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The effect of a water spray barrier on a tunnel fire

P F LINDEN, PhD, Department of Applied Mathematics and Theoretical Physics, University of Cambridge,
S F JAGGER, PhD, Health and Safety Executive, Buxton, Derbyshire,
J M REDONDO, PhD, MAET, Department of Applied Physics, GDF, Barcelona, Spain
R E BRITTER, BEng, MA, PhD, FIMA, Department of Engineering, University of Cambridge
K MOODIE, MSc, Health and Safety Executive, Buxton, Derbyshire

SYNOPSIS A laboratory model of a water spray barrier on the flow of combustion products from a fire in a tunnel is presented. The model and a theoretical description of the flow show that there is an optimal strength for the water spray, which leads to a reduction in temperature and of concentration of the combustion products by a factor of about 40%.

NOTATION

- B buoyancy flux
- g gravitational acceleration
- ρ density
- U velocity of ceiling layer
- W velocity of water spray barrier
- Q volume flux
- α thermal coefficient of expansion
- c_p specific heat at constant pressure
- H heat flux
- D tunnel diameter
- T temperature
- c constant
- r c_a/c_f
- k constant
- T_R temperature ratio

1 INTRODUCTION

The combustion products from a fire in a tunnel flow along the roof of the tunnel as a gravity current. In the absence of ventilation in the tunnel (the case considered here), this flow is driven by the density difference between the hot gases and the ambient air, and forms a stable ceiling layer occupying typically the upper one-third or one-quarter of the tunnel. The large density difference between the ceiling layer and the underlying air implies that almost no mixing occurs, and the concentration of noxious gases remains approximately constant with distance from the fire. The hot layer does cool as a result of heat transfer to the walls and so the flow gradually decelerates. Despite this cooling, large velocities of the front of the hot layer occur. With a temperature difference of 100°C in a tunnel 4 m in diameter, the front velocity $V_f \sim 2\text{ms}^{-1}$. Smoke particles are carried with this front velocity and their rapid spread along the tunnel is a major obstacle to evacuation procedures.

We investigate here the possibility of using a water spray barrier (WSB) as a means of mitigating these effects. A WSB has been suggested (1), as a means for controlling the spread of dense flammable or toxic gases released into the atmosphere as a result of an accident. The confined geometry of a tunnel means that the WSB has some novel and unexpected features.

The WSB consists of an array of nozzles positioned around the perimeter of the tunnel, in a plane normal to the tunnel axis. The spray is predominantly downwards and is directed in the plane of the WSB. A number of nozzle configurations were tested and it was found that the performance of the barrier was only weakly dependent on the nozzle placements provided the flow covered the roof of the tunnel.

We, therefore, concentrate here on describing the effects of the WSB on the hot ceiling layer as a function of the strength of the WSB (determined by the flowrate). The quantitative performance can be described in simple terms once the qualitative features of the flow are established, and we develop a simple model of the flow based on our experimental observations. The laboratory model is described in §2 and the results are given in §3. The theoretical model is described in §4, measurements on the effect of a WSB on a real fire are presented in §5 and some conclusions are given in §6.

2 LABORATORY MODEL

We restrict attention to a tunnel closed at one end, with the fire near the closed end. The WSB is placed some distance downstream of the fire towards the open end. This configuration is equivalent to WSBs placed on either side of the fire in an open-ended tunnel. There is no ventilation flow within the tunnel

The experiments were conducted in water, and a source of salt solution was used to represent the buoyant plume produced by the fire (2). In this case, since salt solution is dense, the 'ceiling layer' flows along the floor of the tunnel. In the subsequent discussion the observed flow is inverted so that the description refers to the real situation. The model of the tunnel is a cylindrical perspex tube 100 mm diameter and 3.5 m long. It was immersed in a tank containing stationary fresh water measuring 10m × 0.4 m × 0.2m. The WSB consisted of 7 nozzles around the perimeter of the tube. A sketch of the apparatus as shown in figure 1.

Salt solution was pumped from a reservoir to provide the buoyancy flux associated with the fire, and released through a small (5 mm diameter) source on the floor of the tunnel. A second reservoir contained fresh water which was pumped to supply the WSB. Both flows were monitored by in-line flow meters. A small amount of dye was added to the salt reservoir, and the motion was also viewed using shadowgraph images. Measurements of salt concentration in the ceiling layer were made using conductivity probes at 6 locations downstream of the fire on either side of the WSB as indicated on figure 1.

The experimental procedure involved establishing the 'fire' plume by turning on the flow from the salt reservoir. The WSB was turned on and held fixed
throughout the duration of the experiment, except in a few cases when it was turned off for a period to look at some transient features of the flow.

The buoyancy flux (B_f) produced by a fire of heat output H is given by

$$B_f = g\alpha H/\rho_a c_p \ , \tag{1}$$

where g is the acceleration of gravity, ρ_a is the density of air and C_p is the specific heat at constant pressure. The thermal expansion coefficient $\alpha = 1/T$, where T is the absolute temperature. The buoyancy flux depends only weakly on the temperature, and it is proportional to the heat output H. The buoyancy flux B_s produced by salt solution is given by

$$B_s = g\Delta\rho Q/\rho \ , \tag{2}$$

where $\Delta\rho$ is the density difference between the salt solution and the fresh water (density ρ) and Q is the source volume flux. Note that this additional volume flux Q is not produced by a real fire (provided expansion effects are small). However, entrainment into the plume above the source is very large and produces a volume flowrate much greater than Q. Suitable choices of $\Delta\rho$ and Q in (2) ensured that undesired volume flux velocities were small compared with the buoyancy driven speed of the gravity current (typically $< 10\%$).

A WSB works by entraining air and driving a jet containing air and spray downwards. It is the momentum flux and the turbulence in this jet which deflects and mixes the gravity driven ceiling layer. These main effects can then be modelled by water jets in water provided the momentum flux is scaled to the momentum flux of the gravity current. This scaling is expressed as

$$\left(\frac{\rho V^3}{\rho W^3}\right)_S = \left(\frac{\rho_a V^3}{\rho W^3}\right)_F \ , \tag{3}$$

where V is the speed of the ceiling layer, W is the mean vertical velocity of the WSB jets and, as before, the subscripts S and F refer to the salt model and the fire respectively.

3 EXPERIMENTAL RESULTS

3.1 Qualitative results

When the source of salt solution was initiated, a plume rose to the ceiling of the tunnel and the buoyant fluid flowed along the tunnel roof away from the blind end. There was also initially a flow of salt solution towards the blind head of the tunnel but this was reflected from the end wall and eventually all the buoyancy flux travels downstream towards the WSB. The current has the characteristic shape of a gravity current (3) with a raised head on the rear of which are Kelvin-Helmholtz instabilities which mix the flow with the ambient air beneath. As the head of the current approaches the WSB, it is first affected when it gets to within about 2 diameters of the position of the WSB. At this point the recirculation set up by the WSB begins to affect the propagation of the current. The turbulence produced by the WSB causes the current to mix vertically and to be spread out across the cross section of the tunnel. At low flowrates the extent of the mixing was less than the tunnel diameter but at higher flowrates the WSB mixed the flow across the entire cross section.

A clear picture emerges from these qualitative observations. Upstream of the WSB the combustion products travel as a gravity current along the roof of the tunnel. The depth and velocity of this current depend, in a manner described below, on the heat output from the fire. Generally, the depth of the flow is between $\frac{1}{4}$ and $\frac{1}{3}$ of the diameter D of the tunnel.

The WSB sets up two recirculating regions, one on either side of the barrier. Previous work (4) showed that the along tunnel extent of these regions is about $1.5D$ and is relatively insensitive to the flowrate from the WSB. This insensitivity results from the fact that the downflow in the WSB entrains air at a rate proportional to the WSB flowrate, and the resulting inflow balances the outflow at about this downstream distance.

When the current reaches the edge of the upstream recirculating region it is entrained into it and mixed vertically. Typically, in practical situations the strength of the WSB is much greater than the gravity current ($W \gg V$ in (3)), and the current is completely mixed over the cross-section of the tunnel. As the gravity current continues to flow into the zone mixed by the WSB, this zone increases in buoyancy until gravitational forces drive an outflow on the downstream side of the barrier.

The characteristics of this outflow region are similar to those that occur when a buoyant source is released with high momentum into a tunnel (5). The outflow layer 'lifts-off' and flows along the roof of the tunnel again in the form of a gravity current. In this case, though, in contrast to upstream of the WSB, the depth of the current is now approximately $\frac{1}{2}D$.

In summary, these observations show that there are two effects of the WSB.

1. There is a delay in the downstream propagation of the combustion products as the current passes through the WSB.

2. The current downstream of the WSB is deeper, and because it has been mixed by the turbulence associated with the barrier flow, cooler than the current upstream of the WSB.

3.2 Quantitative results

The contrast in the behaviour of the gravity current on the two sides of the WSB is most clearly seen in plots of the density (or equivalently the temperature) measured at the 6 locations shown in figure 1. The temperature is plotted against time at the 6 locations in figure 2. In this case a heat output of a $10MW$ fire is simulated. The arrival of the front of the ceiling layer is marked by the increase in temperature above ambient. With the exception of probe 3 this initial increase in temperature is rapid confirming the qualitative observations that the leading edge of the gravity current is a sharp front. As can be seen from figure 1, probe 3 is close to the WSB, and the emerging layer has not sharpened into a front by the time it reaches this position.

The speed of the front before the WSB between probes 1 and 2 is the same as the ultimate speed after the WSB (between probes 5 and 6). The speed of transfer across the WSB (between 2 and 3) is very large as a result of the rapid mixing caused by the recirculating motions on either side of the WSB. There is then a delay before the gravity current reforms and arrives at probe 4. The nett effect is to cause a delay in the arrival of the ceiling layer on the downstream side of the WSB.

The most marked effect is the reduction in temperature as the layer passes through the WSB, as a result of the additional entrainment of ambient air of temperature T_0. This temperature reduction is shown in figure 3, which shows the ratio $T_R = \frac{T_2-T_0}{T_1-T_0}$ of the temperatures on the upstream (T_1) and the downstream (T_2) sides of the WSB, plotted against the flowrate from the WSB. At low flowrates very little mixing occurs and the ceiling layer passes through the WSB with no significant reduction in temperature. At larger values a reduction of about 45% in temperature is observed. The experiments also showed that further increase in the flow rate did not increase this temperature reduction.

4 THEORETICAL MODEL

4.1 Steady-state model

The WSB causes a recirculation of heat and combustion products back towards the fire. The mean temperature on the fire side increases until the heat flux on the downstream side of the WSB equals the heat output of the fire H. If the fire remains constant, a steady-state is reached. A schematic of this steady-state is shown in figure 4. Here Q_i and T_i refer to the volume flux and the temperature of the flow, respectively, with $i = 0,\ 1,\ 2,\ 3$ referring to the ambient air, the ceiling layer upstream, the ceiling layer downstream and the recirculating region upstream, respectively.

We assume that the region around the WSB is well mixed, so that

$$T_2 = T_3 \ . \tag{4}$$

Neglecting expansion of the gases, volume conservation implies

$$Q_1 = Q_3 = Q_f \text{ and } Q_2 = Q_0 = Q_a \ , \tag{5}$$

where f and a stand for fire side and air side, respectively. In the steady-state the heat fluxes in the ceiling layers are equal to the fire output, i.e.

$$H = \rho c_p Q_f (T_1 - T_3) = \rho c_p Q_a (T_2 - T_0) \ . \tag{6}$$

The volume flux Q_f produced by the fire depends on the form of the fire source. For a small fire, the flow can be approximated as a buoyant plume and, see (3), the volume flux is related to the heat output by

$$Q_f = c_f H^{1/3} D^{5/3} \ , \tag{7}$$

where $c_f = \frac{6}{5}\beta(\frac{9\beta}{10})^{1/3}\pi^{2/3}(\frac{g\alpha}{\rho c_p})^{1/3}$, where $\beta \simeq 0.1$ is the entrainment constant for the plume.

Downstream of the WSB, the flow is controlled by gravity current dynamics which imply (see (6)) that the maximum depth of the ceiling layer is $\frac{1}{2}D$, and

$$H = (\rho c_p)^{3/2} c_a^{3/2} (T_2 - T_0)^{3/2} D^{5/2} \ , \tag{8}$$

where $c_a^{3/2} = (\frac{g\alpha}{\rho c_p})^{1/2}\frac{k\pi}{8}$, and $k \simeq 0.5$ is a constant (4).

Substituting (4), (7) and (8) into (6) and re-arranging we find

$$\frac{T_2 - T_0}{T_1 - T_0} = \frac{1}{1 + r} \ , \tag{9}$$

where $r = \frac{c_a}{c_f} = \frac{5}{24}\frac{k^{2/3}}{\beta}(\frac{10}{9\beta})^{1/3} = 2.9$. As a result the relative reduction in (9) is $T_R = 0.25$, which is significantly larger than the experimental value given in figure 3.

The gravity current speed (8) assumes that the ceiling layer is propagating into a stationary fluid. However, there is an equal and opposite velocity in the cooler, lower layer (see (5)) and hence retaining the same relative speed we reduce the constant k by one-half to $k \simeq 0.25$. Then $r \simeq 1.83$ and $T_R = 0.35$ which is in reasonable agreement with the experimental values.

The volume flux Q_a in the ceiling layer downstream is given by

$$Q_a = r Q_f \ , \tag{10}$$

implying that (since $r \sim 2$) that the WSB entrains roughly Q_f on both sides and mixes approximately equal amounts of ambient air and combustion products.

5 MEASUREMENTS IN TUNNEL FIRES

Some real fire experiments were also carried out in an underground fire gallery approximately 200m long and with an effective diameter of 2.0m. Again a blind head situation was examined. The fires, comprised of pools of mineral oil situated 46m from the blind heading and with a heat output of approximate ly 500kW. The WSB, situated 36m downstream of the pools, delivered 38 l min^{-1} at a nominal 7 bar pressure from three nozzles. The experimental situation differed slightly from the laboratory in that, with the barrier inactive, a small volume of ventilation air was supplied at the bulkhead ($\sim 0.75m^3/s$).With the barrier in operation this air was supplied from a duct 1m downstream of the barrier. The effect of this ventilation air is expected to be small.

The gallery was fully instrumented with thermocouple arrays up to a distance of 80m from the fire. In addition, the condition of the water sprays and ventilation were continuously monitored. Attempts were made to measure some flow velocities in the tunnel using pitot tubes, and the combustion products were monitored for oxygen, carbon monoxide, carbon dioxide content and smoke density. The pool was placed on a load cell arrangement to measure the rate of fuel consumption.

Analysis of the data proved problematic due mainly to the total absence of flow visualisation. Video records suggested that smoke fall-out from the hot stratified ceiling layer was appreciable, resulting in almost total obscuration over the full tunnel height.

The temperature data exhibited great variability but generally showed the establishment of a hot ceiling layer about 10m downstream of the fire. A typical vertical temperature profile is shown in Figure 5a with temperature normalised by the value at the ceiling, and the height expressed as a fraction of the tunnel diameter. The two profiles shown, with and without the WSB in operation show the minor effect of the barrier close to the fire (and upstream of the barrier). Temperatures in the hot layer close to the fire reached $\sim 200°C$. Near the WSB the effect is more marked as shown in Figure 5b. The gravity current layer which occurs in the absence of the WSB is destroyed by the influence of recirculation zones. Thus lower layers show an increase in temperature, the middle layers are cooled but those close to the ceiling are unaltered.

A long way downstream of the WSB further effects were noticed as the profiles in Figure 5c, taken at 80m from the fire, illustrate. Without the WSB a marked but deepening ceiling layer is observed. The increase in depth of the ceiling layer is caused by heat loss to the walls and turbulence generated by roughness on the tunnel walls and shear instability between the two layers. With operation of the barrier a less distinct layer results due to additional cooling effects of the water spray, and additional mixing caused and turbulent energy input to the layer by the high momentum water jet.

In addition to the barrier producing a more homogeneous profile, average values of the temperature in both layers are reduced. Thus a typical example, just downstream of the barrier, shows layer-averaged temperatures reduced by a factor of just over two from values $\sim 55°C$. At large distances from the barrier the reduction factor is smaller, due to the balancing effect of wall heat loss, a reduction factor of approximately 1.5 - 1.6 being typical.

In order to compare with the laboratory experiments the factor T_R can be computed using temperature data upstream and downstream of the barrier. The real fire experiments give typical values of $T_R \sim 0.1$ to compare with a figure for the laboratory experiments ~ 0.4. The difference in these figures lies in the cooling effect of the WSB in the real fire experiments, in addition to the momentum-induced mixing effects.

Again using temperature data, the velocity of the layer can be inferred from the times of arrival of the hot ceiling layer at different points along the tunnel both initially and on turning off the barrier. In general, the velocity of the gravity current for fires with a heat output $\sim$ 500kW decays with distance from the fire being in the region of $2 - 2.5$ ms^{-1} at distances $\leq$ 20m from the fire to $0.75 - 1.0$ ms^{-1} at 80m downstream as the gravity current layer cools and the density difference between it and it surrounding environment decreases.

6 CONCLUSIONS

We have presented a laboratory model of a water spray barrier on the ceiling layer produced by a fire in a tunnel and compared the results with measurements of a real fire. Based on flow visualisation, a simple theoretical model of the steady-state is proposed which shows that the effect of the WSB is to mix the ceiling layer to produce a cooler, deeper layer on the downstream side. The cooling (and the corresponding reduction in the concentration of smoke and combustion products) results from entrainment of ambient air by the flows induced by the WSB. (The cooling effect of the spray droplets is ignored in the model.) It is shown that the excess temperature and the concentration levels are reduced by about 40% downstream of the WSB.

It is of interest to note that the behaviour of the WSB is somewhat unexpected. For example, provided the ceiling layer is mixed over the tunnel cross-section, the effectiveness of the WSB in reducing the temperature given by (9) is independent of further increase in the strength of the flow in the barrier. The reason for this is that the flow is not controlled by the WSB, but is, instead, controlled by the gravity current downstream of the WSB. The current can occupy at most one-half of the depth of the tunnel (see (6)), and hence once this condition is achieved further mixing by the WSB simply recirculates the flow around in the vicinity of the barrier. Additional dilution does **not** occur because the amount of ambient air entrained is also controlled by the gravity driven flow downstream (see equation (5)). This observation is consistent with measurements shown in figure 3.

The WSB produces a region of high turbulent dissipation, and hence requires a large pressure gradient to drive a flow across it. As a result the hot gases are initially recirculated until the temperature difference across the WSB is large enough to drive the heat flux across. Hence, there is an initial delay τ in the propagation of the ceiling layer. Comparison with gravity currents in turbulent surroundings (7) show that

$$\tau \simeq 7 \times 10^{-3} \frac{\rho c_p}{g\alpha H} DLW^2 (\text{sec}) ,$$

where L is the distance of the WSB from the fire. Typical values for a 5 m tunnel and 10 MW fire give values of τ of 200-300 sec.

Measurements with a real fire show very similar behaviour. A hot ceiling layer is produced and this is cooled and mixed by the WSB. The outflowing layer with WSB in operation occupies about one-half the tunnel depth as predicted. An additional effect of the real water spray is the cooling by the water droplets. It is estimated that about 20% of the heat capacity of the WSB is used in this manner. Increasing the flow in the WSB would cool the ceiling layer further and hence increase the effectiveness of the WSB.

ACKNOWLEDGEMENTS

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REFERENCES

(1) Moodie, K. 1986 The use of water spray barriers to disperse spills of heavy gases. *Plant Operations progress*, 4, 234-241.

(2) Linden, P.F., Lane-Serff, G.F. & Smeed, D.A. 1990 Emptying filling boxes: the fluid mechanics of matural ventilation. *J. Fluid Mech.*, 212, 309-335

(3) Simpson J.E. 1988 Gravity currents in the environment and the laboratory 224 pp Ellis Horwood.

(4) Jirka, G.H. & Harleman, D.R.F. 1979 Stability and mixing of a vertical plane buoyant jet in confined depth. *J. Fluid Mech.*, 94, 275-304.

(5) Barrett, S. 1991 The flow of a vertical buoyant jet with high momentum in a long, ventilated tunnel. *J. Fluid Mech.*, (submitted)

(6) Benjamin, T.B. 1968 Gravity currents and related phenomena *J. Fluid Mech.*, 31, 209-248.

(7) Linden, P.F. & Simpson, J.E. 1986 Gravity driven flows in a turbulent fluid. *J. Fluid Mech.*, 172, 481-497.

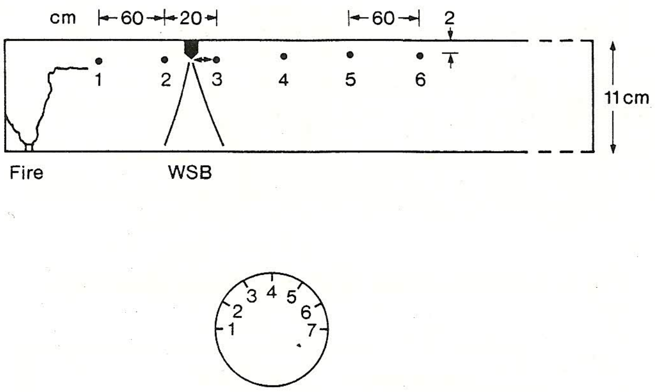

Fig 1 A sketch of the experimental set-up (not drawn to scale) showing the water spray barrier and the measurement locations. The lower figure shows the arrangements of the nozzles on the WSB.

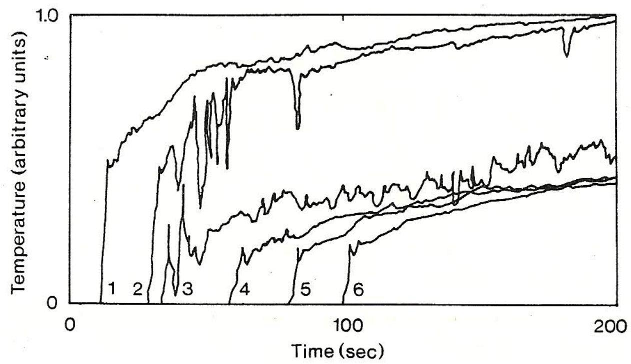

Fig 2 The increase in 'temperature' (in arbitrary units) measured at the 6 measurement points shown in figure 1. Note that 1 and 2 are upstream of the WSB, and 3, 4, 5 and 6 are downstream.

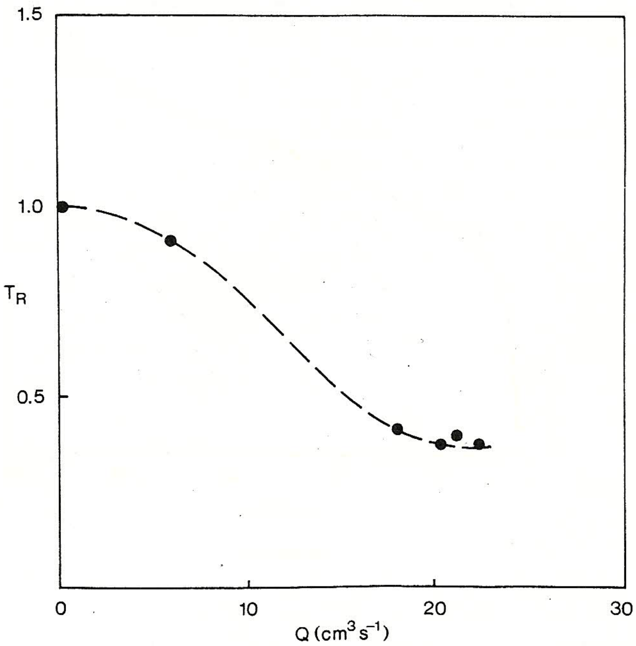

Fig 3 The reduction in temperature T_R plotted against the flowrate Q through the WSB.

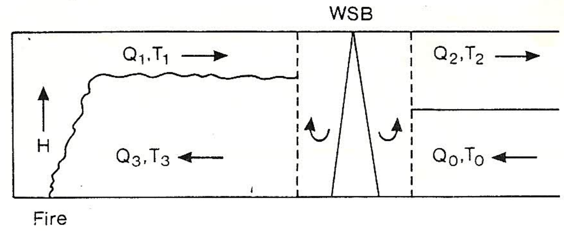

Fig 4 A sketch of the modelled steady-state flow.

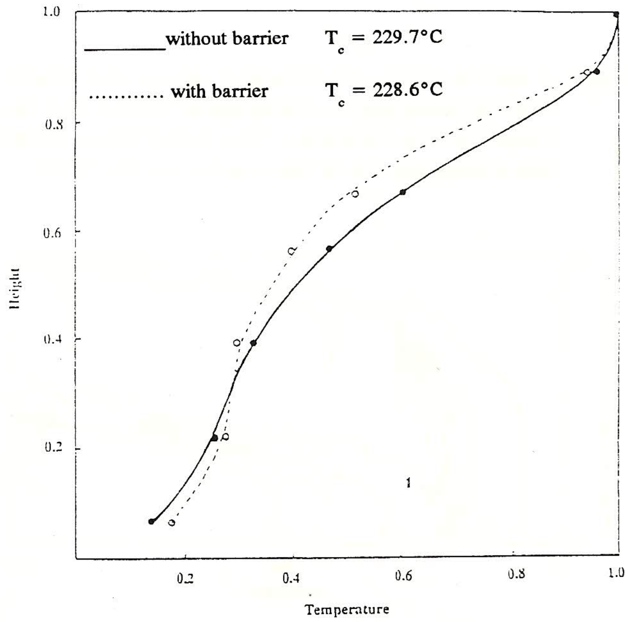

FIGURE 5(a)

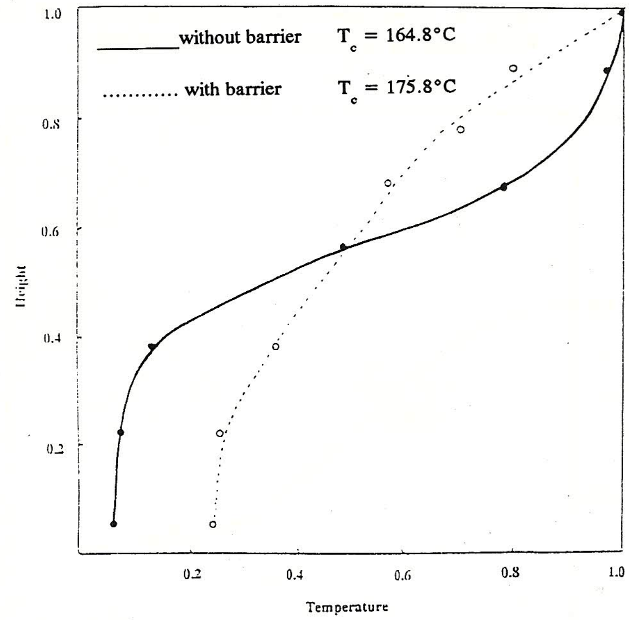

FIGURE 5(b)

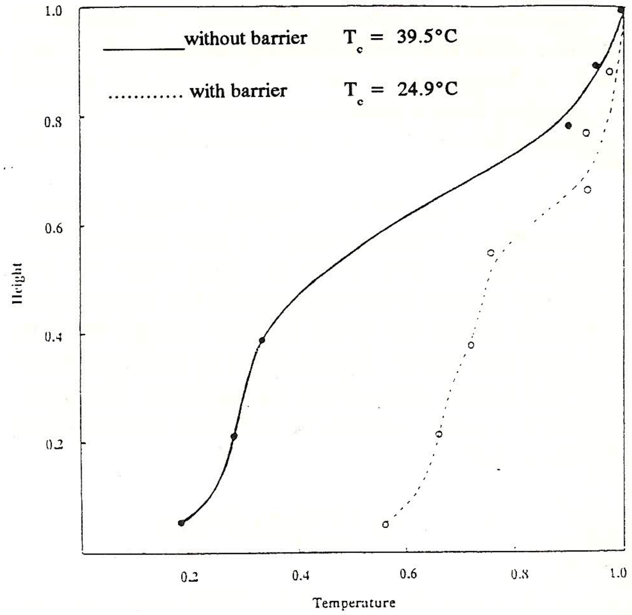

FIGURE 5(c)

Fig 5 Temperature profiles measured at (a) 14m, (b) 30m and (c) 79m downstream of a 500 kW fire in a 2m tunnel. The solid curves were obtained without the WSB, and the dashed curves when the WSB was in operation. The temperature values are normalised by the temperature at the ceiling T_c the value of which is indicated on each figure. The profiles represent average temperatures measured over a period of 10s. The WSB was positioned at a distance of 36m downstream of the fire.