An Analysis of Thermal Environment for Road Tunnel in the Incidence of Fire

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ABSTRACT

In recent years road tunnel fires have erupted in many locations around the world, which calls for the necessity to adopt more fire-effective and economical tunnel construction practices, having systematically analyzed the entire system of the tunnel. In this study, for probing into the basic characteristics pertaining on the thermal environments to tunnel structures, it is aimed at developing some fundamental literature on fire proofing measures of tunnels by setting up standard conditions and then focusing mainly thermal environmental analysis of flow field and concrete surface by numerical simulations, thereby clarifying the thermal distribution of each type of tunnel structure.

In this report, we discussed about relationship between thermal conditions and heat release rate of 30MW, 50MW, 100MW with time progress for two different cross section with rectangular and circular. As a result of this study, thermal environment in the tunnel space to be more cleared. It was clarified that, assuming the same fire scale, circular tunnels are advantageous (in terms of thermal environment) compared to rectangular tunnels.

In addition, airflow rate for preventing of the back layer of smoke flow also was clarified.

Key words: (Road Tunnel, Tunnel Cross Section Shape, Heat Release Rate, Air Temperature, Concrete Surface Temperature)

1 INTRODUCTION

In recent years road tunnel fires have erupted in many locations around the world, which calls for the necessity to adopt more fire-effective and economical tunnel construction practices, having systematically analyzed the entire system of the tunnel. In this study, for probing into the basic characteristics pertaining to the thermal environments to tunnel structures, it is aimed at developing some fundamental literature on fire proofing measures of tunnels by setting up standard conditions and then focusing mainly thermal environmental analysis of flow field and concrete surface by numerical simulations, thereby clarifying the thermal distribution of each type of tunnel structure. It was clarified that, assuming the same fire scale, circular tunnels are advantageous (in terms of thermal environment) compared to rectangular tunnels.

In this study, for probing into the basic characteristics pertaining to the thermal effects on tunnel structures, it is aimed at developing to the mitigation of fire protection systems for concrete structure, ventilation systems and other safe systems which will be exposed in the thermal environment.

The thermal environmental analysis is implemented by Computational Fluid Dynamics (CFD). The results of CFD, always we compared with suitable references to thermal environment.

2 BASIC CONDITIONS FOR FLUID DYNAMICS SIMULATION

2.1. Heat release rate for calculation

Heat output in the incidence of fire depends on the scale of fire. Here we assume a heat output of 30 MW due to burning of a Heavy Goods Vehicle (HGV), and the maximum temperature inside the tunnel to reach 1000 Celsius (PIARC Report 1999).[1)]

Figure1 presents most probable development of total released energy and heat release rate for

HGV introduced from EUREKA Report$^{2)}$, in the case of HGV fire, the maximum heat release rate exceeded 100 MW with the time duration 10 - 20 minutes. This heat release rate seems to be maximum value for HGV fire without dangerous goods transportation.

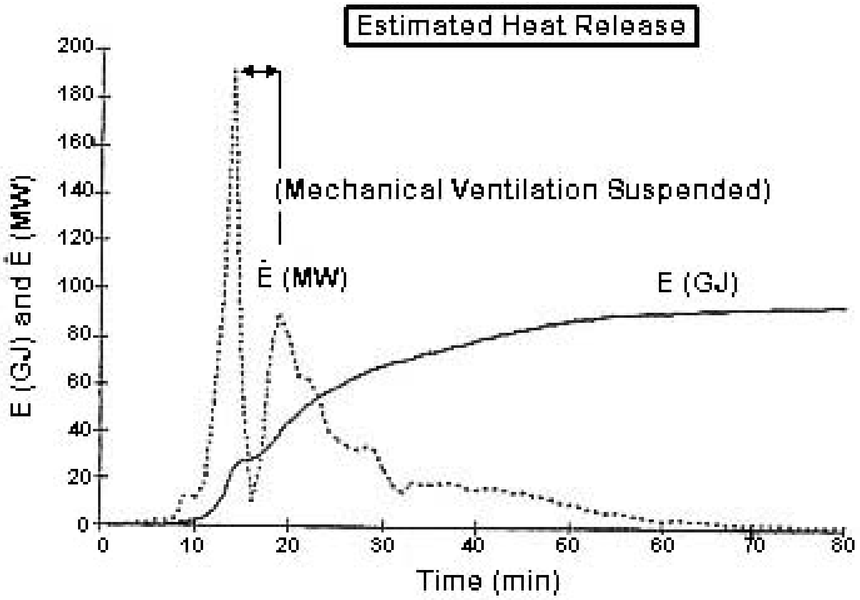


Figure 1 Most probable development of total released energy and heat release rate for HGV$^{2)}$

Based on these 30MW to 100MW of HGV heat release rate, from PIARC and EUREKA REPORT, and also 50MW fire could be assumed in real situation for fire of HGV.

In this report, we discussed about relationship between thermal conditions and heat release rate of 30MW, 50MW, 100MW with time progress for two different cross section with rectangular and circular sections.

The thermal output curve is arranged as shown in Figure 2 below.

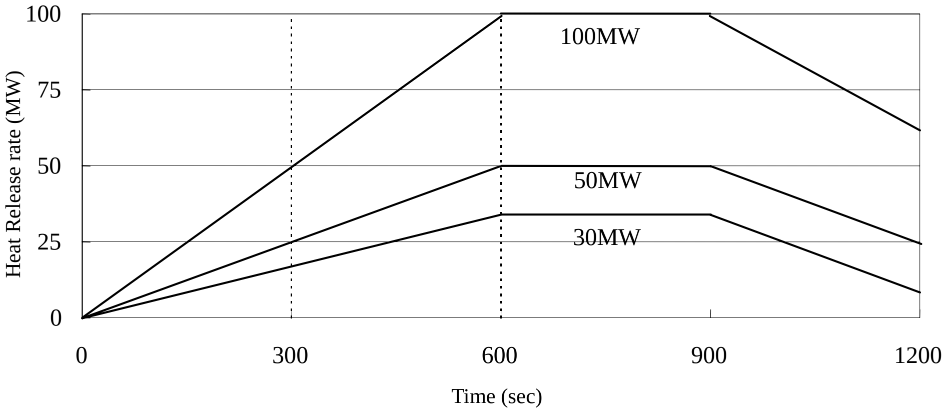


Figure 2 Heat release curve in tunnel in the incidence of fire

2.2. Conditions and location of heat output for tunnels

For the heat output source, a heavy goods vehicle has been assumed, where it is set to that meshes in an area of vehicle width of 2.2m and length of 6m receive the effect of this heat output. Figure 3 shows the basic configuration of heat output source of vehicles in road tunnels.

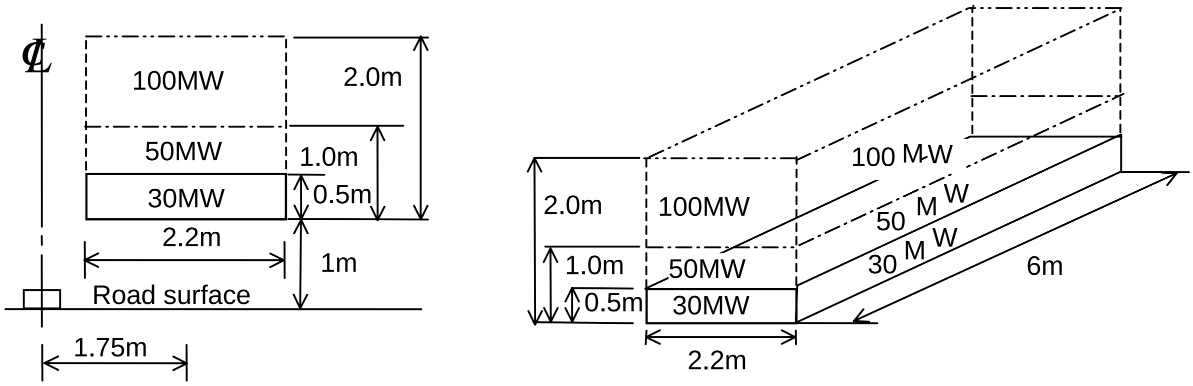


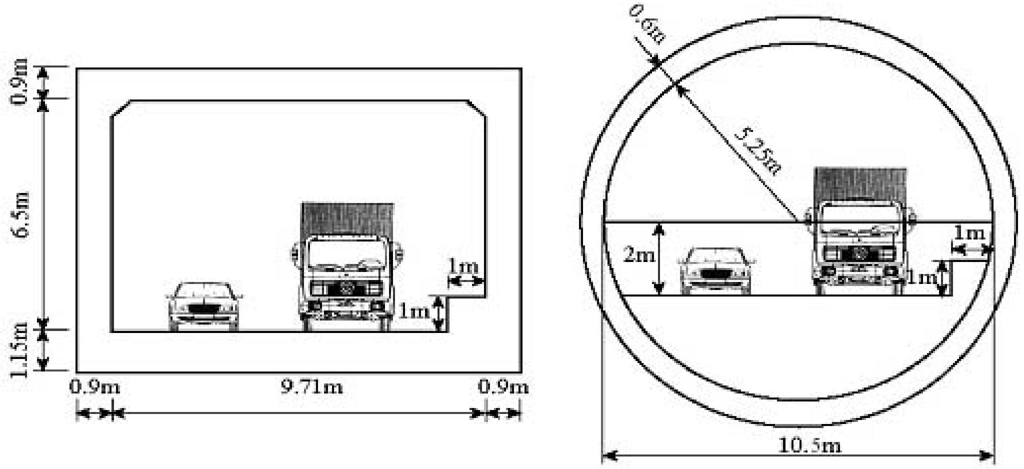
Figure 3 Basic configuration of heat output source of road tunnels

Basically, if the thermal capacity of burning goods is constant, heat release rate should be determined by the contact area with air (oxygen). Therefore for the purpose of simplification for comparing with each heat release rate, the basic configuration of heat output source was fixed at increase of the height of burning goods. (Bigger heat output source mount on smaller output source.)

2.3. Standard Cross-section

From the topographical, geological conditions of the tunnels, and point of view from flow and thermal distribution field, rectangular and circular section have a different character, therefore, circular and rectangular cross-sections are employed in the present analysis. Figure 4 presents these standard cross-sections.

In road tunnels, kinematics gauge of both crosssections is similar for each direction. The number of lanes are generally assumed to be two, with uni-directional traffic. Therefore in actual roads, this becomes two tubes.



Rectangular section Circular section

Figure 4 Standard cross-section of road tunnels

2.4. Basic Equations of Fluid Dynamics

The basic equations of fluid dynamics (Continuity equation, Navier-Stokes equation and Enery equation) have been adopted for forecasting air flow and temperature through a numerical analysis. Further, the κ - ε model has been used to make turbulent flow realistic here.

2.5. Heat Transmission to Structure

Here these computations are assumed to be a problem of heat conductivity between fluid and solid portions. Solid portion is assumed to be of equal sides, that heat transfer within the solid is governed by the following equation:

$$\frac{\partial(\rho e)}{\partial t} = \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right)$$

ρ : Density T : Temperature
e : Internal energy k : Thermal conductivity coefficient
t : Elapse time x_i : Cartesian coordinate

Further, heat transfer between fluid and solid portions, it assumed that continuity in this process is a key to the solution.
The effects of heat radiation to the thermal environments in the tunnel structure was not take into account to the CFD simulation, due to the simplify and shorten of calculation time.
The effects of heat radiation are acting to the increment of the air and structural temperature.
Therefore, for the evaluation and discussion in the actual conditions, the appropriate margins for safety design should be take into account form this predicted results of thermal environments.

2.6. Various Computational Conditions

For computations in this respect, the following coefficients pertaining to air inside the tunnel and concrete surface of tunnel have been used as in Table 1:

Table 1 Tunnel condition and coefficients of computational model

Item		Confirmed value
Tunnel length		Tunnel length 450m within fire source
Air	Density	28.96 kg/kmol (mol weight)
	Molecular viscosity	1.81 x 10^{-5} kg/m·s
	Specific Heat	1006 J/kg·K
	Conductivity	0.02637 W/m·K
Concrete	Density	2300 kg/m^3
	Specific heat	840 J/kg·K
	Conductivity	1.6 W/m·K
Heat transfer coefficient		automatically set value by ventilation condition
Heat release rate		30MW

2.7. Mesh Condition for Computations for Tunnels

Considering total number of meshes for computations and computational difficulty, concerning the cross-section, 320-360 meshes for fluid portion and 360 - 430 meshes for solid portion have been adopted. Further, 100-140 cross-sections at 1 - 5m intervals have been selected in the longitudinal direction of road. Thus, the total number of meshes amounted to 80,000 - 100,000.

2.8. Mesh Condition and Dispersion

In this analysis, modeling is achieved through a virtual mesh configuration, and adopting a finite volume method, the governing differential equation of preservation of mass, movement, and energy of fluid and solid bodies is used to determine the dispersion.

2.9. Ventilation Conditions

If we assume a fire in a tunnel due to a burning vehicle that produces a heat output of 30 MW, from existing literature [1), 2)] we can judge that a wind velocity of 2.5 m/s may be appropriate to control smoke, that we set the wind velocity in tunnel upstream of fire source to be 2.5 m/s. In an actual fire, there are vehicles in the upstream of fire source causing aerodynamic resistance and turbulence flow. However, this problem is one that should be tackled as a ventilation system issue, therefore, will not be considered here. This argument thus leads to setting a resulting wind velocity of 2.5 m/s.

In the case of 50MW, 100MW fire, critical wind velocity for prevention for smoke of back layering to be found in the process of calculation, then the longitudinal wind condition to be fixed.

On the point of view of egress environment, the inhalation of fume and smoke are one of the major factors of the serious damage to the human body.

If in the case of back layer spread to entire section of tunnel space at upstream side from fire source, the air flow velocity should be increased. However, in the case of the depth of back layer from ceiling to downwards to carriage way is still shallow at the 2.5m/s wind velocity, in other words, the clearance of visibility space still sufficient for evacuation, the ventilated air velocity did not revise in calculation.

3 DETERIORATION OF STRENGTH IN CONCRETE

It is a well known fact that the strength of concrete will be reducted in the case of temperature increased at certain level.

Generally, if in case of concrete temperature increase up to 200°C, the basic performance of concrete assumed at 100%. However, Dr. E. Richter mentioned fallowing issues to concrete performance under the thermal condition, [3)] "as lasting plastic deformations in the reinforcement are avoided through temperatures 300°C, it is assured that only a short period is required to repair the tunnel after the fire."

Based on these opinion, in the case of predicted results will be exceed 300°C. The appropriate fire protection mitigations should be adopted to the structure.

4 COMPUTATIONAL RESULTS AND DISCUSSION

4.1. Circular Cross Section

Figure 5 presents air temperature distribution in the case of 100MW fire as a example. The back layering near the ceiling part has been occurred. However, the thermal environment for evacuation is still ensured to the equivalent height of tunnel passengers under the 2.5m/s of ventilated air velocity.

The peak air temperature at closest point of concrete surface exceeds easily by 1500°C.

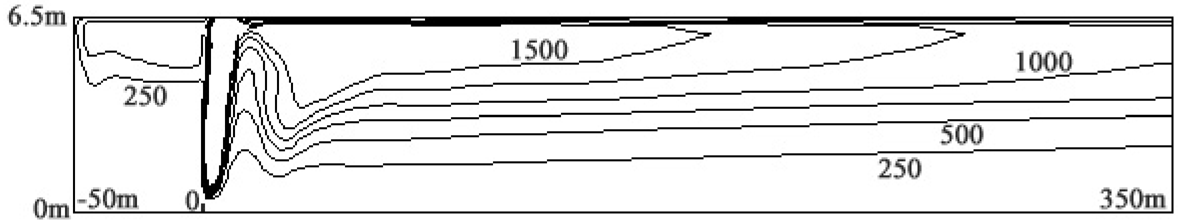


Figure 5 Example of air temperature distribution of circular cross section in a traffic space (Central section of fire source, HRR=100MW, elapse time : 900sec)

Figure 6 presents the temperature distribution in the concrete tunnel lining in the case of 30MW, 50MW and 100MW fire. If ventilated wind velocity to be created 2.5m/s for these heat release rate, then in circular tunnel cross-sections the area where temperature exceeds 200°C is small, and concrete structure is not susceptible to great damage.

In the case of 50MW fire within circular section, the temperature distribution in the concrete surface of ceiling part at above of fire source and side wall exceed 300°C. It seems to be not serious damage to concrete linings, such as collapsed structures, leakage of waters, etc.

In the case of 100MW fire within the circular cross section, some parts of ceiling above fire source will be reached to 670°C. Under this thermal condition, it becomes very serious collapse will occur in the concrete lining. If in the case of 100MW fire to be adopted to design criteria, it may be necessary to mitigation measures for fire protection systems for concrete structure.

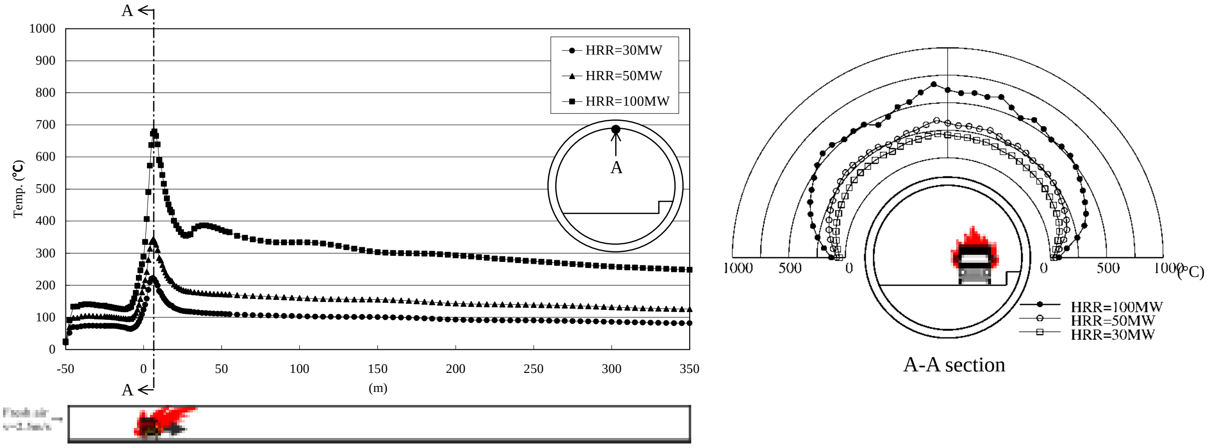


Figure 6 Temperature distribution in the concrete tunnel lining in the case of 30MW, 50MW, 100MW fire with circular cross-section

4.2. Rectangular Cross-section

Figure 7 presents air temperature distribution in the case of 100MW fire, the depth of back layering near the ceiling part is deeper than circular section within the air velocity 2.5m/s. However, minimum height is still ensured for the evacuation at the upstream side from fire point.

The peak air temperature at closest point of concrete surface exceed easily by 1500°C.

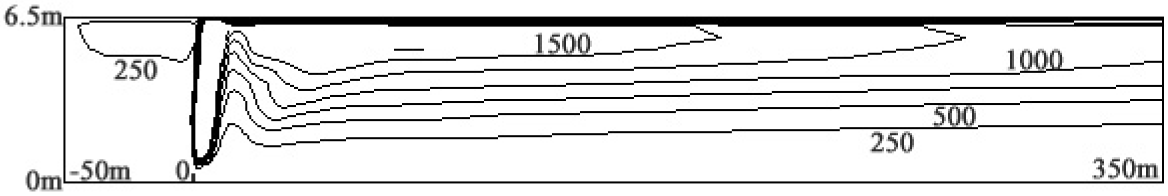


Figure 7 Example of air temperature distribution in a traffic space of rectangular cross section (Central section of fire source, HRR=100MW, elapse time : 900sec)

Regarding to the comparison with Figure 5and Figure 7. The temperature distribution at cut section of circular section is higher than rectangular tunnel. However, the temperature variation to lateral direction in circular section is bigger than rectangular section. The thermal distribution to lateral direction in rectangular section is more uniformly than circular section. On the other hand, decrement of thermal distribution to lateral direction in the circular section is bigger than rectangular section.

Figures 8 presents the distribution of concrete surface temperature in the case of 30MW – 100MW fire from CFD simulation results. In the case of 30MW fire, it may be judged that approximately an area of 200m^2 exceeds the permissible temperature of concrete. In the case of rectangular cross-sectional tunnels, the area that exceeds 200°C is much larger than that of circular section counterparts.

In the case of 50MW fire within the rectangular section, this case will be more serious thermal condition than circular cross section.

In the case of 100MW fire within rectangular cross section, the maximum temperature at concrete surface of entire part will exceed 700°C. It means tunnel structure will be collapsed, this phenomena is more than serious than circular section

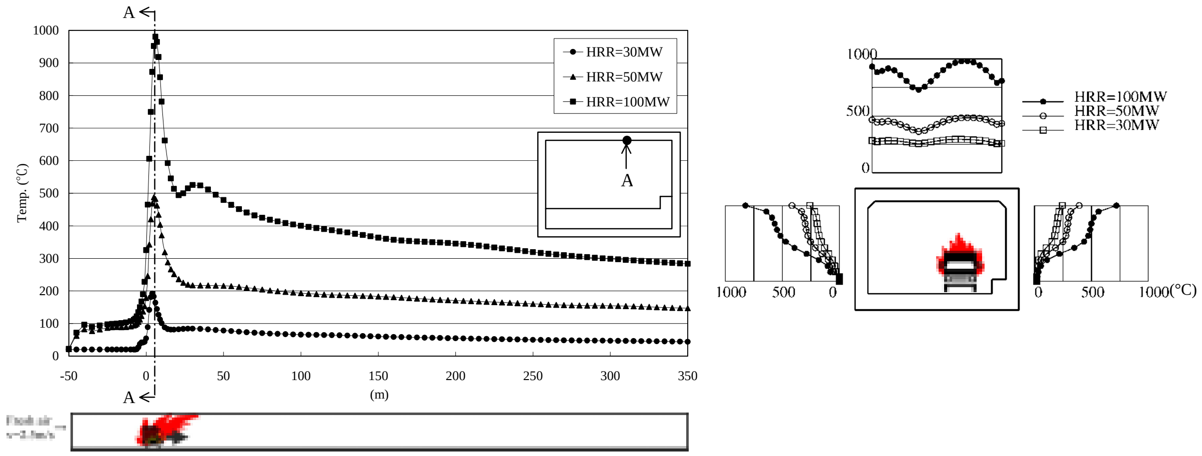


Figure 8 Temperature distribution in the concrete tunnel lining in the case of 30MW, 50MW, 100MW fire within rectangular cross section

5 Conclusions

Present day situation reveals that all over the world many experts have engaged in researches, analyses, and surveys for deepening the understanding of various phenomena governing traffic tunnel fires occurring in several cities around the world. Still at a fundamental stage of this study, based on the initial conditions of fire, in this article it has been attempted to clarify the relationship among cross-sectional shape of tunnel and reduction of strength in concrete due to heat of fire.

In the case of 100MW fire, the maximum air temperature at closest part of ceiling will be exceeded 1500°C within circular cross section. In the case of rectangular cross section, the maximum temperature is higher than circular section due to the differncy of shape of cross section, mass of air volume and thermal air flow field.

In the case of 30MW fire, surface temperatures at concrete ceilings of circular and rectangular tunnel sections were found at 230°C and 315°C respectively. This phenomenon is assumed to be caused due to the lateral air flows in the circular tunnel that function largely. In other words, temperature increases in circular sections even close to the road surface, however, the maximum temperature at ceiling area is much lower than that of rectangular tunnels.

In the case of road tunnels, when circular and rectangular tunnel cross-sections are compared against each other, the area that exceeds 200°C of rectangular section is wider than the case of circular section tunnel. This indicates that even though both sections are subject to same scale of fire, the degree of damage in the rectangular cross-section tunnel is much larger.

In the case of ventilation duct are located at ceiling within rectangular, circular or hose shoe cross section, the thermal environment will be appeared to similar conditions with rectangular cross section.

In the case of 50MW, 100MW fire, the circular cross section is still better thermal environment than rectangular cross section. However, both type of cross section will be occurred to very serious damage near the fire source, therefore, the fire protection mitigation must be necessary.

In spite of the similar heat release condition, the reasons for the differency of thermal environment between circular cross section and rectangular cross section are as follows.

(1) The distance from fire source to ceiling within rectangular cross section is shorter than circular section.
(2) The flow field of longitudinal air rate by mechanical ventilation and thermal flow field from fire source within circular cross section are bigger than rectangular cross section.

Due to these two major differences between rectangular and circular cross section, the value of maximum temperature at concrete surface are controlled.

However, due to the computational conditions, the effects of heat radiation from fire source are not taking into account to this calculation. Therefore in the actual situation, the temperature distribution in the concrete members will be slightly bigger than these predicted results.

In the case of mitigation design for fire protection systems, it is better to leave a margin for the heat radiation effects.

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