CFD Applications of PHOENICS on Building Environment and Fire Safety Design

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ABSTRACT

ARUP has been using PHOENICS software for many years to deal with various CFD modellings in building thermal comfort design, indoor environment, fire safety control strategy and so on and have gained good results recognised by the clients. This paper summarises some selected CFD studies carried out by PHOENICS recently in Arup.

The project introduced in this paper is an urban underground railway station. As the station will be occupied heavily by trains with diesel engines, the mechanical ventilation control system becomes critical in order to satisfy the thermal comfort air quality requirement inside the platform environment. PHOENICS was applied to simulate air quality and the temperature under different pollutant emission rates by diesel engines during peak hours. The proper ventilation design including opening size, location and airflow rate were therefore identified for the assist of the mechanical ventilation system design.

PHOENICS was also employed in the smoke control simulation during an emergency fire occurring at the sloped tunnel which connects the end of the platform and the outside ground railway. Two ventilation shafts were located at both ends of the connecting tunnels and results show how the two shafts can work efficiently under different operating strategies to prevent the platform from being effected by the backlayering of hot fume (smoke) from the fire.

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1. INTRODUCTION

ARUP Sydney has been using PHOENICS software for many years to deal with various CFD modellings in building thermal comfort design, indoor environment, fire safety control strategy and so on and have gained good results recognised by the clients. This paper presents two CFD studies carried out by PHOENICS[1,2,3] (PC version 3.3).

The involved project is an urban underground railway station. As the station will be occupied heavily by trains with diesel engines which emits certain level of particle of combustion waste into the confined platform space, the mechanical ventilation control system becomes critical in order to satisfy both thermal comfort air quality requirement inside the platform environment. PHOENICS was applied to simulate the air contaminate level and the temperature profile under different pollutant emission rates by diesel engines during peak hours. The proper ventilation design including opening size, location and airflow rate were then identified for the assist of the mechanical ventilation system design. Plan and section views are shown in Figure 1.1 and 1.2.

PHOENICS was also employed in the smoke control simulation during an emergency fire occurring at the sloped tunnel which connects the end of the platform and the outside ground railway. The smoke induced by an emergency fire will be controlled by two ventilation shafts located at both ends of the connecting tunnel with different time-dependent operating strategies when the fire is detected. Results show how the two shafts can work efficiently to prevent the platform from being effected by the backlayering of hot fume (smoke) from the fire.

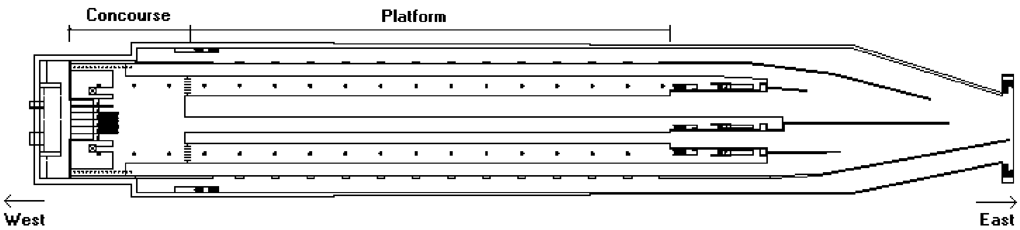


Figure 1.1 Station plan view

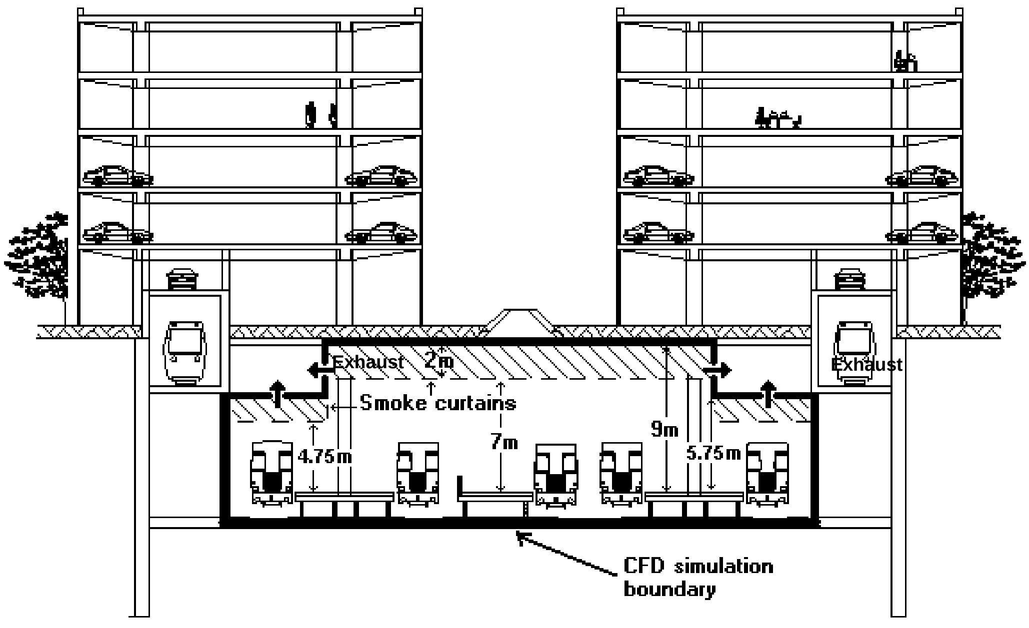


Figure 1.2 Station cross-section view

2. AIR QUALITY OF STATION PLATFORM

2.1 Background

Since the proposed station ventilation system is comprised of high level and under-platform exhaust systems to deal with the contaminants and heat discharged by trains driven by diesel engine, further comprehensive and particular investigations using CFD simulations are required. In order to provide all the information as detailed as possible to support the final technical design of station ventilation system, the CFD simulations should cover all potentially risky scenarios in both normal ventilation and emergency fire ventilation.

CFD investigations are carried out by PHOENICS for the station ventilation mode based upon the finding of the interaction or mixing ratio between the pollutant gases (CO, CO_2, NO, etc.) discharged by diesel trains and the fresh air supplied by air duck around platform. The trains inside the station are at idle status within varied types and numbers of carriage combinations.

According to some prototype exhaust tests of the real diesel train, even in idle status the discharge gas from the train contains many tiny black particles that are brought towards the ceiling of station, accumulate there and make the ceiling turn into black. These harmful particles may also fall down to the platform to endanger the occupants when the thermal fume turns cool. Therefore the discharged gas need to be exhausted effectively out of the platform region, while a higher ventilation capacity may be required for exhausting the discharges from moving trains.

The task for CFD simulation is to establish an available diagram of computing domain which functions like a real ventilation system by satisfying all the physical and mathematical conditions. A series of comparative simulations are carried out to find whether the current ventilation design is effective or not. The key points for the effectiveness of a ventilation design will be testified by studying certain items, eg., mixing ratio between pollutant gases and ambient fresh air under a certain ventilation system, or by searching the temperature changes to verify whether the ventilation system works properly.

2.2 PHOENICS Domain and Settings

It is found that for the present project a simulation of thermal flow process within 400,000 cells will take more than 30 hours to be carried out on the above PC with the PC version PHOENICS software, and the size of output data file becomes too large to be treated easily. Therefore the sizes of computing domain for the simulation scenarios have to be limited so that attention can be paid around those regions where thermal fume movement is more sensitive from the view of air ventilation and fire safety controls. Some major settings used in PHOENICS program are listed in Table 1.

Table 1 Major settings in PHOENICS program

Main Settings	Descriptions
Total cells	X=73, Y=138, Z=36
Turbulance model	Standard *K-e* (KEMODL)
Differencing scheme	HYBRID
Global convergence criterion	0.01%
Reference temperature	15 ^{o}C in winter, 27 ^{o}C in summer
Boundary effect on turbulence	Off
Coefficient for auto wall functions	LOG-LAW
Total number of iteration	2000
Domain material	40 dummy fluid (self-edited)
density	1.18
viscosity	1.83E-05
specific heat	1005
conductivity	0.026

Two scenarios (Case 1 & Case 2) have been modelled by focusing on the movement of discharged gas around the discharge pipes of trains in summer and winter conditions. The trains are in idle inside the station and all of them are supposed to be the ADL (the carriage with diesel drive engine). The full cross section area is concerned in the simulation domain but its longitudinal distance is shorten by 22 metres in order to maximally increase the number of cells in the width (45 metres) and height (10 metres) of the cross section.

It is assumed in these cases that the idle trains occupy all the five tracks at the same time and each train has one ADL at its one end that stops near the western end of the platform. Details of the geometry of the trains, platforms and ventilation facilities are shown in Figure 2.1. Case 1 corresponds to the winter ventilation mode within a domain normal temperature of 15°C, while Case 2 refers to the summer mode with a normal temperature of 27°C. Table 2 gives all the details of the train discharges inside the platform and the mechanical ventilation design conditions.

All computations are carried out on Compaq personal computer with Pentium III chips at 800MHz and 256MB main memory.

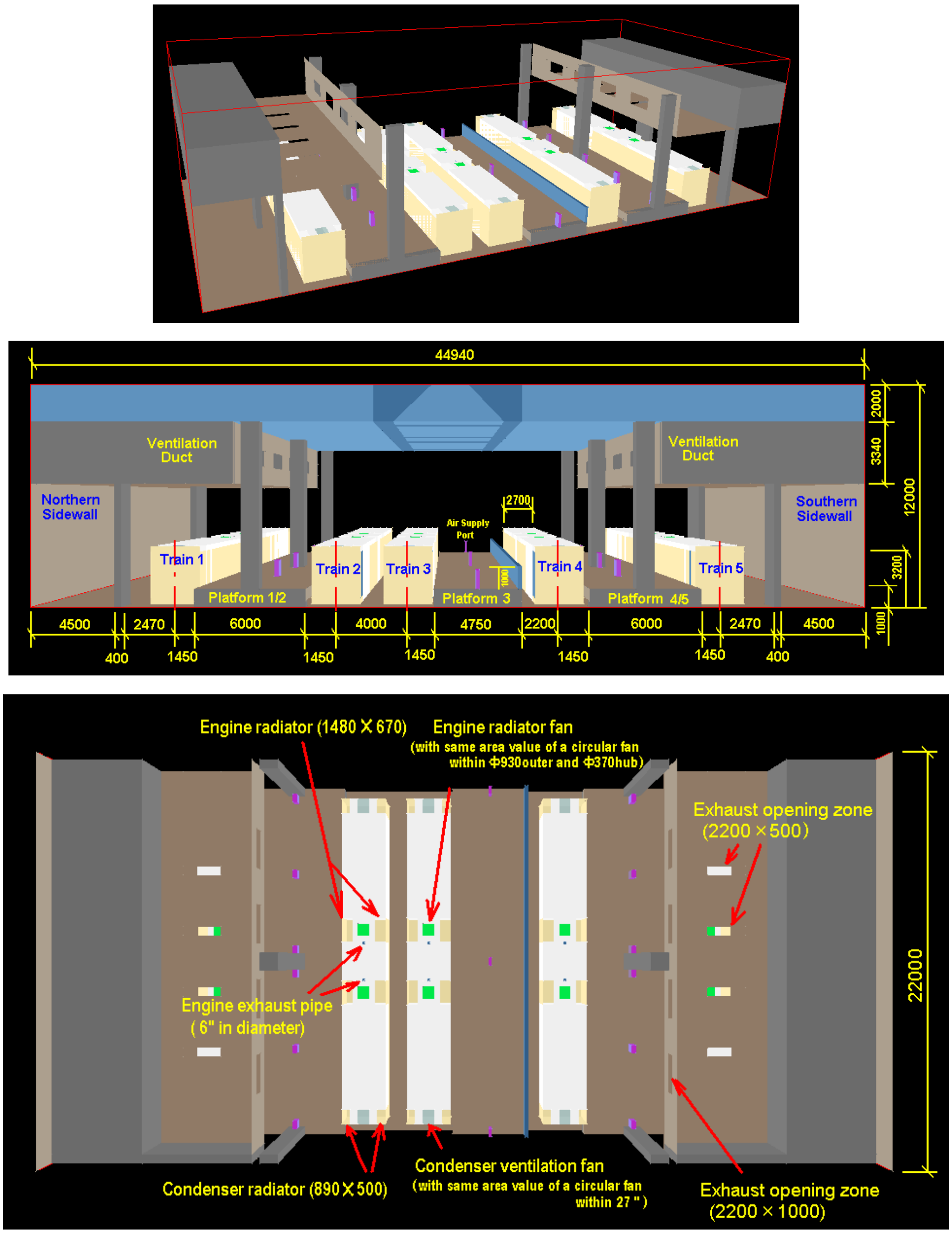


Figure 2.1 Geometry of simulation domain for Case 1 & 2

Table 2 Parameters and conditions for CFD simulation Case 1 & 2

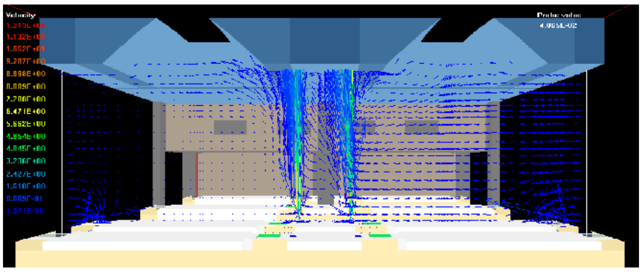
1. Train	
Number of tracks*:*	5
Status of train:	idle
Number of carriages for each train:	1 (ADL)
LengthûWidthûHeight:	20mû2.7mû3.2m
Location of engine discharge zones:	middle of ADL carriage, Diameter: 150mm (6”)
Distance between two exhaust zones:	2.18m
Discharge rate (temperature)	13m/s (200°C) for one train near western wall and 7.5m/s (90°C) for other four trains
Discharge relative concentration:	1.0 (represents the initial relative density of any discharged containment)
Operation of radiator fans :	Case 1, winter: all fans do not operate when in idle Case 2, summer: all fans operate when in idle
Engines	
Radiator fans:	Two fans (∅930, 14m/s, 27°C) around the middle of carriage, extract hot air upwards
Radiators:	Two radiators (1.48mû0.67m) for each radiator fan
Air condensers:	
Radiator fans:	One fan (∅27 ”, 6.4m/s) at each end of carriage, respectively, suck the air downwards
Radiators:	Two radiators (0.89mû0.5m, 30°C) for each radiator fan
2. Simulation Domain	
LengthûWidthûHeight:	22mû45mû10m
Total number of cells:	Nx=73, Ny=138, Nz=36, total: 362,664
Normal temperature:	15°C (corresponding to a winter operation mode) and 27°C (corresponding to a summer operation mode)
Thermal and fluid boundary conditions:	
Ceiling, ground, northern and southern wall:	adiabatic walls
Columns:	adiabatic blockage
West and East sections:	free-flow-in/out sections within the external temperature same as the internal normal temperature
3. Ventilation Capacity	
Total occupied by 2 ducts near ceiling:	350m³/sû90%û30%=94.6 m³/s, where --350m³/s refers to the total ventilation capacity required for three of the 150 metre-platform; --90% means the part of ventilation capacity performed by the ceiling ducts; --and 30% is the percentage of total ventilation capacity distributed in the domain area.
Exhaust opening zones:	Four (2.2mû1.0m) on each duct in simulation domain
Total occupied by 3 ducts under platforms:	the rest 10%: 350m³/sû10%=35m³/s, for each platform: 35m³/sû20m/150m/3= 1.56m³/s
Exhaust opening zones:	Four (2.2mû0.5m) on each duct in simulation domain
4. Air supply	
Rate of each air supply port:	1.56 m³/s within a height of 1.03m
Number of air supply ports required Longitudinally:	3 ports/11m (for each shared platform) 3 ports/22m (for platform 3)
Temperature of air supplied:	same as domain normal temperature
Make-up air:	from west and east side of platform, more make-up air enters domain from west side (close to the escalators of station) within the same temperature of domain

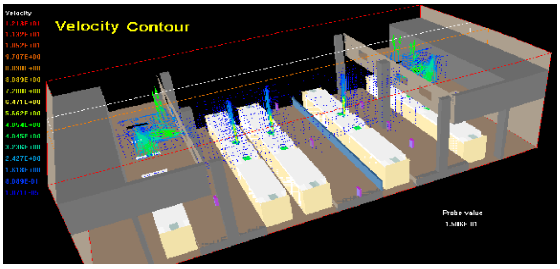
2.3 Results and Discussions

2.3.1 Case 1 (winter condition)

Figure 2.2 (a) & (b) are the velocity vector profiles that show the mechanism of station ventilation process. It is clear from figures that when train discharging and ventilation exhausting start, the hot gas was firstly pushed towards the ceiling, spreading transversely and longitudinally along ceiling driven by buoyancy force, then part of the hot fume was exhausted out through the two ducts. While a large quantity of air was extracted from the domain region, the relevant make-up air flows into the domain from both opening sides to balance the pressure drop.

Since the western side (right hand side in (a)) is close to the end of platforms where escalators transfer the passengers leaving/entering the platform, a larger volume of make-up bulk air will flow into platform region than that from the other side. This condition was modelled by setting different pressures on each boundary to control this unbalanced air supplying.

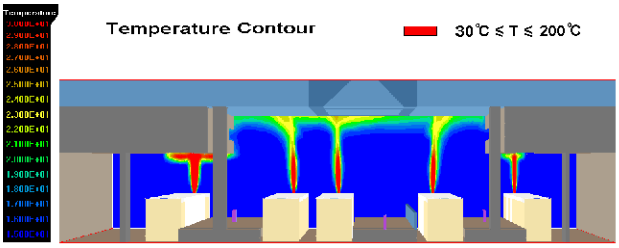




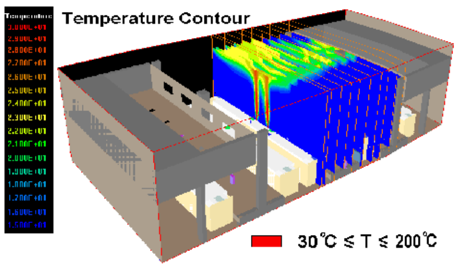
(a) Velocity profile cross trains and platforms (b) Velocity profile along platforms

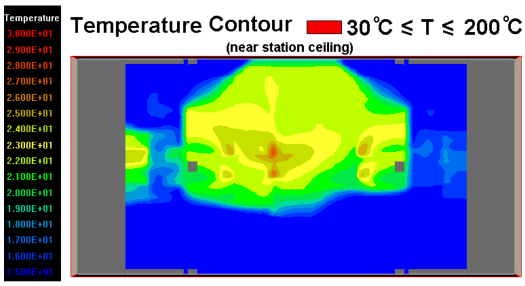
Figure 2.2 Mechanism of station ventilation process

Figure 2.3 (a), (b) and (c) present the temperature status of the domain when thermal gas discharge and ventilation interact to each other. Because the gas within high temperature and concentration is cooled and diluted immediately after it is discharged from the pipe of train, the spatial region occupied by the gas fume is very difficult to distinguish. The high temperature and concentration regions are gathered only around the discharge zones. Therefore, the following figures relating to temperature and concentration profiles use the colour legend that sets a middle value instead of the maximum value as the highest colour (red) so that the distributions with lower values can be distinguished easily.



(a) Temperature contour along cross section





(b) Temperature contour along longitudinal section (c) Temperature contour near the station ceiling

Figure 2.3 Temperature profile induced by the train discharging

In these figures, the red colour shows the profile of the thermal fume within temperatures higher than 30°C. It is clear that the diluted gas fume layer is quite high above the platform, so the risk of heat radiation towards the occupants is low. Same results can also be found from Figure 2.4 that shows the isothermal surface with different temperature boundary values.

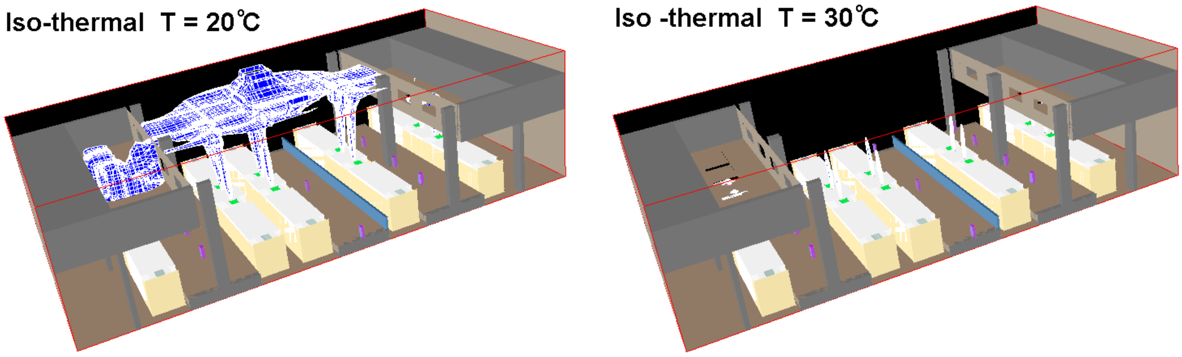
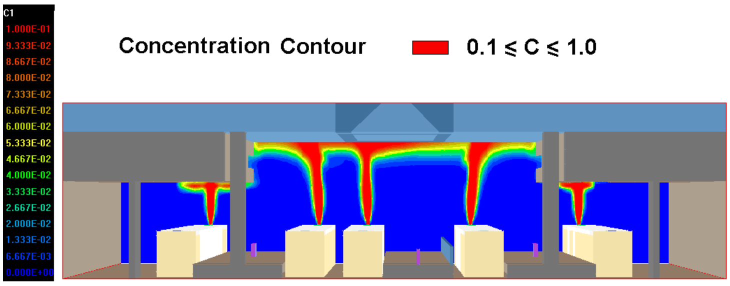


Figure 2.4 Isothermal surface of discharged gas

Similar method can be applied to the results of concentration too. Figure 2.5 is the relative concentration contour, and Figure 2.6 is the isothermal surface with the value of 5%. Furthermore, Figure 2.7 is presented as an example of converting the absolute value of concentration through the relative one obtained initially by the computation. This figure shows that the layer height of allowable concentration of CO (25ppm) is acceptable based on the computation results. Details of derivation from the relative mixing ratio C1 to the absolute concentration is summarised in Appendix A.

However, there is still quite amount of gas fume accumulating near ceiling, although within low temperature and concentration. This is because of the very wide and high ceiling area so that the rising gas fume (especially those discharged by Train 3) stays far away from the exhaust ducts. It is also noticed that part of the fume discharged from Train 3 flows over the central line jointing into the other fume from Train 2. This movement may cause a falling of chilled containment gas towards Platform 3 where passengers could be endangered, thus further investigation is required such as settling a vertical plate near ceiling along the longitudinal central line.



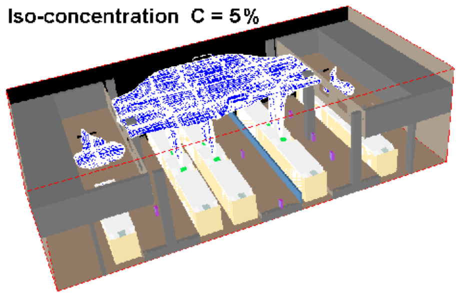


Figure 2.5 Relative concentration of containment (C=0.0 ~ 1.0)

Figure 2.6 Iso-concentration surface of discharged gas (C=5%)

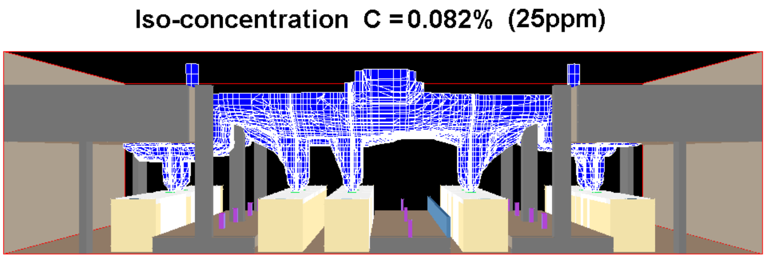
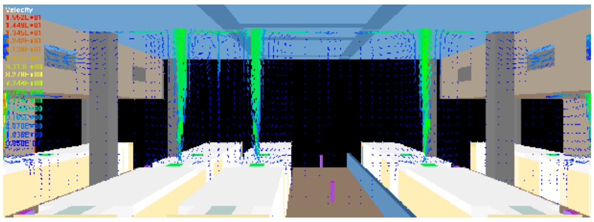


Figure 2.7 Example of C=0.082% (corresponding to an absolute value of 25ppm for CO)

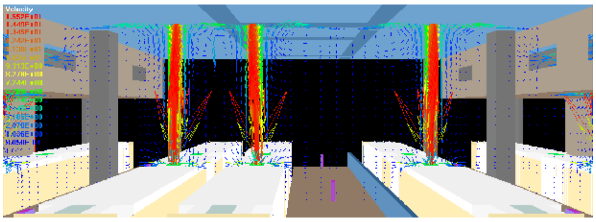
2.3.2 Case 2 (summer condition)

Case 1 discussed by above section represents the idle train mode as the train operates in winter with no radiators of engines and air-conditioners operate. In summer, however, both the engine radiator fans and condenser radiator fans will activate even the train is in idle mode. Since the engine radiator fans are located very close to the engine discharge pipes within much higher ventilation velocities (up to 14m/s), the blown out airflow may disturb the stratified layering status of containment gases near ceiling. Case 2 refers to this situation by simulating the combination effect of all discharges and ventilation activities.

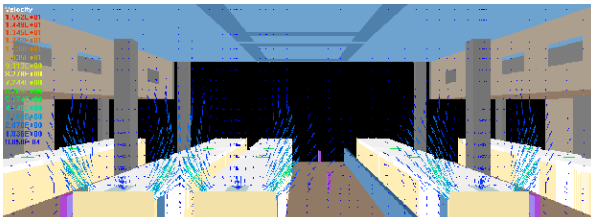
Figure 2.8 shows the velocity features on different cross sections when all ventilation and discharges are involved, and Figure 2.9 gives the velocity contour on longitudinal sections.



(a) Velocity contour on cross section of engine discharging pipes

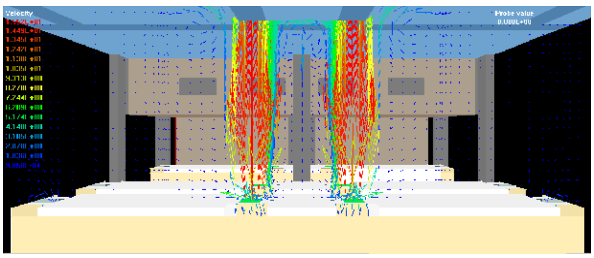


(b) Velocity contour on cross section of engine radiators and fans

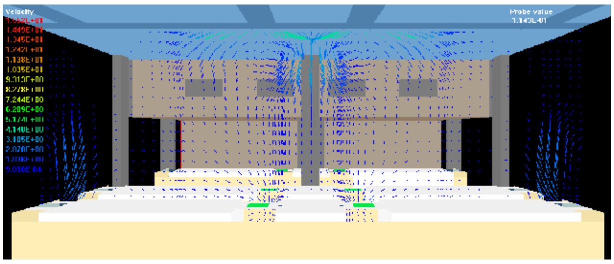


(c) Velocity contour on cross section of condenser radiators and fans

Figure 2.8 Velocity contours on different cross sections



(a) Velocity contour on longitudinal section of radiator fans and engine discharge pipes



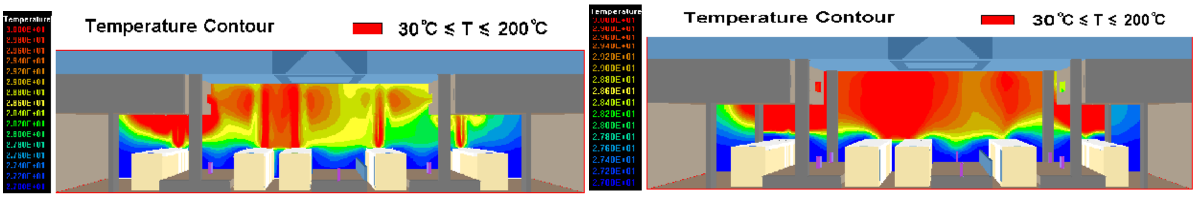
(b) Velocity contour on longitudinal section of radiators of engine and condenser

Figure 2.9 Velocity contours on different longitudinal sections

Comparing to the velocity features of Case 1, the air movement of this case is more complex because of the interaction among different ventilation and discharging facilities. This may leads to a well mixed fluid domain but the air containing certain level of containment materials may also be driven towards the platforms by the circulating flow.

Figure 2.10 & 11 show that compare to Case 1, the hot layer within temperature over 30°C is broader and thicker, and at the level of 2 meters from platform the temperature of some areas have risen more than 1°C from the initial one. This may bother the passengers from view of thermal comfort standard.

This is because the ambient temperature itself in summer is quite high, so the discharged hot gases can not be cooled effectively. Meanwhile, the operation of radiators and fans drives the hot gas expanding widely with fully blended.



(a) Temperature contour on cross section of engine discharge pipes

(b) Temperature contour on cross section between two discharge pipes

Figure 2.10 Temperature profile

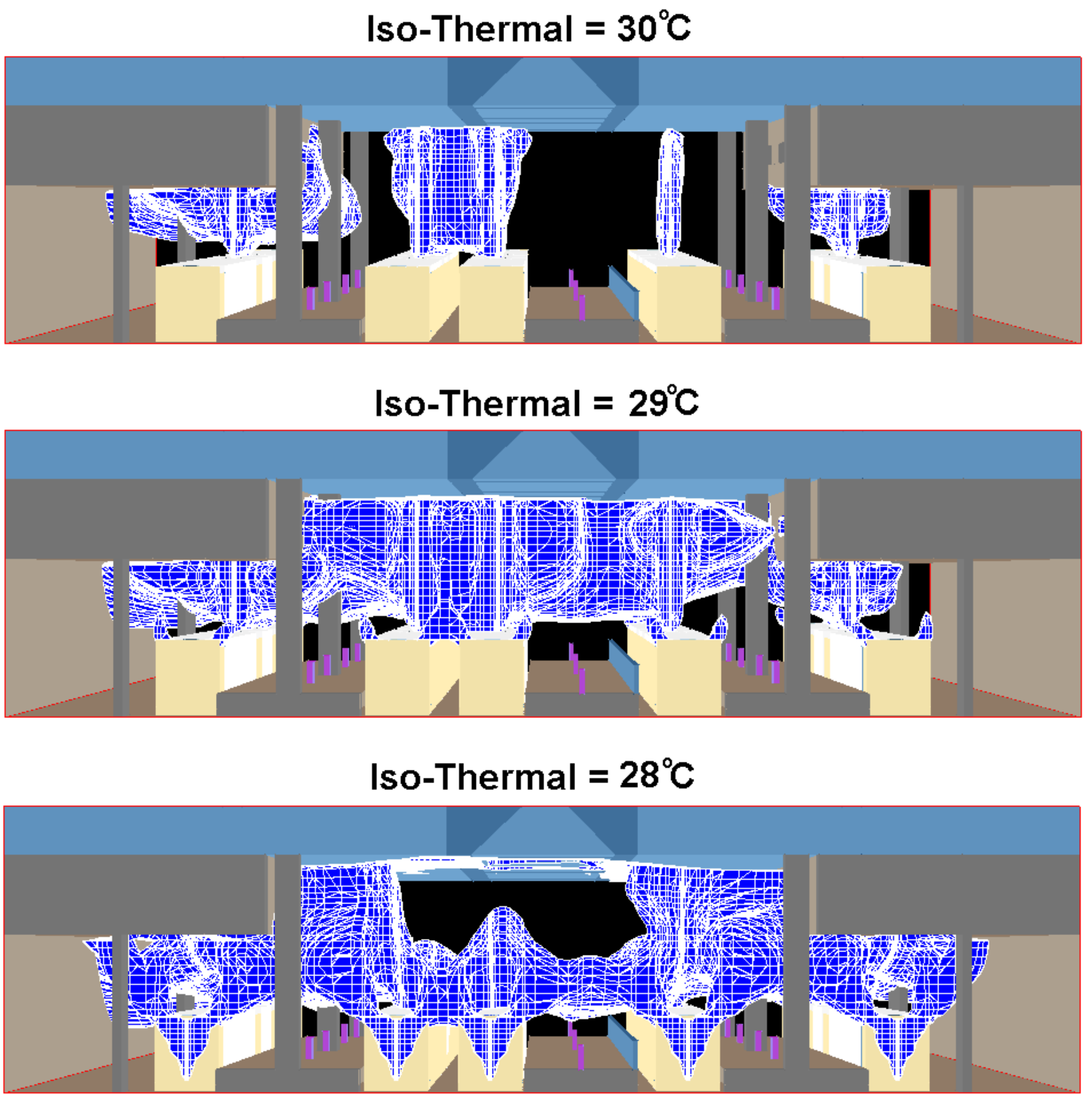
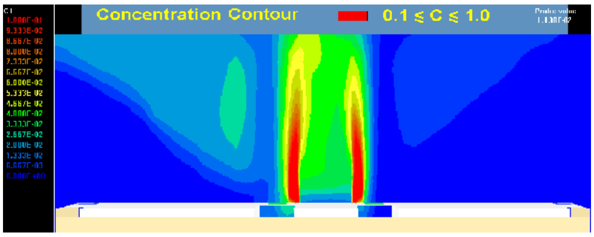
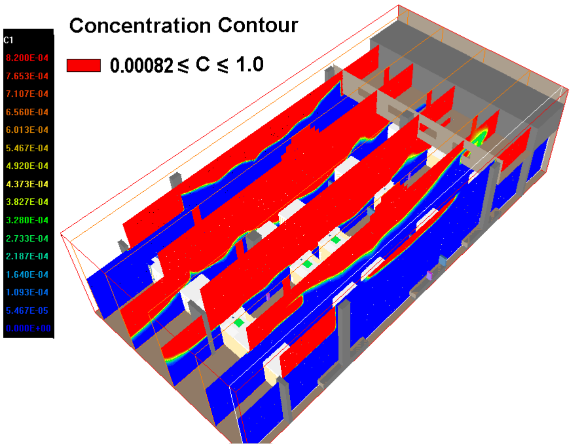


Figure 2.11 Isothermal surface of hot air layer within 30°C, 29°C and 28°C

This mixing effect may also influence the distribution of concentration of containment materials, although the total quantity of discharged gas is the same as that in winter mode. Figure 2.12 & 13 show that although the core part of concentration of discharged gas is kept around the pipe at the top of trains, the containment region has expanded because of the mixing effect among discharging, ventilation and circulation of radiators and fans. Comparing with Figure 1.9, the height of polluted air layer within a relative CO concentration of 0.082% (or absolute CO concentration of 25ppm) is quite close to the platforms, especially around the discharge pipes. Thus further sensitive study is considered to be required.



(a) Temperature contour on longitudinal section of engine discharge pipes



(b) Temperature contour on cross sections (example of CO concentration of 25ppm)

Figure 2.12 Concentration contours

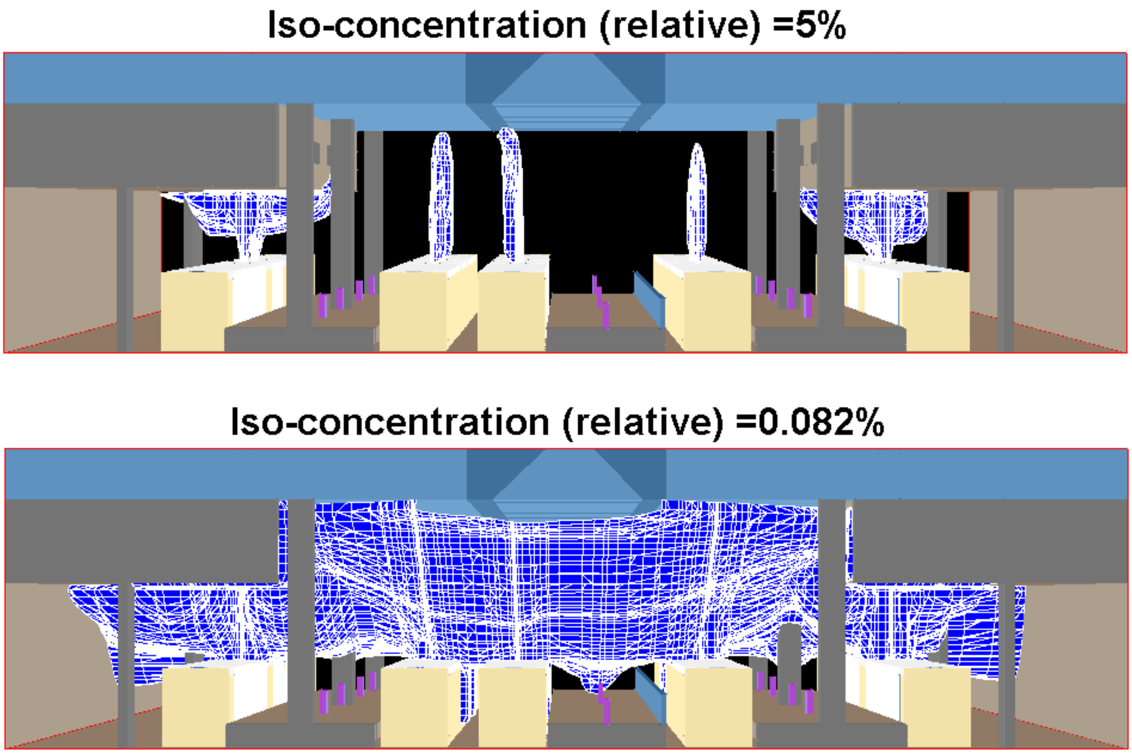


Figure 2.14 Iso-concentration surface within different relative values

2.4 Summary

The mechanical ventilation system designed for an underground railway station has been simulated through CFD. Results show that:

- In winter condition, the layer height of allowable concentration of CO (25ppm) is acceptable. However, there is still quite amount of gas fume accumulating near ceiling although within low temperature and concentration. It is also noticed that the discharged hot fumes interact to each other between neighbouring tracks. This movement may cause a falling of chilled containment gas towards Platform 3 where passengers could be endangered, thus it is recommended that a vertical separating plate near ceiling along the longitudinal central line be installed.

- In summer condition, the air movement is more complex because of the interaction among different ventilation and discharging facilities. This may leads to a well mixed fluid domain but the air containing certain level of containment materials may also be driven towards the platforms by the circulating flow. Compare to winter condition, the hot layer within temperature over 30°C is broader and thicker, and at the level of 2 meters from platform the temperature of some areas have risen more than 1°C from the initial one. This may bother the passengers from view of thermal comfort standard.

- The mixing effect in summer condition may also influence the distribution of concentration of containment materials, although the total quantity of discharged gas is the same as that in winter mode. Results also show that although the core part of concentration of discharged gas is kept around the pipe at the top of trains, the containment region has expanded because of the mixing effect among discharging, ventilation and circulation of radiators and fans. Comparing with winter case, the height of polluted air layer within a relative CO concentration of 0.082% (or absolute CO concentration of 25ppm) is quite close to the platforms in summer, especially around the discharge pipes. Thus further sensitive study is considered to be required.

3. TUNNEL SMOKE CONTROL DURING EMERGENCY FIRE

3.1 Background

After carrying out the CFD study on internal air quality control of the platform, PHOENICS was used again in the evaluation of the smoke control policy during emergency fires in the sloped tunnel which connecting the platform and the ground railway. The following sections describe the key input data, engineering assumptions and some key results from the CFD simulations.

The simulations represent two different fire scenarios within the tunnel. The resulting environment and tenability in the tunnel after a fire is analysed and presented including; transient air movement velocities, temperatures and smoke concentrations.

The tunnel is approximately 450m long from the station box (west) to the tunnel portal (east) and has a general cross-sectional area of 8.9m by 6m shown as Figure 3.1 & 3.2.

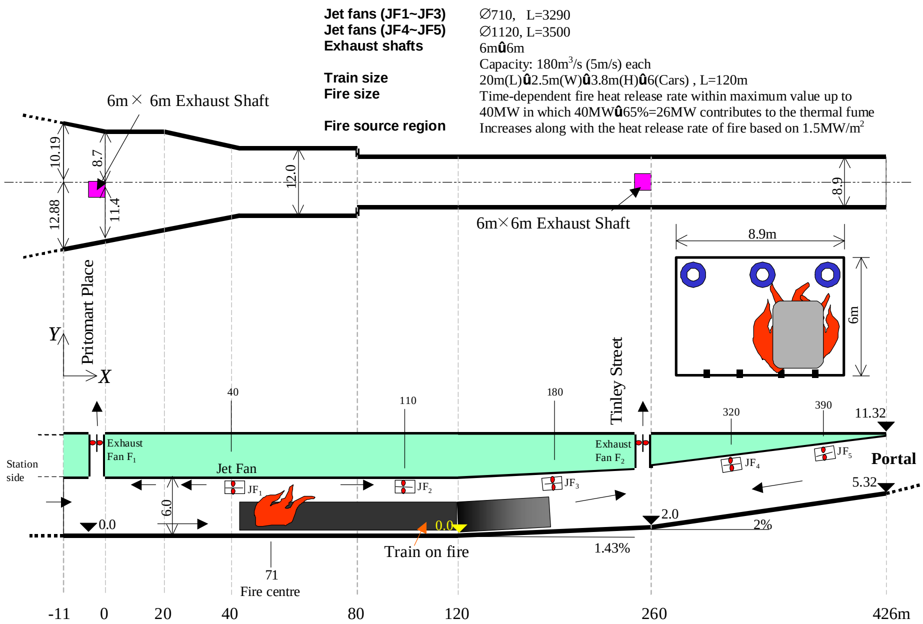


Figure 3.1 Tunnel plan view and centreline section

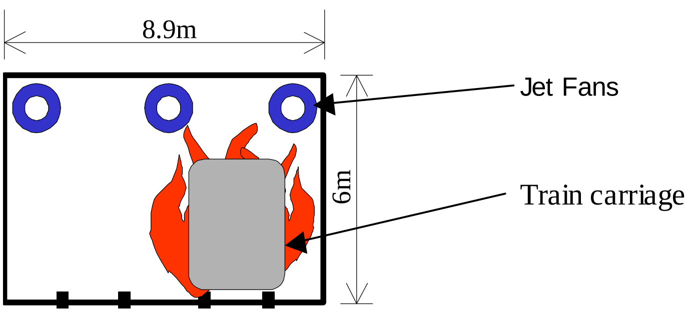


Figure 3.2 Tunnel cross-section

The three-dimensional velocity and temperature distribution within the flow domain were simulated. Furthermore, smoke optical density has been modelled as a species concentration relative to a source concentration.

The simulations have been carried out in a transient manner to visualise the behaviour of the spread of smoke and hot gases over a period of time under a fire situation. The fire is assumed to be well ventilated as the supply of oxygen for combustion through the smoke management system is plentiful, ie the fire is assumed fuel controlled. This is considered appropriate as the tunnel has a large volume and furthermore fresh make-up air will be supplied by the mechanical smoke management system.

3.2 PHOENICS Domain and Settings

The actual geometry of the tunnel has been simplified to suit the PHOENICS model. The three-dimensional model includes the tunnel structure, jet fans (as obstructions only), exhaust shafts, train and mechanical smoke management system as shown in Figure 3.3 & 3.4.

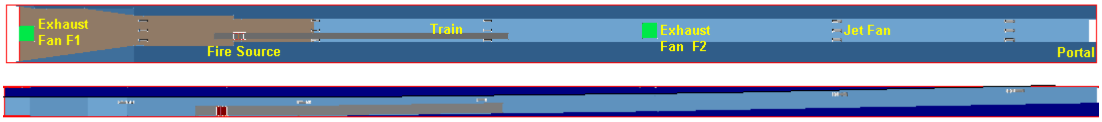


Figure 3.3 Tunnel model

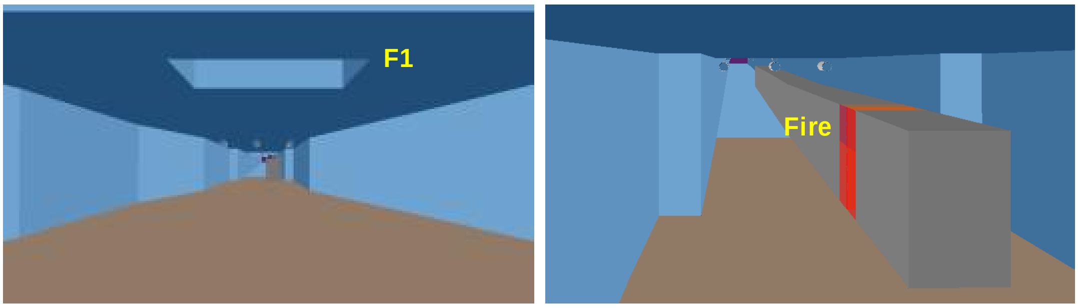


Figure 3.4 Tunnel model

The dimensions of the CFD model is 437mû23mû11.32m and the size of the model is 178û37û22 non-uniform cells. A Cartesian co-ordinate system with manual embedded cell refinement has been adopted for meshing. Local refinement has allowed increased resolution for the model, in particular for areas near to the fire.

3.2.1 Boundary Conditions and Fire Safety Criteria

The temperature for the ambient environment and all surface boundaries has been specified as 20°C in the tunnel and 25°C outside the tunnel.

All walls, columns, ceilings and floors are assumed adiabatic, ie no heat loss through the construction is modelled. This is considered a conservative assumption as the smoke temperature will be overestimated close to the fire source and hence create higher heat flux levels towards the escaping occupants. Furthermore, as the smoke temperature will be overestimated, the volume of the smoke layer will also be somewhat overestimated.

The transient spreading behaviours of smoke including temperature and concentration and velocity field have been simulated using the modified $k-e$ turbulence model (KECHEN Model). The hyper differential scheme has been used to evaluate the temperature and velocity fields of the domain. The outputs include longitudinal and cross sectional graphic contours of temperature [°C], smoke concentration [%] and velocity [m/s] profiles.

The station flow-in boundary condition was controlled by setting a relative pressure difference at the interface. The boundary condition at the tunnel portal was set either with pressure or velocity for different time periods. Furthermore, exhaust shaft fan F1 was either set with pressure when working as a pressure relief/make up air opening or with a set velocity when working as an exhaust fan.

In the PHOENICS code employed in the analysis of this report, the combustion process of diesel train fire itself is not simulated. Instead, the fire source simply occupy the middle part of the engine carriage within a defined spatial region at which time-dependent heat release rate is given and smoke generation rate is set as unit. Therefore the fire source works like a huge 'electric heater'.

3.2.2 Fire Safety Criteria

The purpose of the smoke management system within the tunnel is to maintain a safe environment with adequate visibility and limit the temperatures in order to allow a safe escape in the event of a fire.

Based on the limits in NFPA 130 'Fixed Guideway Transit Systems'[(4)] (refer summary of literature review above), the tenability criteria for life safety in the tunnel are assumed to be:

- if the hot layer remains above **1.5m**, a temperature limit of **200°C** (=2.5kW/m² radiation from the hot smoke layer) will apply.
- if the hot layer falls below **1.5m**, the temperature should not exceed **60°C** and/or the visibility not be less than **6m** (ie the optical density should not exceed $0.14m^{-1}$).

A minimal visibility of 6m and a temperature of 60°C are considered acceptable for the consequence analysis of the tunnel, as it involves only very limited way-finding and occupants will be able to evacuate in either direction of the tunnel.

3.2.3 Calculation of Visibility (or Optical Density)

Theoretical

Visibility is defined as

$$Vis = \frac{1}{OD} \qquad (1)$$

Furthermore, optical density is calculated as:

$$OD = POD \times C_m \qquad (2)$$

where OD = optical density (m^{-1}),

POD = particle optical density (m^2/kg_{soot}),

C_m = mass concentration of smoke (kg_{soot}/m^3),

Therefore, given a POD of 3300 m^2/kg[(11)] for flaming combustion, a visibility of 6m correlates to a mass concentration of smoke (C_m) of approximately $5.0*10^{-5}$ or 0.00005 kg_{soot}/ m^3.

Based on a soot concentration (C_{source}) at the fire the tenability limit for smoke concentration (C_m) can be expressed relative to the concentration at the fire source:

$$F = \frac{C_m}{C_{source}} = \frac{5.0 \times 10^{-5}}{1.32 \times 10^{-3}} = 0.0378 \approx 3.7\% \quad (3)$$

Experimental

Given that the spread soot particles, ie smoke, normally is dominated by the buoyancy driven flow in the fire plume and the ceiling jet it is considered that the PHOENICS model may over estimate the smoke spread, and hence the volume of the smoke layer, in tunnels with high forced ventilation flows such as a longitudinal tunnel ventilation.

Mizuno(13) presented the comparisons between practical fire test and numerical simulations on smoke density. The smoke density C_s is described as in the following relation:

$$t = \frac{I}{I_0} \exp(-C_s l) \quad (4)$$

where t is the visibility, I is the measured intensity, I_0 is the intensity without smoke, and l is the distance between light source and detector. The author suggested that C_s=0.4 [1/m] might be considered as a critical value for the passenger to be able to evacuate. In fact, this value corresponds to the optical density:

$$OD = \frac{C_s}{2.3} = \frac{0.4}{2.3} = 0.174 \text{ [1/m]}, \quad (5)$$

which reflects a visibility of approximately 6 metres.

Using the above parameter, Kawabata and Wang(14)(15) gave an numerical study on real scaled tunnel fires. The study indicates that the smoke layer concentration (visibility) and temperature profiles will have certain similarity. Results show that a fire-induced smoke layer with temperature higher than 60-70°C will approximately have a visibility less than 6m. Therefore, the authors recommend that the simulation results on temperature as the major criteria for tunnel fire safety design.

3.2.4 Fire Source

Fire Growth Rates

A large developing fire within one of the carriages is assumed to develop at a 'slow' ($0.003kW/s^2$) to 'fast' ($0.047kW/s^2$) t^2-growth rate, depending on the interior materials in the carriage and the ignition source. A 'fast' growing fire is therefore considered to be a conservative assumption for as 'worst credible' fire scenario.

As a 'worst case' fire scenario a fire developing outside a train that has stopped in the tunnel between the two vent shafts and is leaking diesel is assumed. A diesel pool could potentially grow as a 'fast' ($0.047kW/s^2$) to 'ultra fast' ($0.19kW/s^2$) fire. However, due to the provision of ballast between the sleepers and on the concrete slab with the tunnel the build up of a pool is prevented and the impact of the slope minimised. A 'fast' growing fire is therefore considered to be a reasonable assumption.

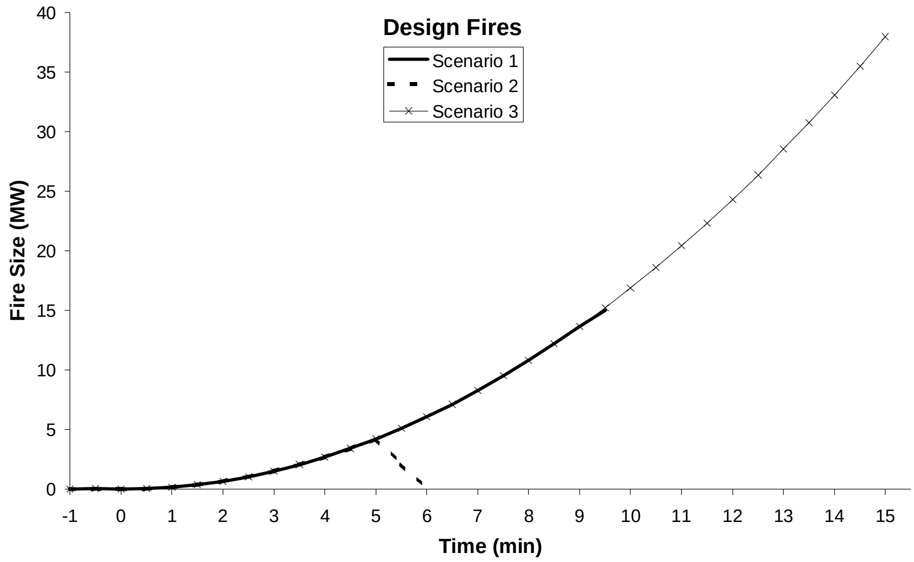


Figure 3.5 Design Fire Scenarios - Heat Release Rates (including 1min pre-fire period)

Convective Heat Release Rate

It is assumed that 35% of the heat released from a fire is radiation and 65% convective heat release, Q_{conv}. In the CFD modelling only the convective heat release rate is modelled. Road tunnel fire tests have indicated as low as 50% convective energy but as the absorption of radiant heat in the smoke layer is not modelled, it is considered reasonable to assume 65% convective heat release to adjust for approximations in the modelling.

3.2.5 Fire Scenarios

Based on the hazard identification study it can be seen that a fire within one of the train carriages (Scenario 1) is the most likely scenario. The hazard identification also indicates that no incidents due to a diesel spillage on trains had been recorded in the researched studies. However, a diesel spillage fire scenario is considered a 'worst case' fire scenario for occupant safety and smoke management for fire fighting operations and will be further analysed both with foam suppression and without the suppression as a sensitivity analysis.

Table 4 Summary of Design Fire Scenarios

Fire Scenario	Description
No.1 - Carriage Fire	This fire scenario is considered appropriate as a 'worst credible' fire scenario for a fire breaking out inside a train that has stopped in the tunnel between the two vent shafts. The fire is assumed to be an exponentially ‘fast’ (0.047kW/s²) growing fire with the maximum fire size 15MW, as a fully developed carriage fire.
No. 2 - Suppressed Diesel Fire	This fire scenario is assumed reasonable as a 'worst credible' fire scenario for a fire outside a train that has stopped in the tunnel between the two vent shafts and is leaking diesel. The fire is assumed to be a ‘fast’ (0.047kW/s²) growing fire, which is suppressed upon activation of the foam suppression system at track level.
No. 3 - Unsuppressed Diesel Fire (sensitivity analysis)	This fire scenario is a sensitivity analysis of the diesel fire outside the carriage (Scenario 2) in the event of failure of the foam suppression system. The fire therefore continuos to grow to its maximum size 40MW, involving both the diesel and a carriage.

No. 1 - Carriage Fire

Design Fire • Fire Location = Between ventilation shaft F1 and F2, 91 metres away from the station box (west end of tunnel). • Fire Growth Rate = NFPA 'fast' ($0.047kW/s^2$), refer Section 0. • Peak Fire Size = 15 MW (fully developed carriage fire). • Fire Area = Increasing with the heat release rate of fire time-dependently ($1.5\ MW/m^2$).
Fire Characteristics • Heat of Combustion = 30 MJ/kg. • Radiative Fraction = 35%. • Smoke conversion factor = 10% (equivalent to a soot potential $D_m = 300\ m^2/kg_{soot}$).
Smoke Management System • <u>Period A (0-3min): Normal ventilation mode</u> All jet fans work creating a longitudinal flow of air at approx. 2-2.5m/s ($106m^3/s$) from the station end of the tunnel and approx. 1-1.5m/s ($74m^3/s$) from the tunnel portal. This is modelled/controlled by prescribing a flow velocity U=1.37m/s in through the portal and station boundary condition $\Delta P=0$ Pa). The exhaust fan F2 is at full exhaust, $180m^3/s$ (5m/s). Ventilation shaft F1 works as pressure relief/make up air opening ($\Delta P=0$). • <u>Period B (3-4min): Transition period without jet fans</u> All jet fans stopped (portal $\Delta P=0$ Pa). Ventilation shafts F1 and F2 work as in Period A. • <u>Period C (4min to end): Emergency fire ventilation mode</u> All jet fans stopped (portal $\Delta P=0$ Pa). Both shaft F1 and F2 work as exhaust fans at full capacity, $180m^3/s$ (5m/s).

No. 2 - Suppressed Diesel Fire

Design Fire

- Fire Location = Between ventilation shaft F1 and F2, 91 metres away from the station box (west end of tunnel).
- Fire Growth Rate = NFPA 'fast' ($0.047 kW/s^2$), refer Section 0.
- Peak Fire Size = 4 MW (diesel fire size at activation of foam suppression system).
- Fire Area = Increasing with the heat release rate of fire time-dependently ($1.5 MW/m^2$).

Fire Characteristics

- Heat of Combustion = 30 MJ/kg.
- Radiative Fraction = 35%.
- Smoke conversion factor = 10% (equivalent to a soot potential $D_m = 300\ m^2/kg_{soot}$).

Smoke Management System

- Period A (0-3min): Normal ventilation mode

All jet fans work creating a longitudinal flow of air at approx. 2-2.5m/s ($106m^3/s$) from the station end of the tunnel and approx. 1-1.5m/s ($74m^3/s$) from the tunnel portal. This is modelled/controlled by prescribing a flow velocity U=1.37m/s in through the portal and station boundary condition ΔP=0 Pa).

The exhaust fan F2 is at full exhaust, $180m^3/s$ (5m/s).

Ventilation shaft F1 works as pressure relief/make up air opening (ΔP=0).

- Period B (3-4min): Transition period without jet fans

All jet fans stopped (portal ΔP=0 Pa).

Ventilation shafts F1 and F2 work as in Period A.

- Period C (4min to end): Emergency fire ventilation mode

All jet fans stopped (portal ΔP=0 Pa).

Both shaft F1 and F2 work as exhaust fans at full capacity, $180m^3/s$ (5m/s).

No. 3 - Unsuppressed Diesel Fire (sensitivity analysis)

Design Fire

- Fire Location = Between ventilation shaft F1 and F2, 91 metres away from the station box (west end of tunnel).
- Fire Growth Rate = NFPA 'fast' (0.047kW/s²), refer Section 0.
- Peak Fire Size = 40 MW (involving both maximum diesel fire size and a fully developed carriage fire).
- Fire Area = Increasing with the heat release rate of fire time-dependently (1.5 MW/m^2).

Fire Characteristics

- Heat of Combustion = 30 MJ/kg.
- Radiative Fraction = 35%.
- Smoke conversion factor = 10% (equivalent to a soot potential D_m = 300 m²/kg_{soot}).

Smoke Management System

- <u>Period A (0-3min): Normal ventilation mode</u>

All jet fans work creating a longitudinal flow of air at approx. 2-2.5m/s (106m³/s) from the station end of the tunnel and approx. 1-1.5m/s (74m³/s) from the tunnel portal. This is modelled/controlled by prescribing a flow velocity U=1.37m/s in through the portal and station boundary condition ΔP=0 Pa).

The exhaust fan at Tinley Street (F2) is at full exhaust, 180m³/s (5m/s).

Ventilation shaft F1 works as pressure relief/make up air opening (ΔP=0).

- <u>Period B (3-4min): Transition period without jet fans</u>

All jet fans stopped (portal ΔP=0 Pa).

Ventilation shafts F1 and F2 work as in Period A.

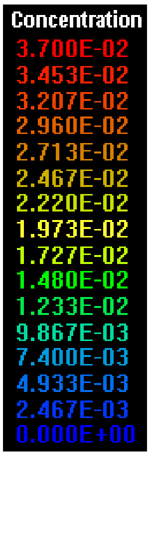
- <u>Period C (4min to end): Emergency fire ventilation mode</u>

All jet fans stopped (portal ΔP=0 Pa).

Both shaft F1 and F2 work as exhaust fans at full capacity, 180m³/s (5m/s).

3.3 Simulation Results

Figure 3.6 ~ 3.11 show the temperature and smoke concentration slices along the centre of the tunnel and the raised walkway on the side of the tunnel where the train has stopped (1-8min). The colour red indicates smoke temperatures above 60°C and smoke concentration above 3.7% (=6m visibility). The legends of smoke concentration and temperature are shown as the right images.



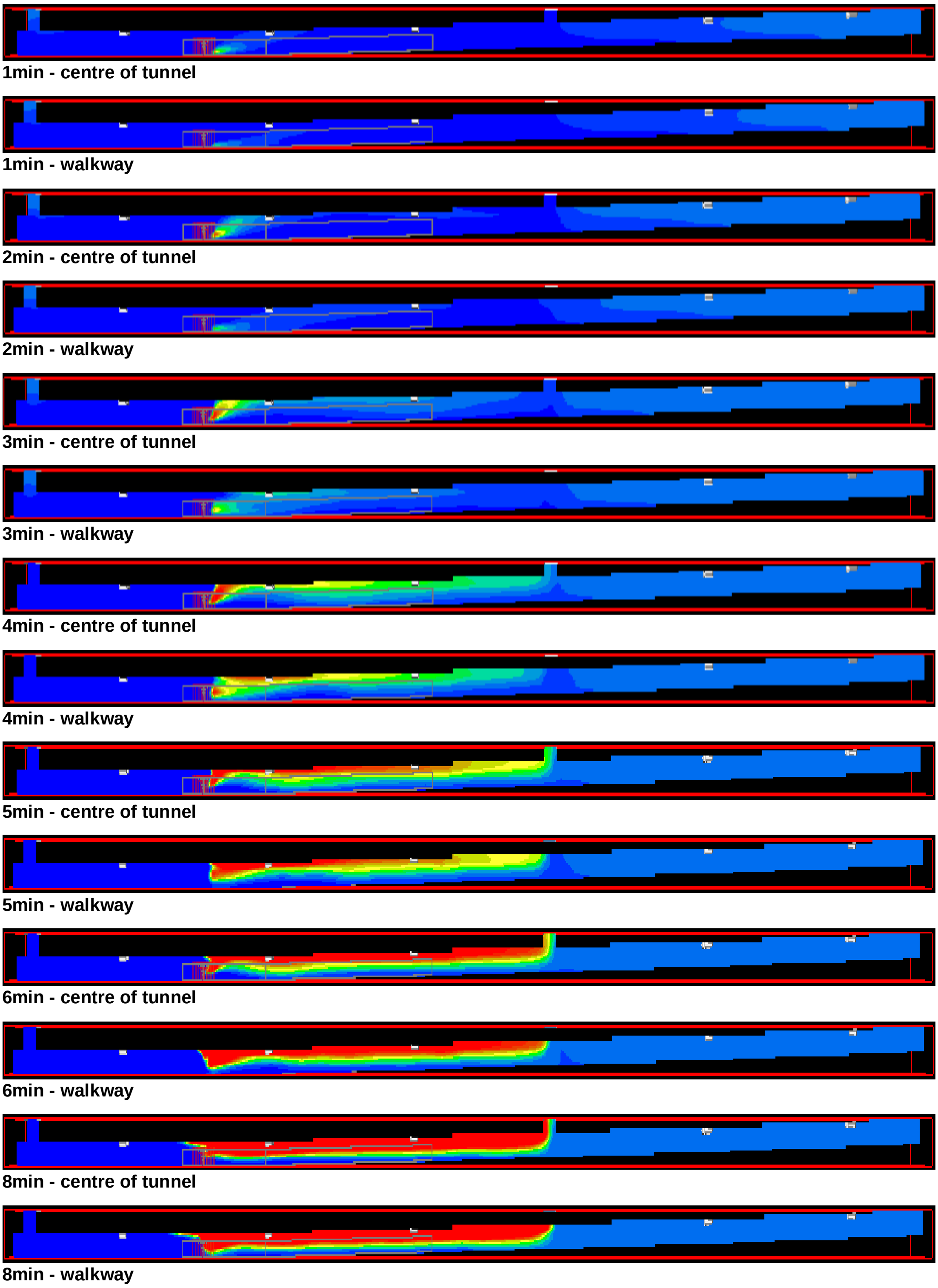


Figure 3.6 Temperature slices along the centre of the tunnel and the raised walkway.

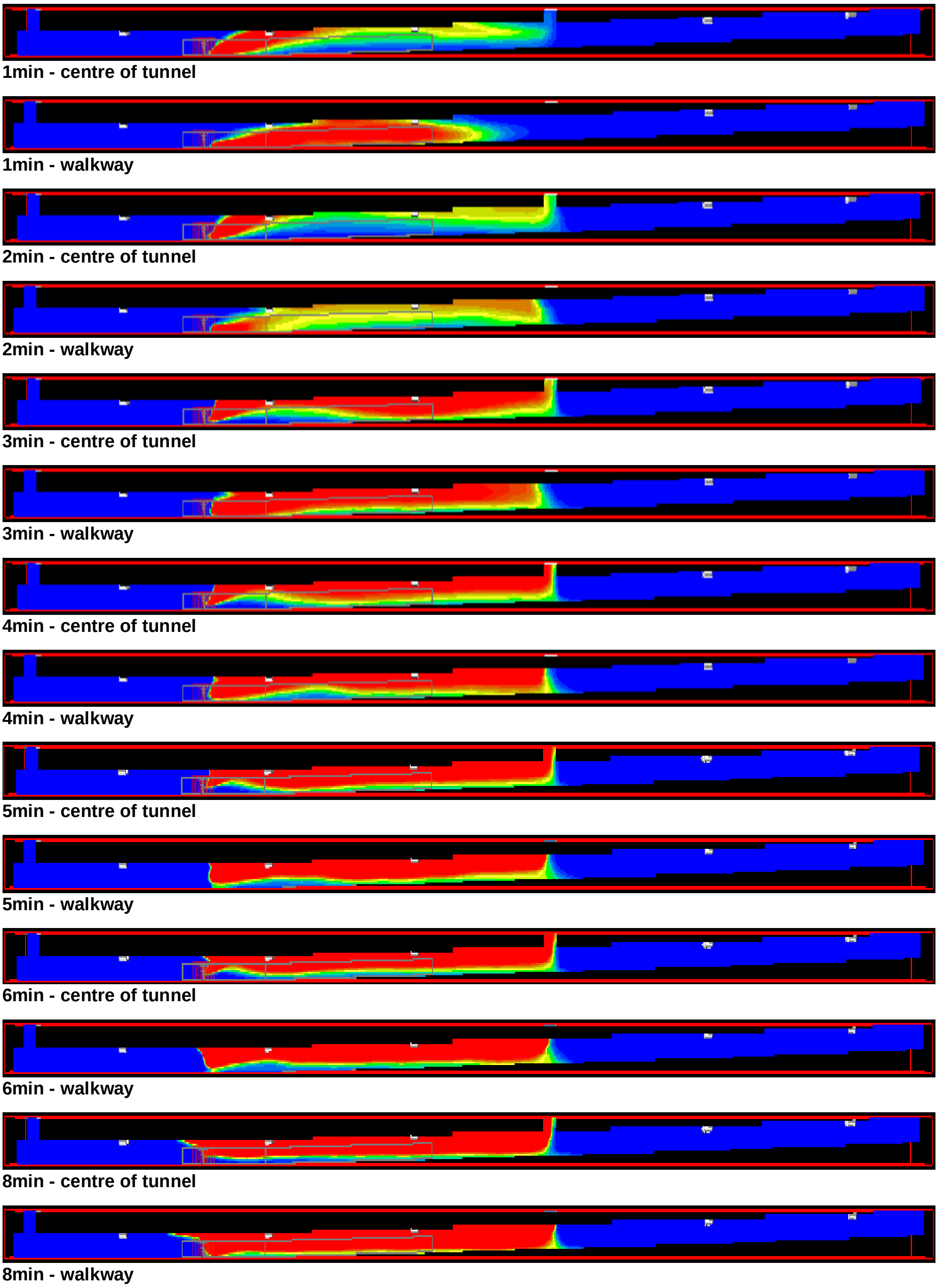


Figure 3.7 Concentration slices along the centre of the tunnel and the raised walkway.

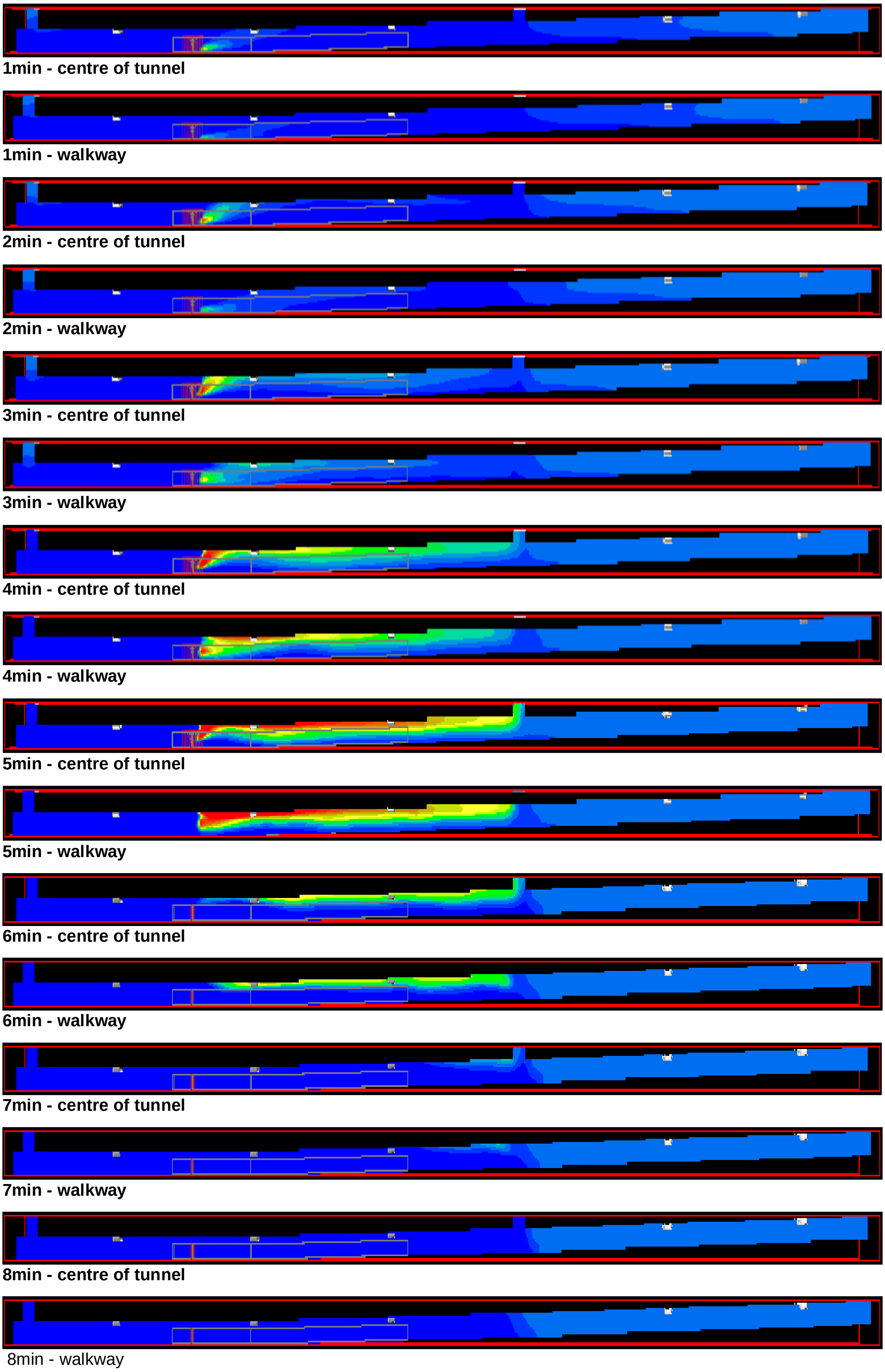


Figure 3.8 Temperature slices along the centre of the tunnel and the raised walkway.

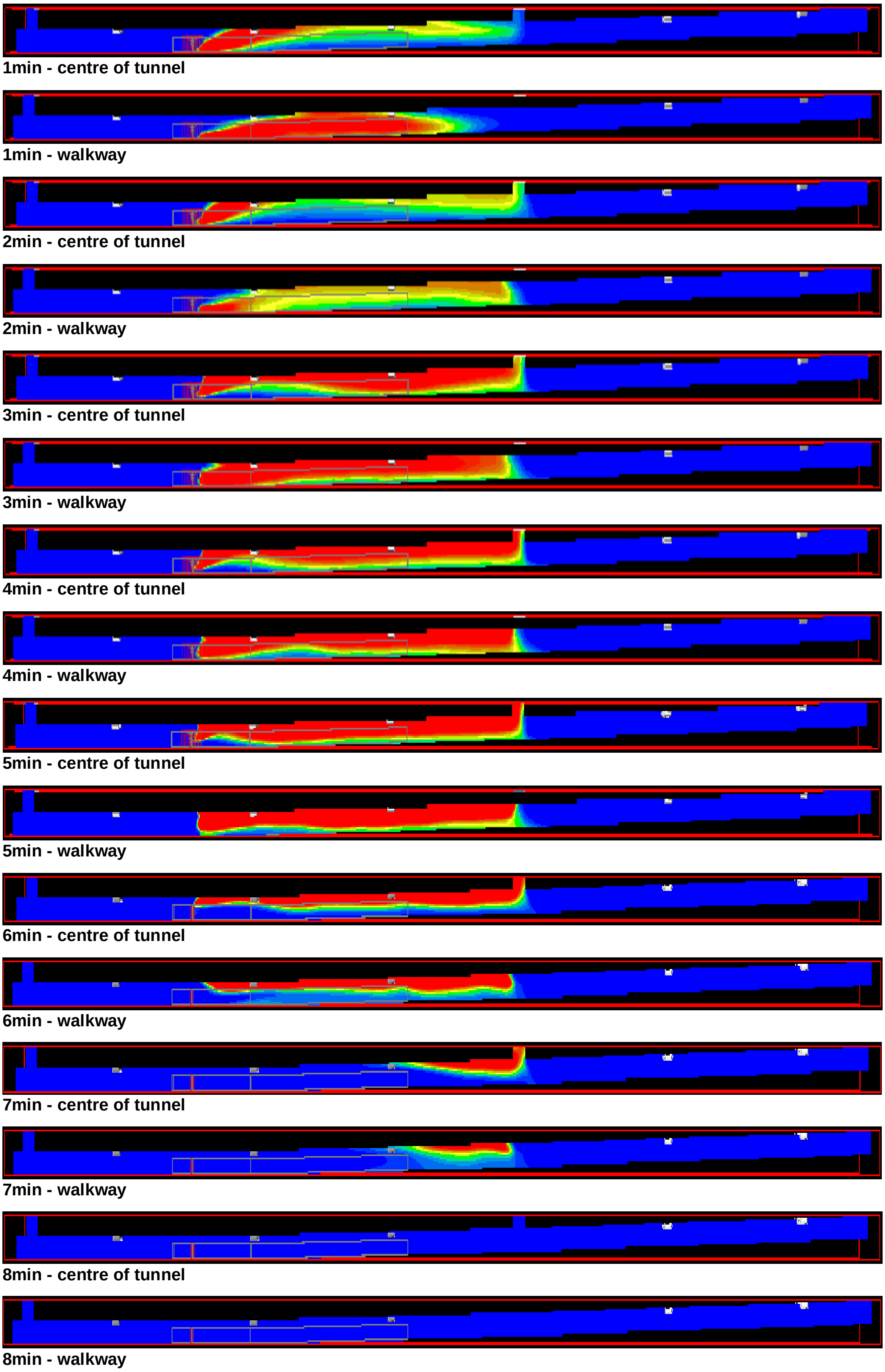


Figure 3.9 Concentration slices along the centre of the tunnel and the raised walkway.

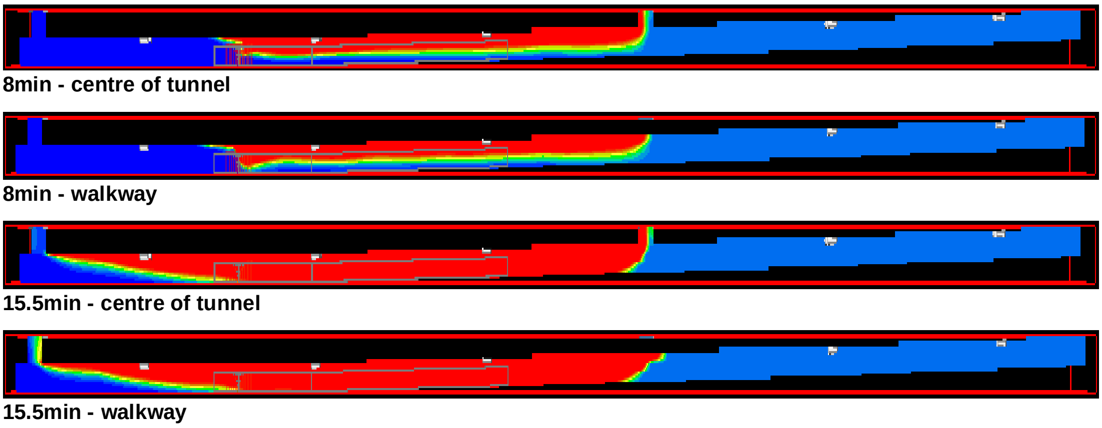


Figure 3.10 Temperature slices along the centre of the tunnel and the raised walkway.

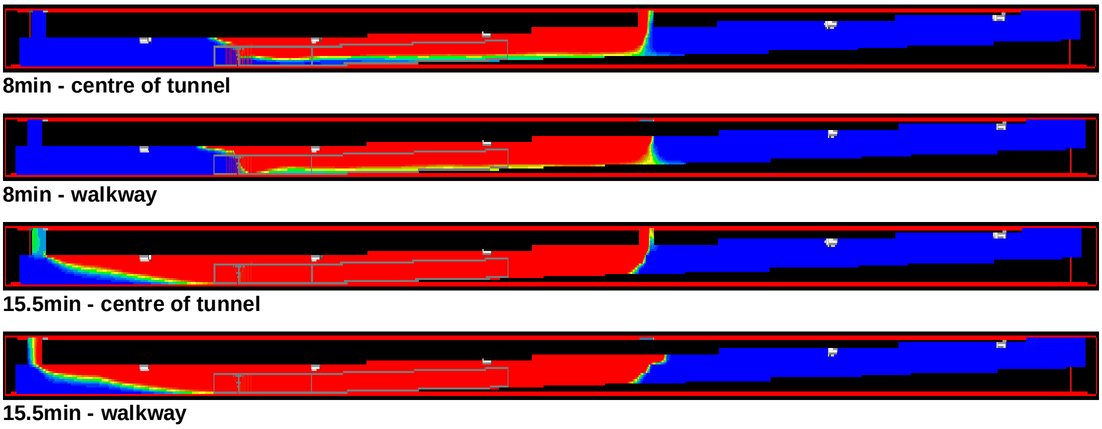


Figure 3.11 Concentration slices along the centre of the tunnel and the raised walkway.

3.4 Discussions

Scenario No. 1 - Carriage Fire

Based on the calculated temperature profiles it can be seen that a smoke layer with temperatures over 60°C (and hence the visibility is less than 6m as per Sections **3.2.2**) starts building up after 5 minutes. However, occupants can still evacuate below the warmer and denser smoke where the visibility is more than 6m and the smoke temperature below 60°C.

After approximately 10 minutes, when the fire has reached its maximum size (15MW), the smoke layer has descended down to 1.5m above the raised walkway at the side of the tunnel and untenable conditions occur. See Figure 4.1 below.

Even for the calculated smoke concentration ('species concentration') it can be seen that untenable conditions (3.7% = 6m visibility) do not occur until approximately 5 minutes after the start of the fire. Note that untenable conditions initially only occurs downwind of the fire. It is not until approximately after 10 minutes that untenable conditions develop upstream of the fire.

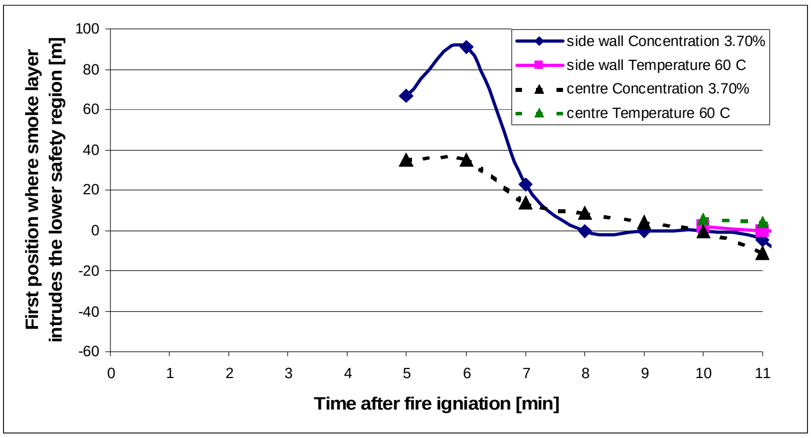


Figure 4.1 First downwind occurrence of untenable smoke

Scenario No. 2 - Suppressed Diesel Fire

Based on the calculated temperature profiles from scenario 2 (with the suppressed diesel fire) it can be seen that the smoke layer starts building up and that the temperature close to the tunnel roof exceeds 60°C and hence the visibility is less than 6m. However, occupants can still evacuate below the denser smoke where the visibility is more than 6m and the smoke temperature below 60°C.

Upon activation of the foam suppression system, the tunnel is cleared from smoke in a few minutes. Even for the calculated smoke concentration ('species concentration') it can be seen that it is only for a short limited time period that the untenable (concentration >3.7%) smoke layer descends below 1.5m. Again, upon activation of the foam suppression system, the tunnel is cleared from smoke in a few minutes.

Scenario No. 3 - Unsuppressed Diesel Fire (sensitivity analysis)

The calculations show that for an unsuppressed large fire (40MW) backlayering towards the station will occur. It can be seen that backlayering starts to occur to some extent after approximately 6-8 minutes.

After this, the smoke slowly (0.1-0.4m/s) moves further and further back towards the station. However, the calculations show that the smoke exhaust fan at F1 exhausts all smoke moving back against the station and no smoke spread into the station occurs.

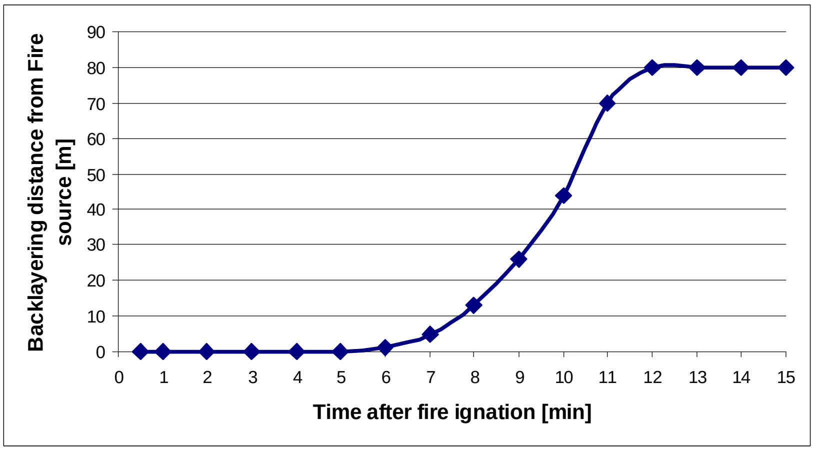


Figure 4.2 Backlayering distance as a function of time.

After approximately 10 minutes untenable conditions begin to develop upstream of the fire as the backlayering of smoke moves towards the west end of the tunnel and the station.

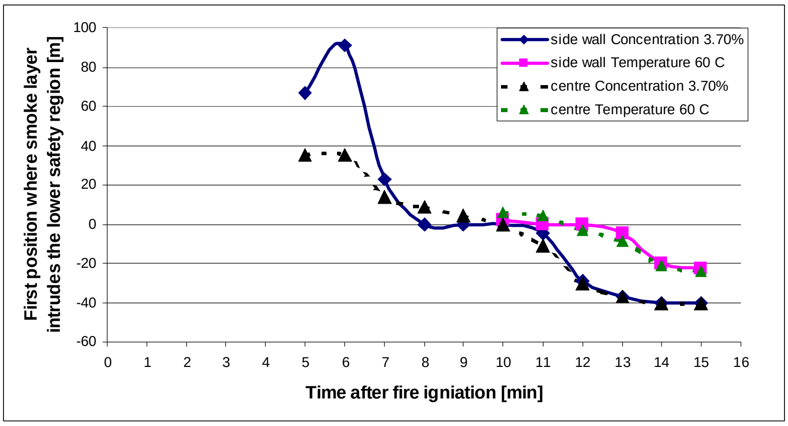


Figure 4.3 First downwind occurrence of untenable smoke.

At the end of the simulation (15.5min) the longitudinal airflow through tunnel is largely decreased and the buoyancy flow from the fire has grown larger in relation to the longitudinal airflow. It can been seen from the calculations that at this stage the temperature (>60°C) and concentration (>3.7%) profiles show relatively good agreement as anticipated in accordance with the discussion in Sections 3.2.2.

3.5 Summary

There design fire scenarios have been simulated using PHOENICS. Results show that in either case the fire safety environment for the occupants is reasonable according to the calculated internal temperature, CO concentration levels at different time after fire starts. Therefore, it is proved that the design smoke control/ventilation system during different fires will be able to provide a reasonable fire safety condition.

4. CONCLUSIONS

PHOENICS applications on building internal air quality control and emergency fire smoke control strategy have been carried out. Very detailed thermal and fluid behaviours of internal air have been analysed, which either identified the efficiency of the ventilation systems or provided the optimisation to the design features. All these results show that PHOENICS can deal with very broad fluid dynamic modelling, and is the most cost effective tool in professional engineering consultant services.

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APPENDIX A

DERIVATION OF ABSOLUE CONCENTARTION FROM THE RELATIVE MIXING RATIO C1

1. Number of train types is: *1 ADX (idle) with 2 pipes.*

2. For each pipe, the emission of CO is

$$348.7\left[\frac{g}{hr}\right]*\frac{1[hr]}{3600[s]}*\left[\frac{1}{2}\right]=0.048\left[\frac{g}{s}\right] \quad \text{CO mass emission rate at inlet of pipe}$$

3. For each pipe, the discharge rate is

$$7.5\left[\frac{m}{s}\right]*(p\ \frac{0.015^2}{4})\left[m^2\right]=0.00133\left[\frac{m^3}{s}\right] \quad \text{Volume of air at inlet of pipe}$$

4. Concentration of CO near pipe inlet is

$$\frac{0.048\left[\frac{g}{s}\right]}{0.00133\left[\frac{m^3}{s}\right]}=36\left[\frac{g}{m^3}\right]=\frac{36\times10^3[mg]}{1.18[kg]_{airat27^oC}}=3.051\times10^3\,\text{PPM}$$

5. For the Maximum Allowable Pollutant Level of CO, ie. 25ppm, the relative concentration of CO (C1 in simulation results) is

$$\text{MACO}=\frac{25[ppm]}{3.051\times10^3[ppm]}=0.00082 \text{ (relative value)}$$

6. Use this MACO to display the iso-concentration surface of C1 on PHOENICS to check the containment situation at required position or height inside the station.