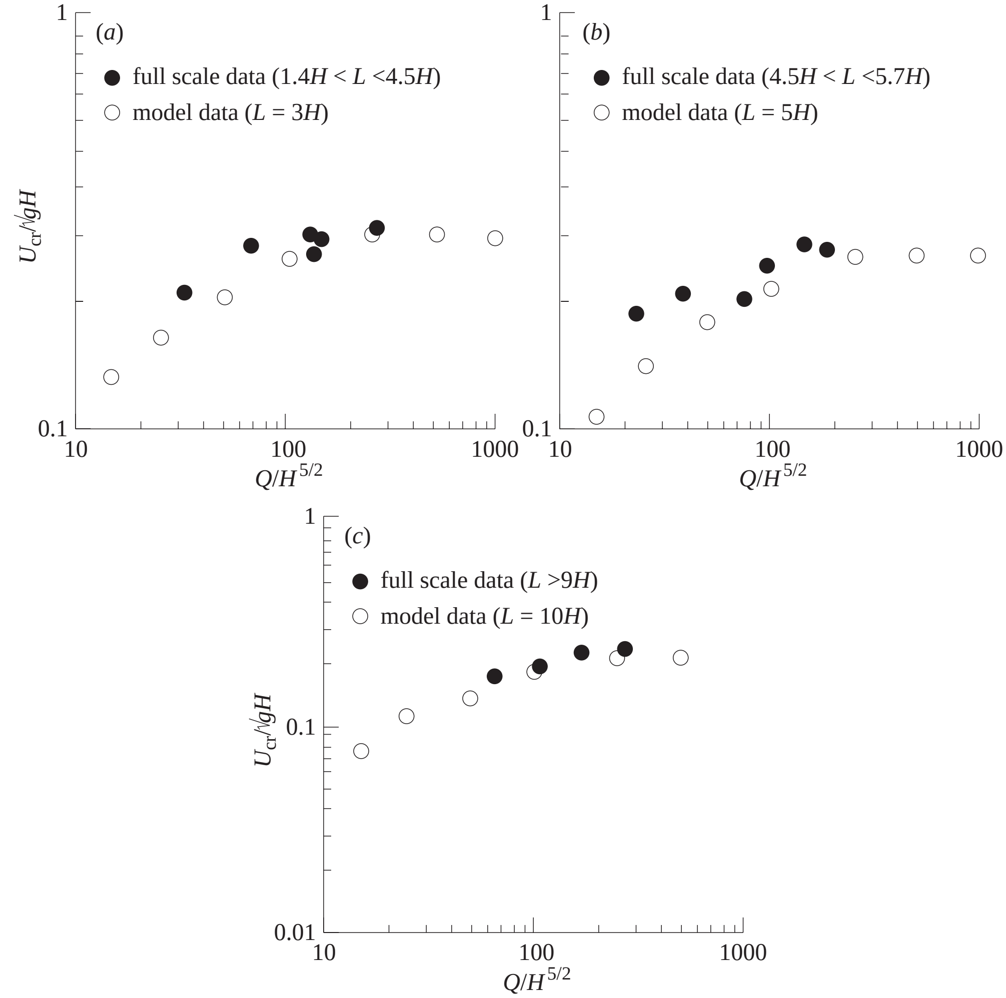

Figure 5. Variation of dimensionless critical velocity with normalized heat release rate (from Oka *et al*. 1996). (The extent of back-layering, L, is indicated in terms of the tunnel height, H.)

more sophisticated models, typified by CFD analyses, have also captured details of the complex flows in the immediate vicinity of the fire. Further downstream, where conditions are homogeneous, simple models have been devised to simulate the movement of combustion products through a complete network of tunnels. The objectives here are to describe the physical basis of these diverse models, to highlight their capabilities and inherent limitations, and to survey applications of the models. Experimental confirmation of model predictions is required periodically to ensure the reliability of the method; examples of such 'validation' exercises are also given in this section.

(*b*) *Simple empirical models*

In general, simple empirical models comprise one, or two, algebraic equations designed merely to specify the critical velocity needed to prevent upstream movement of smoke from a fire in a tunnel. They in no way seek to predict downstream conditions. Thomas (1970) was the first to propose a simple relationship to determine the critical velocity needed to prevent the upstream movement of smoke from fire in a tunnel. He reasoned that the flow character depended, in essence, on the ratio of buoyancy to inertial forces over a cross-section of the tunnel, and that this ratio could be described by a global parameter having the form of a modified Froude number, Fr_{m}:

$$Fr_{\mathrm{m}} = \frac{gH\Delta\theta}{U^2 T}, \tag{3.1}$$

where g is acceleration due to gravity, H is tunnel height, $\Delta\theta$ is the temperature rise above ambient, U is ventilation velocity and T is the hot layer temperature. Thomas assumed that the critical condition, when back-flow is just suppressed, occurs when Fr_{m} is of order unity, that is when the inertial and buoyancy forces are similar.

By substituting an expression relating $\Delta\theta$ and Q, the heat-release rate (convective component only), into (3.1), the following relation is derived:

$$U_{\mathrm{cr}} = k\left(\frac{gQ'}{\rho_0 c_p T}\right)^{1/3}, \tag{3.2}$$

where U_{cr} is the critical velocity, Q' is the heat release per unit width of tunnel W, ρ_0 is the ambient air density, c_p is the specific heat capacity (of air) and the constant k is of order unity. Most models described in this section for the determination of U_{cr} adopt forms which are very similar to that above. They are thus based on the notion that the dynamics of an upstream-propagating hot layer are governed by a single parameter, the Froude number. Assuming that a representative value for T can be identified, and that k can be prescribed from suitable experiments, then this modelling approach is clearly attractive because of its simplicity. Unfortunately, it does not stand up to close scrutiny. This is essentially because these models do not seek to account for the complex near-fire flow field and its interaction with the fire source and the particular tunnel under consideration. The possibility that large fires may have flaming regions extending axially over many tunnel heights is also not considered. The near-fire conditions, which are responsible for generating the upstream-propagating hot layer, may, in these circumstances, remain largely unchanged over a wide range of Q'. In this case the model can be expected to overestimate the critical velocity.

The failings of such models are graphically illustrated by the large-scale tunnel fire trials of Bettis *et al*. (1993, 1994*a*), described briefly in § 2 *b*. These show that, in this case, the expected cube-root dependency of U_{cr} on Q' does not seem to occur. Indeed U_{cr} appears to be near-independent of fire heat output in these trials. This finding is independently supported by the CFD simulations of Lea (1995), carried out to specifically address the U_{cr} versus Q' relation. For a tunnel geometry similar to that of Bettis *et al*., and over a similar range of heat output, the CFD data also suggest that U_{cr} is near-independent of Q'. The simple empirically based approach is thus not even qualitatively correct in this instance. Models of the form of equation (3.2) have typically been developed by a theoretical approach, as here, incorporating very limited experimental input, for example to provide a value for k. Such models are then often applied to tunnel fire scenarios far outside the range of the original experimental data used to develop the model. In these circumstances, given the complexity of tunnel fire physics, it should be no surprise if the models are found to be inaccurate outside of their experimentally validated range.

Thomas (1970), for example, has tested his theoretical model against data obtained from methyl alcohol fires of up to 50 kW in a 0.9 m^2 wind tunnel. The fuel was contained in 1 cm wide trays, located 1.5 m from the open end of the tunnel. Velocities of 1 m s^{-1} or less were found sufficient to control upstream-propagating smoke layers. Thomas found that $k = 1$ gave a fair correlation for these data. In addition, a single data point obtained from observations in an unspecified railway tunnel also agreed with this correlation. These small-scale experiments are clearly unrepresentative of full-scale tunnel fires in almost all respects. The single large-scale data point is of no value without an exploration of the parameter space in equation (3.2). To be fair, Thomas does caution against extrapolation of his findings to other geometries. However, the history of these simple models shows that such warnings have usually not been heeded.

Hinckley (1970) deduced a similar cube-root relationship, in this instance for the velocity of hot gases travelling along the underside of a shopping mall roof, initially open at one end only. By following a theoretical approach comparable to that of Thomas, Hinckley derived the velocity of these gases, v, to be

$$v = K'\left(\frac{gQT}{c_p\rho_0 T_0^2 W}\right)^{1/3}, \tag{3.3}$$

where T_0 is ambient temperature. The constant K' was found to have a value of 0.8 based on limited data on the movement of hot gas layers in relatively short corridors without forced ventilation. Hinckley defined Q as the 'heat content of the layer crossing a plane across the mall', which is again effectively the convective heat release from the fire. In some of these experiments the 'corridor' was formed from side screens hanging beneath a ceiling and was thus without a floor. The velocity of the 'nose', or front, of the layer, v', was given by a similar relationship, but with the inclusion of an algebraic function of the depth of the layer (d) and the height of the mall (H), designated here by K. Hinckley referred to the theoretical work of Benjamin (1968) on inviscid gravity currents of low-density difference, in giving an expression for v':

$$v' = CK\left(\frac{gQ}{c_p\rho_0 T_0 W}\right)^{1/3}, \tag{3.4}$$

where C is an empirical constant, taken by Benjamin to be 0.82 based on gravity current experiments.

The effect of a forced draught through an open-ended mall was also considered by Hinckley, and in this case the critical velocity is given by equation (3.4) with v' replaced by U_{cr}. K is constrained to take on values between 0.8 and 1.25, and C assumed to be approximately unity by Hinckley. In fact, Hinckley's relation for critical velocity, equation (3.4), has little foundation on experimental data from fires in tunnels or corridors. Rather, it relies on Benjamin's theory for the dynamics of low-density difference inviscid gravity currents. As such it would be surprising if it were valid for hot layer temperatures above about 250 °C. Although this relation bears some similarity to equation (3.3), it should be emphasized that even that expression remains untested by Hinckley for the real cases of interest, namely forced ventilated fires in tunnels. These observations are important, because it is Hinckley's

Table 1. *Smoke spread rates as calculated by Heselden (1976)*

(For fires in a hypothetical road tunnel 5 m high × 10 m wide and due to the notional fire sources indicated. Smoke is assumed to propagate symmetrically towards both ends of the tunnel at the initial velocity shown.)

notional fire source	car	van	lorry or coach	petrol spill 1	petrol spill 2
heat output from fire, Q (MW)	3	10	20	50	100
initial velocity of smoke layer, *ca.* $U_{\rm c}$ ($\rm m\,s^{-1}$)	1.3	2.2	3	5.3	6.7

work which Heselden (1976) used to calculate values of $U_{\rm cr}$ for hypothetical tunnel fires. Heselden's results (table 1) were used by the PIARC (1987) to inform its recommendations on design critical velocities for longitudinally ventilated road tunnels. Both the PIARC's recommendations and Heselden's original work are widely used as the basis for specifying fan requirements in vehicle tunnels.

Heselden interpreted Hinckley's theoretical work in a slightly different manner to that in which it was originally presented. Thus Heselden stated that the initial velocity of a smoke layer, $v_{\rm i}$, could be found from

$$v_{\rm i} = CK\left(\frac{gQT}{c_p\rho_0 T_0^2 W}\right)^{1/3}. \tag{3.5}$$

Again, the critical velocity is given upon replacement of $v_{\rm i}$ by $U_{\rm cr}$, which assumes that the velocity required to halt the motion of a propagating hot layer is equal to the initial velocity of that layer. Equation (3.5), in effect, extends Hinckley's relation for layers of low-density difference (3.4) to layers in which the density can be substantially different from ambient. Heselden (1976) assumed that K is equal to unity and fixed C at 0.8 by reference to the limited set of Glasgow Tunnel fire experiments (Heselden 1976). In these experiments, which took place in a naturally ventilated 690 m long tunnel open at both ends, the velocity of the propagating smoke layers was estimated from an average of upstream and downstream rates of advance, as determined by observers spaced at up to 37 m intervals. Such a crude determination of layer speed inevitably contains multiple sources of error. The heat output was not measured, apparently being estimated. From just three sets of experimental data Heselden then determined C, despite the fact that neither heat output nor critical velocities had ever been measured. It is startling that one of the supposed seminal works on the backing-up of smoke layers against longitudinal ventilation is based on data which are of questionable relevance, were crudely determined and were so sparse. An attempt was made by Heselden to compare the Ofenegg tunnel fires data (Haerter 1994) to predictions using (3.5). However, the results are of variable accuracy, and Heselden concluded that 'a reliable comparison is difficult for several reasons'.

The Subway Environmental Simulation code (SES), developed under the lead of Parsons Brinckerhoff Inc. for predicting ventilation flows in tunnel networks, also includes a simple model to calculate the critical velocity, devised by Danziger & Kennedy (1982). Once again, this is based on a Froude number modelling approach,

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similar to that of Thomas. The relevant relations are

$$U_{\mathrm{cr}} = K_{\mathrm{g}} k \left(\frac{gQH}{c_p \rho_0 A T} \right)^{1/3}, \tag{3.6}$$

$$T = \left(\frac{Q}{c_p \rho_0 A U_{\mathrm{cr}}} \right) + T_0. \tag{3.7}$$

In the above, Q should again be the convective heat-release rate from the fire, although this is not stated explicitly by Danziger & Kennedy (1982). The cross-sectional area of the tunnel appears as A and K_{g} is a 'grade correction factor', to be applied for fires in sloping tunnels and derived from the work of Bakke & Leach (1960), who studied methane layer propagation in sloping tunnels. However, the magnitude of the density difference, and the nature of the source of the buoyant flow are very different in these two cases. It is by no means certain that gradient effects can be represented in such a simple manner, nor even that Bakke & Leach's data are relevant to ventilated tunnel fires. The SES fire model predicts that the critical velocity rises as the fire heat output increases. However, the appearance of T in the denominator of equation (3.6) ensures that at large heat outputs the critical velocity tends to an asymptote of near-constant velocity.

This behaviour initially appears to show some similarity to that observed in the recent Buxton fire trials (figure 4). For the model results to remain physical though, T must be set to an upper limit concomitant with some maximum potential flame temperature. For very large heat outputs, T is thus fixed at this upper limit, which for further increases in fire size means that the critical velocity again rises with the one-third power of heat output. The value of the constant k was set to 0.61 by Danziger & Kennedy. This figure is based on experimental work carried out by the US Bureau of Mines on fires in small-scale wood-lined ducts, reported by Lee *et al*. (1979). Only four tests were carried out and yet again the applicability of these limited data to full-scale fire trials must be questioned. For instance, the duct is just $0.27\,\mathrm{m}^2$ and lined with fuel on all exposed surfaces, over much of its length. In addition, there are only 10 tunnel heights upstream from the fire and over this length the duct area at its open end decreases to just 55% of its nominal area. Under these conditions the flow will be far from fully developed and thus far removed from conditions encountered in reality for fires occurring well inside long vehicle (or mine) tunnels.

Danziger & Kennedy's value for k, of 0.61, contrasts to that of Thomas who recommended a value of unity, and Heselden who advocated a value of 0.8. These different k-values arise because the experimental measurements, on which they are based, derive from a wide variety of tunnel shapes, sizes and fire scenarios. The differences in the Froude number at which backing-up just occurs, $Fr_{\mathrm{m,cr}}$, are even more marked. This is due to the cube-root form of these relations. Thus $Fr_{\mathrm{m,cr}}$ ranges from unity in Thomas's model to 4.5 in the SES model. Notwithstanding the above, the SES fire model has often been used in tunnel ventilation system design. The model is also incorporated in D'Albrand & Bessiere's (1992) VENDIS-FS tunnel network code, developed at the Institut National de l'Environment Industriel et des Risques (INERIS), as well as Te Velde's (1988) zero-dimensional code for simulating flow in a vehicle tunnel incorporating slip roads.

A simple model for predicting the length of a backed-up smoke layer, L, is given by Vantelon *et al*. (1991). The model is based on experiments conducted in a 1.5 m long semicircular pipe of 15 cm radius, and is thus at very small scale. Vantelon found that the following relationship gives a good correlation of his data:

$$\frac{L}{H} \propto \left(\frac{gQ}{c_p \rho_0 T_0 U^3 H}\right)^{0.3}. \tag{3.8}$$

In Vantelon's experimental work, the backed-up layer length was only varied by about one pipe height at each value of Q. In addition, the heat outputs were tiny; less than 1 kW. Furthermore, the measurements were made at only one scale, so there is no experimental basis for including H as a parameter in equation (3.8), nor for expecting that the relationship is applicable to any other tunnel system. Taken together, these major deficiencies mean that the work is of little value.

Oka *et al*. (1996) have sought a simple explanation of the variation of critical velocity with heat output by examining the buoyancy head produced by fire plumes with flames falling well short of, or extending along, the ceiling. They used results obtained by McCaffrey (1979) for a free plume which suggest that the temperature, and hence the density difference, above a large fire is roughly constant for very large fires for all heights, z, and heat outputs, Q. The buoyancy head then becomes

$$\Delta P_{\text{buoyancy}} \propto H. \tag{3.9}$$

For a small fire the density difference takes the form

$$\Delta\rho \propto Q^{2/3}/z^{5/3}. \tag{3.10}$$

The buoyancy head is then

$$\Delta P_{\text{buoyancy}} = \int_0^H \Delta\rho_{\text{f}}\, \mathrm{d}z, \tag{3.11}$$

$$\Delta P_{\text{buoyancy}} \propto Q^{2/3}/z^{2/3}, \tag{3.12}$$

where H is the height of the tunnel. For no backflow to occur, the dynamic head due to the incoming ventilation must exceed the buoyancy head by some critical value, say C_{crit}:

$$\left(\frac{\Delta P_{\text{dynamic}}}{\Delta P_{\text{buoyancy}}}\right)_{\text{critical}} > C_{\text{crit}}. \tag{3.13}$$

Thus for large fires,

$$U > (C_{\text{crit}} H)^{1/2} \tag{3.14}$$

and the critical velocity is independent of heat output, whereas for small fires,

$$U > C_{\text{crit}}^{1/2} (Q/H)^{1/3} \tag{3.15}$$

and hence the critical velocity varies as $Q^{1/3}$. Thus there appears to be a satisfactory explanation for the experimentally observed variation of critical velocity with heat output.

Models for the prediction of smoke extraction rates required in transverse or semi-transverse ventilation systems are very rare. Spratt & Heselden (1974) present such a model, tested against experimental data from small- and full-scale experiments, though of building geometries rather than tunnels. One consequence of this work is that an optimum extraction rate appears to exist, at which smoke is being removed at the maximum volume flux V without fresh air from lower levels also being entrained. This exhaust rate is critically dependent on the depth of the hot layer d, thus

$$V \propto (T_0 \Delta\theta g d^5)^{0.5}/T. \quad (3.16)$$

Unfortunately, this relationship is untested for tunnel geometries and multiple extraction sites. Current tunnel design practice appears to be based around providing sufficient total suction capacity to cope with nominal smoke generation rates quoted by the PIARC.

Models such as the SES, VENDIS-FS and MFIRE (Chang *et al*. 1990), developed by the US Bureau of Mines, are more commonly used in the design of complete ventilation systems for tunnel networks and for modelling the overall response of these networks to fire. Typically, these models calculate the disturbed network ventilation in the event of fire and allow the user to follow the downstream time-development of smoke movement and its relative concentration. For simulation purposes, the network of tunnels is considered to be composed of closed circuits of airways which intersect at junctions. The equations for conservation of energy for each circuit, and mass conservation at each junction, are applied to give a system of algebraic equations which are solved iteratively.

Network-based approaches provide no detail of the local fire-generated flows nor their interactions with ventilation. This is because they assume that heat and products of combustion are uniformly distributed over a length of tunnel. Nevertheless, these techniques are useful for giving a global view of the consequences of fire in a tunnel network, allowing evacuation strategies to be planned and assessed. In addition, they can provide boundary conditions for more complex modelling methods. Network models appear to have received limited experimental validation in the event of fire, although there is little reason to suspect that they would give misleading results—at least when combustion products have cooled to near-ambient conditions.

(*c*) *Phenomenological models*

Phenomenological models attempt to predict the main features of fire-generated flows in unobstructed tunnels, both upstream and downstream, and their interaction with longitudinal ventilation. They thus provide more detail than the simple empirical approaches, but less than the multidimensional information available from CFD techniques. Solutions are typically achieved by solution of a set of ordinary differential equations. There are relatively few published models which fall into this category. The examples given below are due to Hwang *et al*. (1977), Daish & Linden (1994) and Charters *et al*. (1994). The first of these employs an integral approach, whilst Charters presents a zone model of tunnel fires. Daish & Linden's model is a hybrid of the two, using an integral method only for the hot stratified layer, coupled with an algebraic relation for the thickness of the mixing layer which exists below the hot layer. In each approach the domain of interest has typically been split into several distinct regions, for instance a plume impinging on the tunnel crown and downstream hot and cold layers. In this way, attempts are made to address the key phenomena which occur in identifiable regions of interest.

In the integral approach, one-dimensional integral equations for mass, momentum and energy conservation are approximated over each of these regions. The resulting ordinary differential equations are then solved using commonly available techniques.

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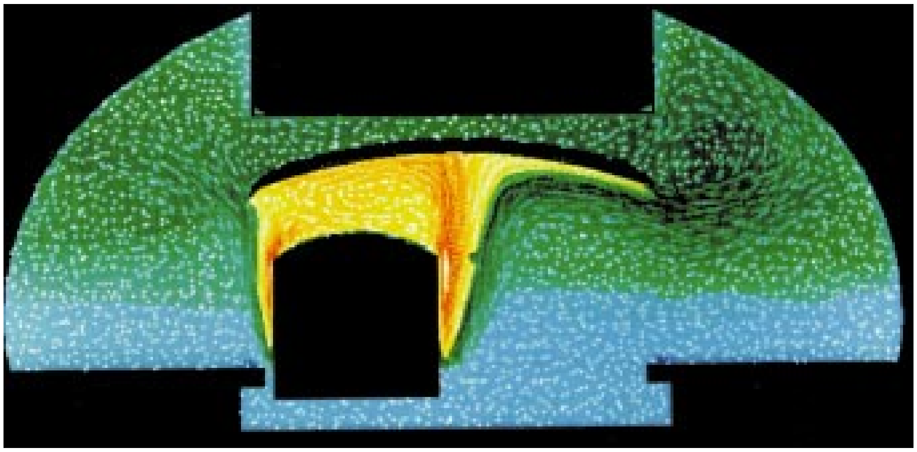

Figure 6. CFD simulation of fire in a metro system showing temperature and velocity fields in the fire plane (courtesy of Mott McDonald).

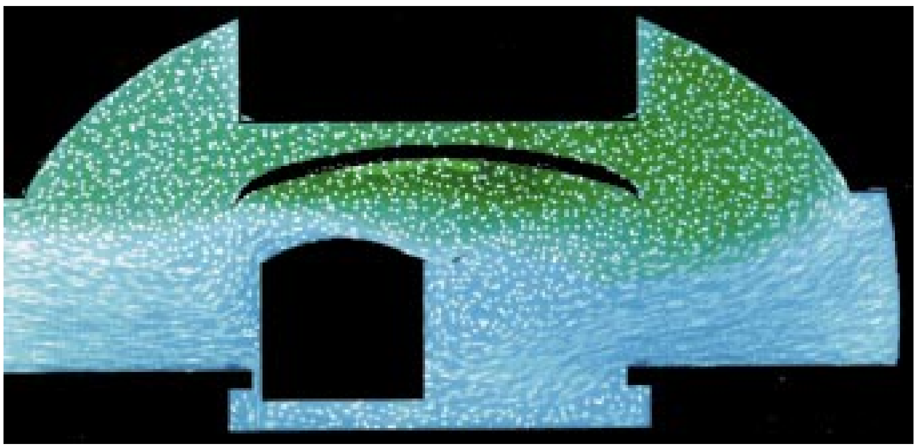

Figure 7. CFD simulation of fire in a metro system showing temperature and velocity fields in the plane of an open cross-passage upstream of the fire with air flow from left to right (courtesy of Mott McDonald).

With a zone modelling approach, the fire environment is split into discrete volumes and zero-dimensional relations are approximated over each of these regions, or zones. These relations express the exchange of mass, momentum and energy at zone boundaries, assuming uniform conditions within each zone. Consequently, the domain may be split into many zones in an attempt to retain some dimensional detail; in the case of a compartment fire suitable zones would be the flame plume, the hot smoke layer and the cold air layer below. The main advantage of this class of model is that, in principle, the major physical phenomena of importance are represented and so gross features such as the existence of a backed-up smoke layer, or evolution of ceiling layer temperatures, should be reproduced. In addition, the models run quickly on a personal computer. This approach does, however, demand that the important flow and heat transfer processes can be identified and understood *a priori*.

A major criticism of phenomenological approaches is that they are of necessity based on gross simplifications of a complex combustion and fluid flow scenario. This is acceptable if there is a strong experimental foundation for such simplifications, as exists with zone models of compartment fires. Unfortunately, it is debatable if the same can be said to be true of these approaches as applied to fires in tunnels.

Hwang *et al*. (1977) assumed that three distinct regions exist: a plume whose angle of inclination is affected by the imposed longitudinal ventilation, a plume-ceiling impingement zone referred to as a 'turning-region', and a hot ceiling layer. For each of these regions, assumptions are required to yield closed forms of the governing equations. For instance, the plume is initially assumed to be two-dimensional, vertical and with the fuel being instantaneously burned at its base. Entrainment of ambient air is estimated from plume theory, and properties are assumed to be uniform across the plume. Within the turning-region, the fluid density is assumed to be constant. In the ceiling layer, all properties are assumed to be uniform over the cross-section and entrainment rates are again estimated. In addition, there is no feedback from the computed upstream conditions to the plume region. The modelling of the plume is carried out simply to supply initial conditions for calculating the developing upstream and downstream hot layers. In reality, any changes in the upstream flow will affect the fire, with the two regions being coupled in a complex nonlinear manner. Each of these assumptions is open to question, especially those concerning the two-dimensionality of the plume. The only comparison which Hwang *et al*. make between model predictions and measurements is with a single data point due to Eisner & Smith (1954). In this instance the backed-up layer length is grossly underestimated.

Daish & Linden's model shows some similarity to that of Hwang *et al*., but is simpler and based on additional assumptions. The authors assume that the flow is composed of a hot plume and ceiling layers travelling both up- and downstream. In the region downstream from the fire, it is assumed that a layer of air at ambient temperature exists at low level. Such a layer proved difficult to identify in the experiments reported by Bettis *et al*. (1993, 1994*a*), but has previously been identified in other trials, probably with much lower heat outputs. This fire plume is considered to behave according to classical theory and its trajectory is assumed to be unaffected by imposed ventilation. The effect of neglecting the fire plume's inclination is, as yet, uncertain. However, several workers have observed that the plume can be inclined at substantial angles to the vertical. Hwang *et al*.'s simple model for the plume-ceiling impingement region indicates that inclinations of between 45 and 60° to the vertical are possible, and consequently the mass fractions of plume products travelling upstream could be as small as 15% and 7%, respectively.

The performance of Daish & Linden's model was evaluated by comparison with the data obtained from the recent comprehensive Buxton fire trials. The model allows predictions to be made of the evolution of the hot layers—their temperature, depth and propagation distance. Daish & Linden (1994) concluded that the model is able to give a fair representation of the existence of any backed-up flow, the evolution of temperature in the hot layer and the downstream distance at which the hot layer breaks down to well-mixed conditions, providing that '... fire is not too large and the ventilation not too strong'. The position at which breakdown of the hot layer is deemed to have occurred in the experimental trials is, however, somewhat arbitrary, because in reality this layer is not clearly defined in experimental data. The theoretical model does display the same behaviour of continued rise of critical velocity with fire size as the simpler models based on Thomas's work. The authors speculate that the resulting disagreement with the observations of recent experiments may be related to the assumptions made for entrainment into the fire plume or non-Boussinesq effects.

The model of Charters *et al*. (1994), referred to as FASIT (Fire growth And Smoke movement In Tunnels), was designed to simulate either natural ventilation conditions or longitudinal ventilation in which all combustion products travel downstream. It assumes that the near-fire region can be represented by a Gaussian plume and that downstream of the fire three distinct layers can be identified: a hot layer, a mixing layer and a cool layer (but still above ambient temperature). Each of these layers is subdivided into multiple zones. Model output consists of a time evolution of each layer's temperature and depth. Once again, the model is based on a number of assumptions. It has already been mentioned that the fire plume is assumed to be Gaussian, but the conditions for this assumption to hold true are unlikely to be met for fires with flaming over a substantial part of the tunnel height. The initial temperature of the hot layer is taken from the Gaussian plume model and its initial velocity is calculated using relation (3.2). Charters *et al*. (1994) claim that the length of any backed-up layer can be calculated using Vantelon's model and compare their results to temperature profiles measured downstream of a wood fire in a tunnel. The FASIT model captured the qualitative flow behaviour but generally over-predicted the measured temperatures by about 100 °C. It should be noted that in this experiment the fire source was a very large wooden crib, almost one-half the tunnel height, guaranteeing flame impingement on the tunnel crown. In these circumstances a Gaussian plume model is not tenable.

(*d*) *Approaches based on the Navier–Stokes equations*

The increasing availability of powerful computers, combined with the development of efficient numerical techniques, has spawned many complex mathematical models capable of analysing general problems in fluid mechanics through the solution of the fundamental conservation equations. These models are referred to generically as 'field models', in contrast to the 'zone' type considered in § 3 *c*. In a field model, the region of interest is divided into small volumes and the equations representing the conservation of momentum, energy and species concentration, etc., are solved at a point within each volume; this approach permits, in theory, a very fine resolution of the problem in terms of both space and time for all the parameters of interest. The need for powerful computers and efficient solution algorithms stems from the nonlinear nature of the problem. In a zone model, perhaps two or three regions are prescribed empirically. A field model comprises several tens of thousands of 'zones', coupled together through the fundamental equations of fluid motion. This approach allows a more mechanistic representation of the processes which occur to be inserted in the model. Consequently, there is less reliance on gross empirical approximations, and representations of phenomena such as combustion or turbulence can be incorporated at a more fundamental level. Sophisticated graphical post-processing of the raw numerical output data enables the most important features of the flow field to be visualized readily; for example, the temperature fields in figures 6 and 7 are defined by coloured contours (blue *ca.* 20 °C, red *ca.* 800 °C).

The flow behaviour associated with fires is usually three dimensional, turbulent and strongly influenced by buoyancy forces. Rhodes (1989) noted that the simplest

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field models needed to solve equations for velocity components in the coordinate directions (e.g. u, v, w in the Cartesian system), enthalpy (h) and pressure (p), and would employ a fixed value of turbulent viscosity (μ_t) to represent the effects of turbulent mixing. In these simple models, a fire was represented by a prescribed heat source within the computational domain. The general form of the field model equations was given by Rhodes (1989) as

$$\frac{\partial}{\partial t}(r\rho\phi) + \nabla \cdot (r\rho V_\phi - r\Gamma_\phi \nabla\phi) = rS_\phi \tag{3.17}$$

where r is the 'phase volume fraction', ρ is the density, ϕ is the dependent variable, V_ϕ is the velocity vector, Γ_ϕ is the 'exchange coefficient' (laminar or turbulent) and S_ϕ represents the source or sink terms (e.g. heat or mass). The numerical form of equation (3.17) is obtained by integration over a control volume. The resulting set of partial differential equations (PDEs) is solved for appropriate boundary conditions. The inclusion of turbulence into the models requires further assumptions since an exact description of turbulence effects would require an infinite set of PDEs. This is known as the 'closure problem' (Tritton 1988) and is conventionally overcome through the incorporation of an approximate turbulence model; the best known of these being the '$k \sim \varepsilon$' version.

Rhodes (1989) also considered various potential enhancements to the simple CFD fire model. In general terms these refinements involve the additional cell-wise solution of new equations for phenomena previously described by fixed values of global parameters. Such refinements include the following.

(i) *A turbulence model*

The most widely used turbulence model is the two-equation $k \sim \varepsilon$ approximation, in which the kinetic energy of turbulent fluctuations (k), and the rate of dissipation of turbulence energy (ε) are solved for each computational volume using additional PDEs. Although not a 'universal' model of turbulence, it is widely used, and has been developed and validated for many flows of engineering interest. A modified $k \sim \varepsilon$ model has been described by Woodburn & Britter (1995), which includes the effects of buoyancy and wall damping on the turbulence in a more realistic manner and is thus of particular relevance to tunnel fire modelling.

(ii) *A combustion model*

Combustion models require the solution of further transport equations, specifically for the concentrations of reacting and inert gaseous species. Source terms are also required for the prescription of any kinetically controlled reaction rates. The most basic implementation of a combustion model assumes a diffusion-controlled 'single step' reaction of the form: fuel + oxidant $\rightarrow$ product. This dictates an instantaneous reaction between any fuel and oxidant contained within a cell. More elaborate schemes can accommodate chemical kinetic effects by employing a combination of an Arrhenius expression (Drysdale 1985) and some formulation describing turbulent interactions. Whilst these approaches have their uses, they cannot be considered to be 'fundamental' as they do not address the numerous competing chemical reactions occurring in reality. Recent developments in the field modelling of fires have been reported by Moss (1995); in particular, the 'laminar flamelet' representation of combustion chemistry has been successfully applied to simple gaseous hydrocarbon flames. The emerging technology of direct numerical simulation (DNS) has the potential to model the fundamental chemical and physical phenomena associated with such complex combustion systems (Emerson 1995). The advantage of DNS is that the governing equations of turbulent combustion are solved without the approximations used in conventional CFD models. The drawback of the technique is that it relies on the availability of massive computing resources such as the massively parallel processing (MPP) capability of Edinburgh University's Cray T3D supercomputer. In the future, DNS may provide the means of simulating turbulent diffusion flames while retaining all of the important intermediate reaction steps.

(iii) *A radiation model*

Radiation can account for a large percentage of the heat release from a fire source (40–50% is not uncommon). Flux models use further transport equation solutions and therefore fit conveniently into the overall solution scheme. However, either discrete transfer or Monte Carlo methods are thought to be more accurate, and are therefore preferred. The accuracy of radiation models is further dependent on a knowledge of the absorption and scattering coefficients of the fluid medium and the emissivities of the various solid surfaces.

The boundary conditions also require specification and some are applied very simply during the set-up of a model, e.g. no-slip velocity conditions at walls. Heat losses through the walls can be calculated from the wall conductivity and the local temperature gradients. Provided that the boundary conditions and turbulence models are adequate, field models can be used to investigate flow configurations where a zone model would be worthless in the absence of established empirical data for a similar configuration. The accuracy of the models is affected by both numerical errors and physical approximations in the model. Numerical errors might arise from too coarse a computational grid, and may be reduced by successively refining the grid. Errors in the physical models are less easy to identify, and underline the continuing need for model validation against experiments. There have been numerous applications of field models by both fire researchers seeking validation and architects involved in building design. The validation studies have included, amongst others, room and compartment fires, tunnel fires, a simulated six-bed hospital ward and a one-sixth scale sports hall (Rhodes 1989). Of particular relevance are the reduced-scale experiments which followed the King's Cross escalator fire, and which were commissioned specifically to confirm the unexpected predictions of the mathematical model (Moodie & Jagger 1992).

The published literature on CFD studies of tunnel fire problems includes an unsteady two-dimensional model of a fire in a corridor (Ku *et al*. 1976), a similar model but with the addition of a combustion model (Brandeis & Bergmann 1983), and the work sponsored by the Department of Transport in the UK to develop the JASMINE code (Kumar & Cox 1986, 1988); this last code has been used extensively by the Fire Research Station. Recent contributions include those of Bettis *et al*. (1994*b*), Lea (1994, 1995) and Woodburn & Britter (1995). Ku *et al*. (1976) developed a two-dimensional computer model for solving the transient flows induced by a fire in a room/corridor geometry. Combustion effects were not modelled and the fire was represented by a volumetric heat source only. The results were compared

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with small-scale experimental configurations and gave fairly close agreement, except in the region close to the fire source. The discrepancies were thought to be due to the coarseness of the computational grid, inaccuracies in the turbulence model and the omission of a numerical model of radiation effects. Some simulations were also compared to analytical solutions and once again the agreement was very good.

Brandeis & Bergmann (1983) described another two-dimensional numerical model, designed to investigate the problem of accidental highway tunnel fires. This work was motivated by the Caldecott Tunnel fire in 1982 (Egilsrud 1984) and examined the effect of forced ventilation on the transient development of a hydrocarbon spill fire. In order to achieve this, the model included a mathematical representation of the idealized ('one-step') combustion reaction between hexane and air, although this was not used for all runs in order to simplify the model and to give computational economy. The general configuration of the model was chosen to be similar to the Caldecott Tunnel (within the constraints imposed by a two-dimensional grid), although a simulation of the actual incident fire scenario was not attempted. The model domain was 100 m in length and 7.6 m in height and contained a mesh 63 cells long by 25 cells high (giving a total of 1575 cells). The gravity vector was input having both a horizontal and vertical component such that a tunnel with 5° slope was modelled. A parametric study was performed varying the ventilation configuration, combustion reaction rate and external wind velocity; however, the investigation covered only the early phase of fire development so that simulations were of the order of 1.5 s duration. The external wind velocity was varied between 0.1 and 10 m s^{-1}, and the mass-release rate of the fuel was assumed to be between 0.1 and 0.2 kg s^{-1} per metre width of tunnel (it should be emphasized that this represents the rate of fuel consumption and not the rate of smoke production).

The study concluded that the combustion and fluid mechanics were closely coupled, and found that combustion was the primary factor affecting the flow field. The external wind and ventilation configuration were of secondary importance. With increasing reaction rate, the volume of hot combustion products (smoke) was increased. With increased external wind velocity, the area of the flame front was diminished, and was limited to the downstream side of the fire; in one run at 10 m s^{-1} it was predicted that ignition could not occur. Regarding the latter prediction, it was stated that although this was qualitatively correct, quantitative conclusions could not be drawn due to the coarseness of the grid and other simplifications in the model. Evidence of the initiation of stratification was observed, but the long-term stability of this phenomenon could not be ascertained from the results because of the short time scale of the simulations. The effect of the tunnel slope was found to be negligible, but no firm conclusions could be drawn since the upstream boundary conditions were unable to react to the downstream flow conditions. It was concluded that the model had proved adequate for qualitative work, but that a number of modifications were required. These included changes to the upstream and downstream boundaries and the inclusion of 'adaptive gridding' around the flame region in order to improve computational accuracy while retaining computational economy.

The work of Kumar & Cox (1986, 1988) represents some of the most relevant research into the use of CFD for tunnel fire ventilation problems. Their JASMINE model stems from the Fire Research Station's interest in developing field models to analyse fire and smoke spread in buildings. The CFD technique is hoped to replace, in part or whole, the role of full-scale testing once sufficient validation data have been

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accumulated. The model is similar in principle to that of Brandeis & Bergmann (1983), but the JASMINE model is fully three dimensional. In Kumar & Cox (1986), a series of steady-state and transient runs is described, these runs being performed to provide validation data for comparison with the Zwenbergtunnel experiments (Feizlmayr 1976). The effects of ventilation and tunnel gradient were investigated, and as in Brandeis & Bergmann (1983) the combustion was represented by a simple hexane–air reaction with a constant heat-release rate (and therefore reaction rate) for a given ventilation rate. Therefore, in this case the combustion model was used merely to predict the concentrations of various combustion products and was not capable of predicting the ignition characteristics of the fuel mixture computed by Brandeis & Bergmann (1983). The loss of heat due to convection and radiation were lumped together in a local empirical heat transfer coefficient which varied linearly between $5\ \mathrm{W\,m^{-2}\,K^{-1}}$ (at ambient temperature) and $40\ \mathrm{W\,m^{-2}\,K^{-1}}$ (at 100 °C above ambient). This approximation was taken from a previous zone-model heat-transfer assumption, and was adopted for simplicity. The approximation allows for heat to be transferred from the smoke to its surroundings by radiation but does not model radiative heat exchange between neighbouring cells in the smoke layer. This refinement is included in a later study by Kumar & Cox (1988).

The total length of the Zwenbergtunnel was 390 m, with a 5 m width and 4 m distance from the floor level to the underside of the false ceiling. The tunnel had a gradient of 2.18% sloping upwards from the south portal to the north portal, with the former being blocked off but fitted with a fan to provide pure longitudinal ventilation. The computer model assumed a vertical axis of symmetry along the length of the tunnel, so that the width of the model was reduced to 2.5 m. The grid was 29 cells long, 6 cells wide and 9 cells high, giving a total of 1566 cells, approximately equal to that used by Brandeis & Bergmann (1983). Several simulations were carried out with variations of ventilation configuration (natural, 2 and $4\ \mathrm{m\,s^{-1}}$ from south to north) and associated heat-release rate, and with/without the effect of gradient included. The results plotted the distribution of CO_2 and O_2 throughout the tunnel (the simple one-step reaction used did not allow for any production of CO), and the air temperature. Plots were obtained showing the propagation of the 80 °C temperature contour; this value was previously assumed to be the critical life-threatening temperature in the Ofenegg (Haerter 1994) and Zwenberg (Feizlmayr 1976) tunnel tests.

In the case of natural ventilation, the mean velocity of the layer was $1\ \mathrm{m\,s^{-1}}$ uphill towards the open portal in the horizontal tunnel run. When the gradient was included in the simulation, the velocity uphill was nearly doubled, at $1.8\ \mathrm{m\,s^{-1}}$. For the 2 and $4\ \mathrm{m\,s^{-1}}$ forced ventilation cases, the smoke velocities were 3.7 and $6.6\ \mathrm{m\,s^{-1}}$ for the horizontal case. With the sloping tunnel there was a slight increase in these values to 3.9 and $6.8\ \mathrm{m\,s^{-1}}$, respectively. In both forced ventilation cases the 80°C contour extended as far as the open portal (i.e. 282 m). The CO_2 concentration and O_2 depletion values only posed a threat to life at very close proximity to the fire. This prediction was in agreement with the Zwenberg tests (Feizlmayr 1976). In the natural ventilation run, a well-defined interface was set up between the outflowing hot gas layer in the upper region of the tunnel and the inflowing fresh air towards the fire region. This stratification was maintained in the steady-state solution. For the forced ventilation cases, fresh air was maintained behind the fire source, but the stratification was eroded downstream with increasing mean inlet velocity. The study concluded that the predictions in the 'far-field' (i.e. at fairly large distances from the fire) were in close agreement with the experiments, but that in the 'near-field' (close to the fire) the errors were increased. The discrepancies were ascribed to grid coarseness and inaccuracies in the simple turbulence–chemistry interaction theory. However, the model was thought to be of sufficient accuracy to be useful for the study of the tunnel environment in the case of ventilated fires. Gas composition predictions were reasonable in the forced ventilation cases but poor for the naturally ventilated run. The recommendations of the study were that an improved radiation treatment needed to be incorporated and that a time-dependent conduction equation was necessary at the solid boundaries.

The inclusion of a more elaborate radiation model and improved simulation of convective heat transfer at rough surfaces into the JASMINE code is described by Kumar & Cox (1988). The conclusions were that the radiation model improved the realism of the predictions and enabled a more accurate assessment of the hazard of thermal radiation to be made; however, the numerical predictions still showed the same variance with the experimental data as before. The work also highlighted the inadequacy of the present knowledge of convective heat-transfer coefficients for modern building materials.

The most widely acclaimed application of computational fluid dynamics to a tunnel fire configuration is undoubtedly the HARWELL-FLOW3D simulations of the steady-state flow during the King's Cross escalator fire on 18th November 1987 (Simcox *et al*. 1989). The work was carried out as part of the Health & Safety Executive's accident investigation. The aim of the computation was to ascertain the manner in which the smoke and combusting volatiles spread and which parameters dominated the development of the incident. The time-scale for the work was very short and this led to the problem having to be very much simplified. Combustion was not modelled and the fire was treated as a time-dependent heat source. Radiation effects were ignored and all solid walls were assumed to be adiabatic (no heat loss). The $k \sim \varepsilon$ turbulence model was used throughout the study. A 'body-fitted' computational grid was set up to model a single sloping escalator tunnel and the ticket booking hall; the grid was $49 \times 32 \times 12$ in size resulting in a total of 18 816 cells, approximately 12 times the size of the grids of Brandeis & Bergmann (1983) and Kumar & Cox (1986). The computations were the most complex ever solved using the software and initially some convergence problems were encountered. The problem was run on a CRAY-2 supercomputer which required 10 min CPU time to converge successfully to the steady-state solution.

Simulations of varying complexity were conducted, employing transient, steady, compressible and incompressible representations of the problem, and incorporating two distinct buoyancy models. In addition, different boundary conditions were imposed at the base of the escalator shaft in order to assess the impact of train movements upon the flow development. The results were in good qualitative agreement with the pattern of smoke damage to the ceiling; the distribution of temperature contours was found to be geometrically similar to the observed damage to the ceiling finishes. It was concluded that the method provided a good indicator of the path taken by flames and combustion products being convected away from the source of the fire. The most important result of the simulations was the prediction of the 'trench effect' at the fire source. This phenomenon, caused by a combination of the chimney and Coanda effects, resulted in the flames hugging the bottom of the escalator trench and thus preheating the wooden surfaces higher up the tunnel while appearing innocuous. It was this behaviour which prevented the early realization of the seriousness of the incident and which led to the catastrophic flashover. This prediction, that hot gases would be prevented from rising initially, was surprising but was later confirmed by one-third scale tests carried out by the Health & Safety Executive (Moodie & Jagger 1992). The HARWELL-FLOW3D model successfully predicted the suppression of buoyant effects by a combination of other fluid flow phenomena and therefore gives confidence in the method, and in particular the ability to model the turbulence–buoyancy interactions in a three-dimensional time-dependent situation once an adequate grid density is available.

Bettis *et al*. (1994*b*) compared the results of the one-third scale HSL 'phase 2' (i.e. obstructed geometry) tests discussed in § 2 *b* with FLOW3D simulations for two of the nine experiments. Crucially, the CFD simulations were performed 'blind', so that the modellers were unaware of the experimental behaviour in advance; these circumstances were contrary to previous 'tests' of CFD and thus represented a pragmatic trial of the technique's worth as a design tool. The CFD results were found to be qualitatively correct but quantitatively inaccurate. The latter inaccuracy was characterized by an underprediction of the extent of backflow, L, for a given ventilation velocity U and fire size Q. An alternative interpretation is that the critical velocity U_{cr} was underpredicted for a given fire size Q. It was concluded that a ventilation system based on these 'design' calculations would suffer from a reduced safety margin and would not be capable of positive smoke control for fire sizes approaching the maximum design case. Bettis *et al*. (1994*b*) also reported some reservations regarding the validity of Froude modelling in tunnel fire experiments. It was considered that the steep density gradients associated with large fires produced non-Boussinesq effects which would modify the exchange of horizontal momentum in the back-layering region upstream of the fire, leading to an asymptotic value of U_{cr}. Overall, it was felt that CFD was '... still an immature technology, very far from the design tool it is sometimes purported to be' and that the further elucidation of tunnel fire problems would require a combination of better quality CFD simulations and experiments.

Lea (1994, 1995) conducted a series of three-dimensional FLOW3D simulations of the HSL 'phase 1' (unobstructed geometry) tests using a buoyancy-modified $k \sim \varepsilon$ turbulence model and omitting radiative heat transfer effects. The CFD predictions were in qualitative agreement with the HSL trials, revealing the same weak dependence of U_{cr} on Q shown in figure 4. It was suggested that the significant blockage presented by the fire plume produces local flow accelerations which tilt the plume markedly in the downstream direction, reducing the tendency for upstream smoke propagation. Additional simulations were designed to investigate how the flow behaviour, in particular the value of U_{cr}, was influenced by the tunnel aspect ratio (H/W) and the fire size Q. For a given tunnel geometry and fire size, several CFD runs were performed, with the ventilation velocity (i.e. upstream boundary condition) being varied in steps of $0.25\ \mathrm{m\,s^{-1}}$ between runs. It was found that as the tunnel width increased, U_{cr} became more dependent upon the heat output of the fire and that U_{cr} increased with W for a given value of Q. It was stressed that this behaviour ran contrary to the expectations associated with simpler modelling approaches, the observed realignment of the plume being identified as a key factor.

Woodburn & Britter (1995) employed both standard and buoyancy-modified $k \sim \varepsilon$ implementations of FLOW3D to model one of the HSL experiments; the physical fire size was 2.3 MW with an associated mean ventilation velocity of 1.7 m s^{-1}, which led to a back-layer length of 11 m. It was found that the modified turbulence model accurately predicted the extent of the upstream layer whereas the standard $k \sim \varepsilon$ model predicted zero back-flow. The value of L was found, unexpectedly, to be sensitive to variations in Q; however, this was attributed to the characteristics of the combustion model employed and differences between the theoretical and experimental methods for reducing the heat input rate. Predictions of the downstream flow regime were found to be independent of the turbulence model selected. Sensitivity studies indicated that the downstream region was most sensitive to variations in the prescription of natural convective and radiative heat transfer and also to the wall roughness. It was concluded that the upper limit of accuracy of the simulations was $\pm 10\%$, due to uncertainties in the empirical wall roughness data and ventilation velocity profile.

4. Conclusions

(*a*) *Current practice*

The design of longitudinal ventilation systems to control the movement of smoke from fires in tunnels is primarily based on the work of Heselden (1976) or on the Subway Environmental Simulation computer code (Danziger & Kennedy 1982). These, in turn, are based on semi-empirical models that are grossly over-simplified, backed up by sparse, and often inadequate, experimental evidence. The limited experimental data that do exist suggest that, in at least some circumstances, current design methods may be conservative, resulting in forced ventilation capacities significantly greater than those required to control upstream smoke movement.

(*b*) *Experiments*

(i) *General*

Experimental data have been used for three purposes: large-scale fire trials to identify and quantify hazards directly, reduced-scale measurements for use in conjunction with scaling rules to infer conditions in other facilities and for the development and validation of predictive models.

(ii) *Flaws in published data*

There are considerable data available in the literature on tunnel fires. Unfortunately, on closer examination it is apparent that the majority of these data are not of adequate quality or detail to allow effective model development and validation. Three basic flaws are commonly found. Firstly, most workers do not report, and by implication did not measure, the most important modelling parameters of ventilation rate and heat-release rate. Secondly, many experiments have been carried out at a scale which is too far removed from that typical of operations to allow accepted scaling rules to be applied with confidence. Finally, instrumentation has often been too sparse for proper testing of models. These criticisms apply to many of the oft-quoted experiments, such as those in the Ofenegg, Glasgow and Zwenberg tunnels (§ 2 *b*).

(iii) *Recent large-scale data*

The most useful data by far have recently been obtained at HSL Buxton. The still-active Memorial Tunnel fire programme shows some promise of providing useful data, if sufficient attention is paid to the possible upstream propagation of combustion products and if the heat-release rates can be specified unambiguously.

(iv) *Current state-of-the-art*

As a consequence of the above position, there is still an inadequate fundamental understanding of the interaction between buoyancy-driven combustion products and forced ventilation, the validity of extrapolating small-scale results to larger scales, the influence of slopes on smoke movement and the effect of tunnel geometry.

(v) *'Blind-head' tunnels*

In the case of blind-headed tunnels, there is very little published work. For fires ventilated from the blind head, the downstream flow will be similar to that found in longitudinally ventilated systems, and empirical data from the latter will be directly relevant. If the ventilation is inadequate, or fails, the downstream flow character may be different, because the fire will entrain its own supply of air, at low-level. Such conditions may necessitate experiments in a blind-headed facility. However, the basic phenomena of interest remain the same in both ventilation scenarios, such that any work on scaling or slope effects would be applicable to both blind-headed and longitudinally ventilated systems.

(*c*) *Modelling*

(i) *General*

Three types of models are used to predict the consequences of tunnel fires: (semi-) empirical, phenomenological or integral/zone models, and CFD methods.

(ii) *Empirical models*

Simple empirical models for predicting near-fire flows are based on gross over-simplifications, with the result that they are not supported by the most recent and comprehensive experimental data; this includes even those models which are commonly used for specifying critical longitudinal velocities for smoke control. Good quality full-scale data are sparse and insufficient effort has thus far been expended in the validation of the predictions of these simple models.

(iii) *'Far-field' network models*

Simple network models, which do not seek to predict the near-fire flow in detail, are useful tools for assessing the gross effects of fires on tunnel ventilation systems and the movement of combustion products around a tunnel network; here, it is also important to consider the possibility of reverse flow, as it affects the correct prediction of flow direction and smoke propagation at network junctions upstream of the fire.

(iv) *Phenomenological models*

Phenomenological models are based on an understanding of the important physical phenomena. At present, this knowledge is far from complete in the case of tunnel fires. Current models therefore have potential for improvement as further experiments lead to a better understanding of the behaviour of fire-generated flows in tunnels. This class of model may have future use for predicting some of the gross features of fires in unobstructed tunnels, such as stratified flows in the 'far-field' away from the fire. Their advantages are economy, where repeated application is necessary and, in contrast to CFD approaches, there is no requirement for 'expert' users. However, effective model development cannot proceed without a better understanding of the important physical phenomena involved.

(v) *Computational fluid dynamics models*

CFD-based models represent the best way forward for prediction purposes, because they make few prior assumptions about the gross flow character. They cannot presently be used as routine design tools because of the lengthy and costly computations required; however, this position is likely to change rapidly within the next decade. The achievable accuracy of these methods relies essentially on quasi-empirical submodels used to represent complex phenomena such as turbulence and combustion. Reported applications of CFD to tunnel fires are now beginning to highlight the mathematical submodels required to capture these flows, such as buoyancy-modified turbulence models. Developments are hampered by a lack of suitable experimental data, for example, on the volumetric heat-release rate. The earlier two-dimensional CFD simulations of tunnel fires are deprecated in the light of more recent knowledge; a three-dimensional approach is essential in order to capture many important features of the flow, for example the passage of air downstream of a blocking fire plume.

5. Recommendations

The current uncertain position can only be rectified by additional work, primarily to improve our understanding of the key phenomena and to provide usable experimental data for model development and validation. The main areas of uncertainty are as follows.

(i) The relationship between smoke movement and ventilation; can empirical relationships be found?

(ii) The behaviour of smoke; is the distribution of smoke particulates and hot combustion gases well-correlated?

(iii) The effects of scale; can small-scale experiments be used to model full-scale events with the use of appropriate scaling criteria?

(iv) The effects of tunnel slope; how do the relatively small slopes typical of vehicle tunnels affect smoke movement and its control?

(v) The effects of geometry; how do factors such as tunnel shape, or fire location, affect smoke movement and its control?

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(vi) Blind-headed tunnels; how do fires, and the movement of smoke, behave under poorly ventilated or naturally ventilated conditions?

We suggest that the uncertainty in these areas can be best addressed through a combined programme of experimental work and CFD modelling. This would extend the useful data available and give an insight into the details of the phenomena involved. The main requirements are for the following.

(i) Experiments on different physical scales, concentrating on the near-fire area to improve our understanding of the nature of this region.

(ii) Experiments to assess the effects of slope, preferably carried out in a single tunnel, in which the slope can be varied.

(iii) Identical experiments carried out at the same scale but with different tunnel shapes and fire locations.

(iv) Experiments in blind-headed facilities, under poorly or naturally ventilated conditions.

(v) Further application of CFD, to identify key phenomena, and to generate information which is difficult and costly to obtain experimentally.

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