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Original Research Paper

Numerical Studies on Smoke Natural Filling in an Underground Passage with Validation by Reduced-Scale Experiments

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ABSTRACT

The use of computational fluid dynamics (CFD) is becoming more common and reliable as a tool for kinds of buildings fire safety design, but it is not easy to be validated. In this paper, Fire Dynamics Simulator v5.0 is used to investigate the spill plume and the resultant natural filling in the underground transport passage of main transformer of a hydropower station due to the adjacent main transformer hall fire. Ceiling jet temperature decay along the transport passage and smoke layer interface height are simulated. Series of scale model experiments are carried out using pool fires placed at the centre of the main transformer hall. The data obtained from these experiments are later used in a validation study of the FDS simulated results. The FDS simulated results are also compared with the expressions proposed in the literature. The results show good agreement between experimental and numerical predictions. And through suitable adjustment of the constants of the exponential equation, good agreements are also found between the predicted data and calculated results.

INTRODUCTION

Underground hydropower stations are generally constructed in mountains, connecting with the outside only through some channels. Therefore, once a fire occurs in the underground hydropower station, smoke is the most fatal factor, where more toxic gases are released due to incomplete combustion (Babrauskas 1998). People in the fired hydropower station have to escape upward, in the same direction with the movement of the buoyancy-driven toxic smoke. So, smoke control is very important for saving lives in case of such fires (Chow 1998). As the main underground cavities of hydropower station are usually big, compartmentation is not desirable. Smoke control design relies on the understanding of smoke layer interface height and temperature distributions.

Performance-based design (BSI 2001) has been adopted widely for fire safety provisions in big construction projects. There are even engineering performance-based fire codes established in some countries. Fire hazard assessment is a key part and many fire models (Cox 1995), whether appropriate or not, are applied for such purpose.

Zone models have been developed to predict the smoke layer. The results are useful in assessing the time of smoke descending height. The basic assumption of the zone models is that the temperature of the upper smoke layer is the same everywhere and the time to form ceiling jet is potentially ignored (Fu & Hadjisophocleous 2000, Jones 2000, Jones 2001). In tunnels or underground long passages, there are at least two steps in smoke spreading (Hu 2005):

- The ceiling jet forming phase
- The smoke layer descending phase

In the transport passage of the main transformer of the underground hydropower station, the spill smoke temperature will decrease significantly at positions away from the fire source. It might take a long time to form a smoke layer. Therefore, zone models might not be applicable for studying smoke spreading in tunnels or long passages (Bailey 2002, Chow 1996, Forney 1997, He 1999).

Fire field models using the technique of computational fluid dynamics (CFD) (Cox 1995) are popularly used with the rapid development of computer hardware and numerical software. CFD takes the advantage of predicting the fire environment from the fundamental principles on fluid flow and heat transfer. The software fire dynamics simulator (FDS) version 5.0 (McGrattan 2008) developed at the Building and Fire Research Laboratory, National Institute of Standards and Technology, USA is widely used. Smoke temperature, pressure distribution and air flow pattern in the space can be predicted.

In contrast to zone models, which have been well validated by experiments (Peacock 1993), experimental validations of field models have not been carried out to the same extent as zone models (Chow 2009). Validation study

(Mok 2004) will give ideas on how good a CFD model can predict and what should be considered in using the model. Some works on verifying field models are on a specific fire scenario by Chow and Zou (Chow 2005), FDS for the prediction of medium-scale pool fires by Wen (Wen 2007); and comparing FDS 4 combustion model by Thomas et al. (2007). There are very few validations on using the model for large compartment fires (Pope 2006), especially underground large space fires.

In this paper, FDS will be evaluated by studying the spill smoke movement in the transport passage of the main transformer of an underground hydropower station under the main transformer hall fire. Experimental data on the smoke movement are used to validate the simulation results, and both experimental data and simulation results are compared to theoretical expressions in the literature.

MATHEMATICAL MODEL

The reduction of smoke temperature along the corridor has been studied by some researchers as reported in the literature. The temperature decay along the passage appears to follow an exponential function. Some exponential expressions are established by Evers & Waterhouse (1978) empirically and verified by Kim et al. (1998) in a passage of length 11.83m.

A power law distribution is also proposed by Bailey et al. (2002) from their three-dimensional CFD model with large eddy simulation and tests in an 8.51m long corridor as follows:

$$\Delta T = \Delta T_0 (\frac{1}{2})^{x/16.7} \qquad ...(1)$$

where DT is the average temperature rise at distance x along the corridor, DT_0 is the temperature rise near the ceiling over the fire source.

Hu et al. (2005) have conducted full-scale tests along a corridor and the measured data agree well with the power law equation (1) when the distance from the fire source is less than 35m. And through theoretical analysis, he concludes that the decay of temperature of ceiling jet front along the corridor can be simplified as follows:

$$\frac{\Delta T}{\Delta T_0} = e^{-K_1 (x - x_0)} \qquad ...(2)$$

with $K_1 = \frac{a}{r h u}$ ...(3)

This indicates an exponential distribution.

Whether smoke temperature distribution will follow exponential or power law decay along the underground transport passage is still unknown. In this paper, whether the decay of smoke temperature can still be described by exponential distribution as Bailey's expression in such underground passage will be discussed.

EXPERIMENTS

Scale modeling: The approach of scale modeling is well established and has been used in many studies of smoke movement in buildings (Quintiere 1989). Measurements are generally made of smoke temperature, velocity and concentrations. To ensure that the results can be extrapolated to full scale, the reduced-scale model used in this study is designed to meet the scaling relationship provided in NFPA92B.

For a physical model of a building, the primary parameters that must be scaled are the model dimensions, temperature, velocity, and convective heat release rate. The scaling expressions for each of these parameters are as follows:

$$x_m = x_F (L_m / L_F) \qquad ...(4)$$

$$T_m = T_F \qquad ...(5)$$

$$v_m = v_F (L_m / L_F)^{1/2} \qquad ...(6)$$

$$Q_{c,m} = Q_{c,F} (L_m / L_F)^{5/2} \qquad ...(7)$$

$$t_m = t_F (L_m / L_F)^{1/2} \qquad ...(8)$$

Where x = position

L = length

T = temperature

v = velocity

Q_c = convective heat release rate

t = time

F = full-scale

m = small-scale model

In this study, 1:12 is chosen as the modeling scale to investigate the natural smoke filling in the transport passage. According to equations (1-4), temperature scale, velocity scale and heat release rate scale can be obtained as shown in Table 1.

The physical scale model: In order to study the spill smoke movement in the underground transport passage under the main transformer hall fires, fire tests are carried out in an underground hydropower station mock-up located in Xi'an

Table 1: Scales of each parameter.

	$\frac{x_m}{x_F}$	$\frac{T_m}{T_F}$	$\frac{v_m}{v_F}$	$\frac{Q_{c,m}}{Q_{c,F}}$	$\frac{t_m}{t_F}$
Scale	1/12	1/1	1/3.465	1/500	1/3.465

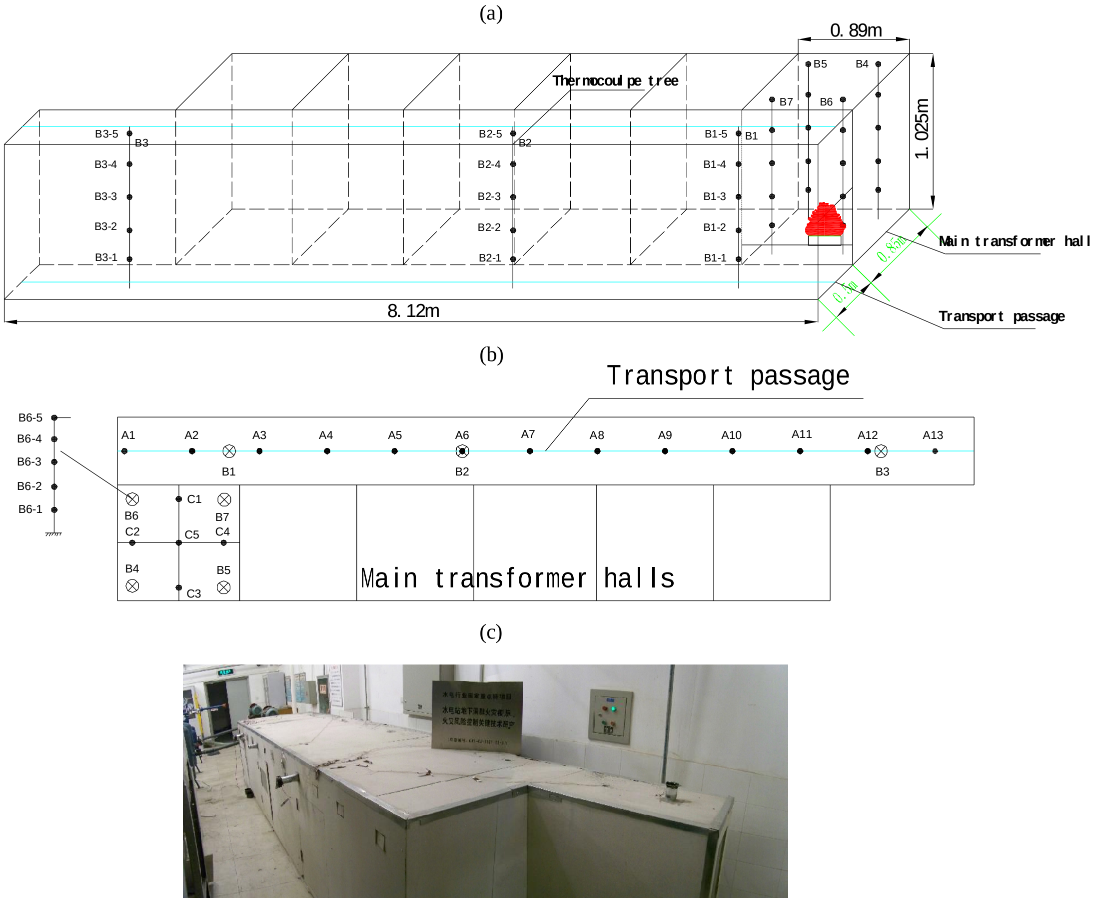

Fig.1: Design of experimental apparatus: (a) (b) schematic view and (c) photo of experimental rig.

University of Architecture and Technology, as seen in Fig. 1. The dimensions of the transport passage are 8.12m (L) × 0.5m (W) × 1.025m (H). The fire source is placed in a main transformer hall, the dimensions of which are 0.89m (L) × 0.85m (W) × 1.025m (H). The opening of the fired main transformer hall is kept at 0.13m.

Three sets of thermocouples (5 thermocouples per string with interval of 0.2m), labelled as B1, B2 and B3, are installed in the transport passage, and four sets labelled B4, B5, B6 and B7 are installed in the fired main transformer hall, to measure the transient smoke temperatures. A set of thermocouples (A1-A13) is used to measure the smoke temperature under the ceiling of the transport passage. All thermocouples are copper-constantan T-type, and the error is less than 0.5°C due to strictly calibration. The smoke layer height of fired main transformer hall is determined using the temperature gradient method. The experimental set-up is shown in Fig. 1, and the test conditions are listed in Table 2.

Diesel is chosen as the fuel of fire source due to its good similarity with the combustible material in the main transformer hall fire of hydropower station. The heat release rates are 1kW, 2kW and 4kW, corresponding to the actual fire of 0.5MW, 1MW and 2MW. The fuel pool is placed at the central floor of the main transformer hall.

Table 2: Experimental conditions.

Test No.	Ambient temperature (°C)	Heat release rate at steady burning stage	
		In the physical experiments (kW)	The full scale equivalent values(MW)
Test 1	17.0	1	0.5
Test 2	17.9	2	1
Test 3	18.0	4	2

BRIEF REVIEW OF KEY EQUATIONS IN FDS

Air flow induced by a fire is compressible and the hot smoke is taken as a thermally expendable gas (McGrattan 2008) in the model FDS version 5.0.

A set of governing equations suitable for simulating fluid flow induced by buoyancy with low Mach number is proposed. The Boussinesq approximation is no longer necessary and constraints on inviscid fluid are removed. Both

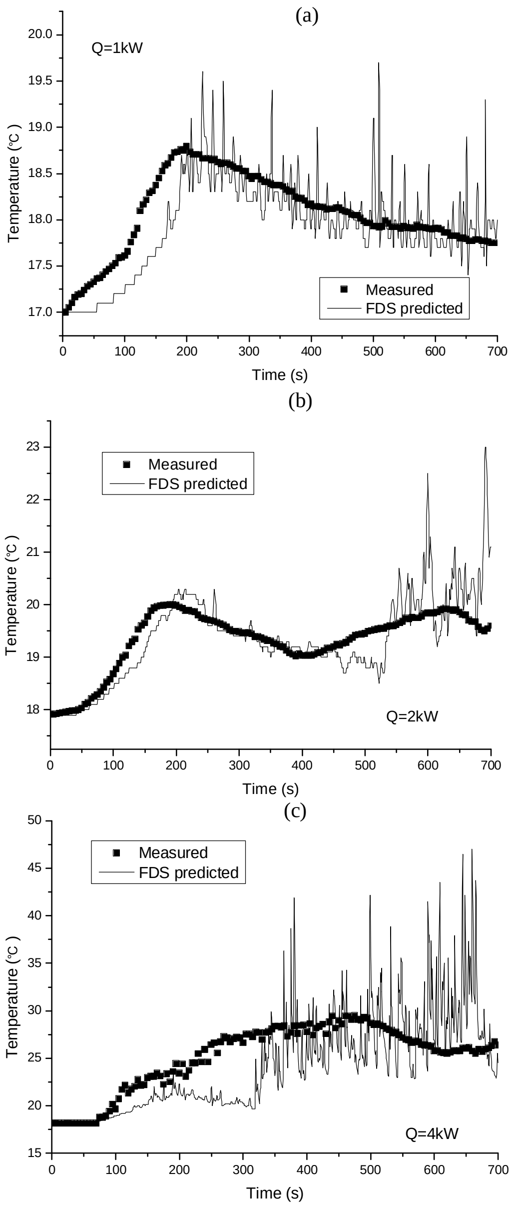

Fig. 2: Comparisons of temperature rises of smoke layer in transport passage (a) Test 1 (b) Test 2 (c) Test 3.

density and temperature are allowed to vary in a wider range (Quintiere 1989).

FDS 5.0 is based on a Large Eddy Simulation (LES). It can well deal with the interaction between turbulence and buoyancy, and obtain more satisfactory results. Therefore, it is widely applied in the simulation of fire process. Different combustion models can be used.

FDS solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires.

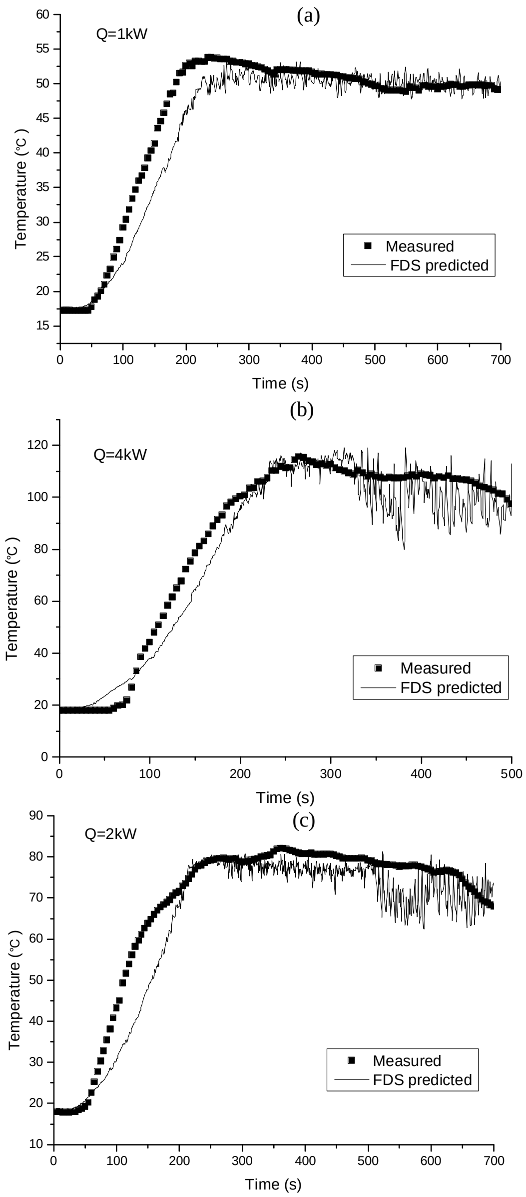

Fig. 3: Comparisons of temperature rises of smoke layer in transformer hall (a) Test 1 (b) Test 2 (c) Test 3.

The governing equations of FDS are as follows:

Conservation of Mass: $\frac{\partial r}{\partial t}+\nabla\cdot r\mathbf{u}=0$ ...(4)

Conservation of Momentum:

$$\frac{\partial}{\partial}(r\mathbf{u})+\nabla\cdot r\mathbf{uu}+\nabla p=rg+\mathbf{f}_b+\nabla\cdot t_{ij} \quad ...(5)$$

Conservation of Energy:

$$\frac{\partial}{\partial t}(rh_s)+\nabla\cdot rh_s\mathbf{u}=\frac{\mathrm{D}p}{\mathrm{D}t}+\dot{q}'''-\dot{q}_b'''-\nabla\cdot\dot{\mathbf{q}}''+e \quad ...(6)$$

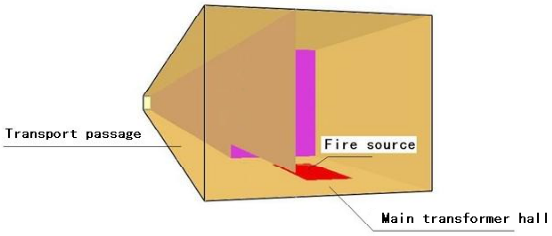

Fig. 4: FDS input schematic.

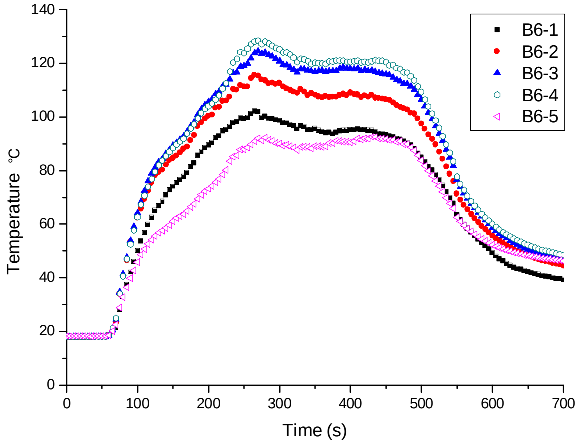

Fig. 6: Temperature rise inside the fired transformer hall measured along B6 in Test 3.

Equation of State: $p = \frac{rRT}{\overline{W}}$ ...(7)

Where r is the gas density, $\mathbf{u}$ is the gas velocity vector, g is the acceleration of gravity, $\mathbf{f}_b$ is the pressure perturbation, t_{ij} is the viscous stress tensor, h_s is the sensible enthalpy, p is the pressure, $\dot{q}'''$ is the volumetric heat source, $\mathbf{q}''$ is the heat flux vector, T is the temperature, e is the dissipation rate, R is the gas constant, and $\overline{W}$ is the molecular weight of the gas mixture.

The mixture fraction model is used to describe the burning process of a fire. The model is based on the assumption that the combustion is mixing-controlled. All species of interest are described by a mixture fraction $f(x,t)$, which is a conserved quantity representing the fraction of species at a given point originated from the fuel. And f would satisfy the conservation law:

$$\frac{\partial}{\partial t}(rf)+\nabla\cdot(ruf)=\nabla\cdot(rD\nabla f) \qquad ...(8)$$

The relation between the mass fraction of each species and the mixture fraction is known as the "state relation" (Chow 2009).

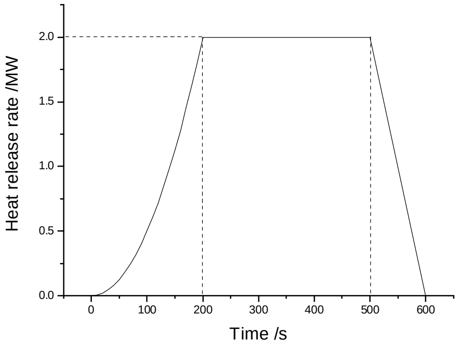

Fig. 5: Input heat release rate for FDS simulation.

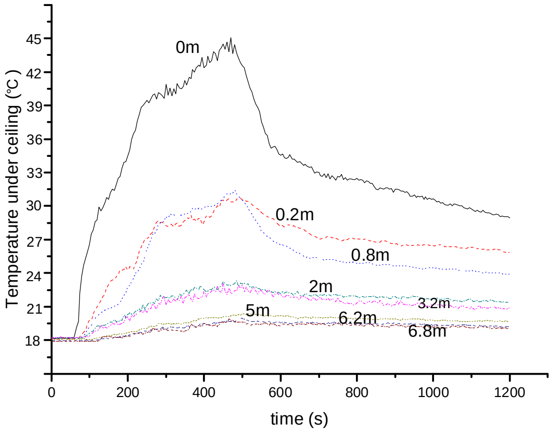

Fig. 7: Typical temperature induced at different distances in the transport passage for Test 3.

COMPUTING DETAILS

The scenario on spill smoke movement from fired main transformer hall to transport passage is studied by FDS in this paper, and the simulations include two parts: first, FDS calculations that simulate the small scale experiments directly are compared to the actual experiments. And then, full-scale FDS simulations are conducted to further study the spill plume and resultant natural filling in underground transport passage of main transformer of hydropower station due to adjacent main transformer hall fire.

Small-scale model: The scenario on smoke filling in the transport passage is simulated by FDS with small-scale model, which is exactly the same with the physical model, using the actual conditions of the experiments. For comparing with experimental results, the thermocouples are set in exactly the same positions as in the experiments to record the smoke temperatures.

The heat release rate per unit area is specified. This will control the burning rate of the fuel in describing a pool fire.

Comparison and validation: Fig. 2 and Fig. 3 present

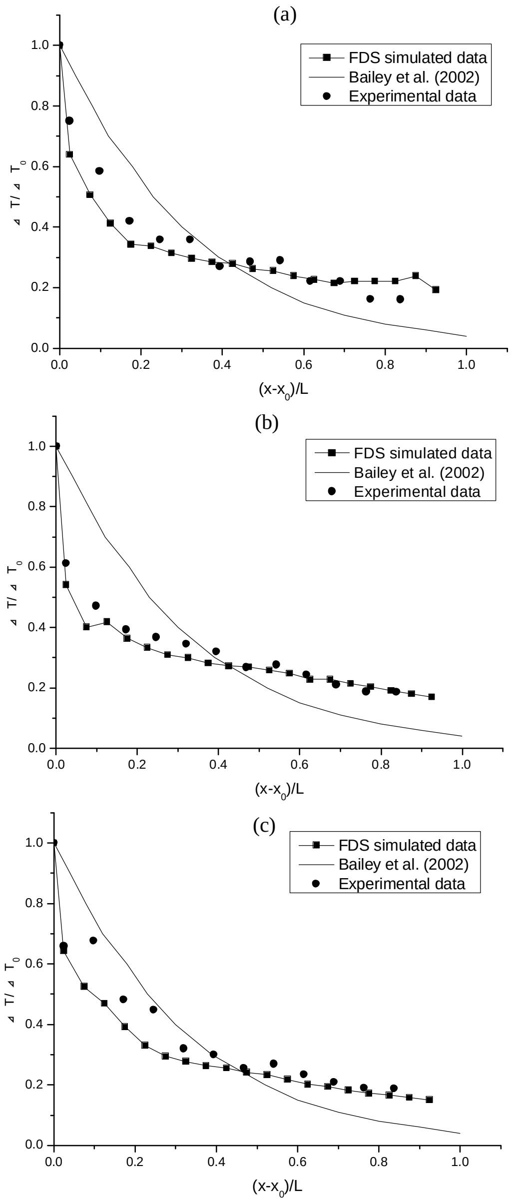

Fig. 8: Temperature decay along the transport passage (a) Test 1 (b) Test 2 (c) Test 3.

comparisons of the temperature rises of smoke layer in transport passage and transformer hall for all tests between the measurement and the FDS prediction. It can be seen that the results predicted by FDS are similar to the experiments, and the FDS predictions are generally in good accordance with experiments for all the tests. Therefore, the CFD software FDS can give relatively accurate predictions on natural smoke filling in underground transport passage of main transformer of hydropower station.

Full-scale model: The dimensions of full-scale transport passage model for FDS are 200m (L) × 6m (W) × 12m (H),

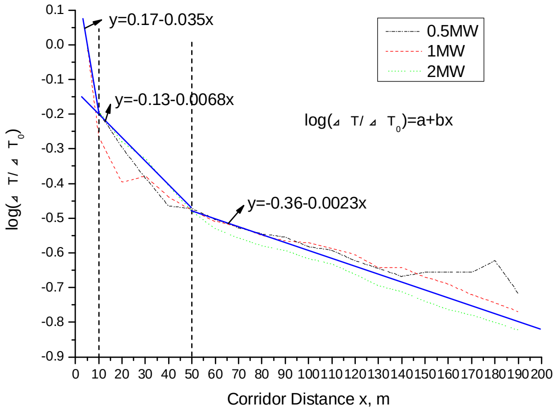

Fig. 9: Log, of the relative temperature excess downstream of the transport passage.

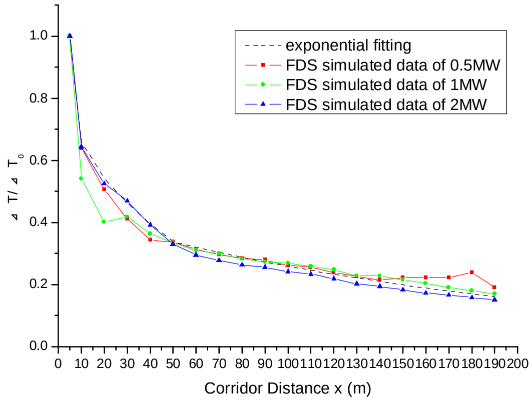

Fig. 10: Comparison of the FDS simulated data and calculated results of Eq. (11)-(13).

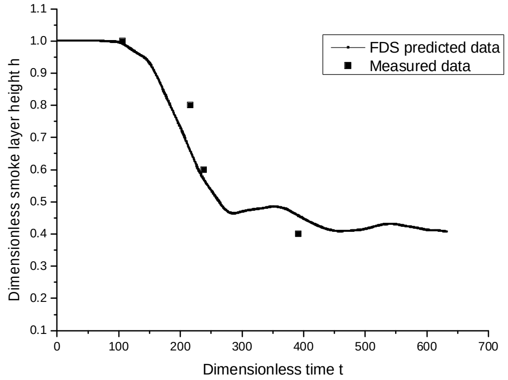

Fig. 11: Dimensionless smoke layer height for the 2MW fire.

and the dimensions of fired main transformer hall are 11m (L) × 10m (W) × 12m (H) with the opening of 11m (W) × 1.5m (H). The input drawing of the numerical model is shown in Fig. 4. For comparing with field results, the thermocouples are set in the full scale equivalent positions as in the experiment to measure the smoke temperatures. The heat release rate per unit area is specified, this would control the burning rate of the fuel in describing a pool fire. The peak heat release rates (HRR) are 0.5MW, 1MW and 2MW. The heat release rate is taken as the curve in Fig. 5 in this FDS simulation.

In this paper, three numerical simulations with different heat release rates are carried out. These three simulations are labelled as case 1-3 and the ambient temperatures are set as 20°C.

RESULTS AND DISCUSSION

Typical temperature distributions measured in the fired main transformer hall and the transport passage in Test 3 are shown in Fig. 6 and Fig. 7. As seen in Fig. 6, the smoke temperatures of the fired main transformer hall are stable during the steady burning of fire. Typical temperatures measured at different distances away from the fire are shown in Fig. 7, taking the 2MW fire as an example. It is observed that smoke temperatures reduce significantly when travelling down the transport passage away from the fired main transformer hall. Temperatures near the fired main transformer hall increase much faster than those at positions far away from the fire. Both, the temperature rise and maximum temperature are detected later at positions further away from the fire, which is possibly because that it takes some time for the spill plume to travel down the transport passage, i.e. 'lagging behind' the fire source (Hu 2005). All the characteristics of the spill plume when travelling down the transport passage are similar to that of Hu's study (Hu 2005) where the fire source is directly located at the floor level of the passage.

The dimensionless temperature decay given by $\Delta T / \Delta T_0$ is plotted against the dimensionless distance $(x - x_0) / L$ from the fire in Fig. 8 (a), (b) and (c) for different heat release rates. It can be seen that the predicted data by FDS agree well with the experimental data. The predicted data descend a little more quickly at the positions near the fired main transformer hall. The descending rate of $\Delta T / \Delta T_0$ start to slow down when the spill plume travels along the transport passage, and better agreement between the simulated and experimental data are found. However, either the FDS simulated data or the experimental results do not agree well with the results predicted by Eq. (1), it appears that the decays of temperature of the spill plume down the transport passage can not be simply fitted by an exponential equation in terms of Eq. (2) according to Hu et al. (2005).

According to the research of Bailey et al. (2002), the upper layer temperature rise above ambient is given by $\Delta T\,(l) = T_u(l) - T_{amb}$. These temperature rises are scaled by the inlet temperature rise ΔT_0, and transformed using log $(\Delta T / \Delta T_0)$. The resulting data are presented in Fig. 9. Note that the results can be divided into three parts with different x, each part is nearly linear and that all plots under the three different heat release rates lie within a group. This implies that the relative temperature falloff is independent of the inlet temperature rise. The temperature curves presented in Fig. 9 are approximated by straight lines for the three regions using a linear least squares curve fitting procedure. This lit is given in the form of

$$\log(\frac{\Delta T}{\Delta T_0}) = a + bx \qquad ...(9)$$

This is equivalent to

$$\frac{\Delta T}{\Delta T_0} = C_l 10^{hx} \rightarrow C_l (\frac{1}{2})^{x / h_{1/2}} \qquad ...(10)$$

Where $C_l = 10^a$ and $h_{1/2} = -\log(2) / b$.

Take the region $x > 50$ for example, $h_{1/2}$ could be approximated by $h_{1/2}$ = log (2)/0.0023 ≈ 130.88, where b = -0.0023 is given in Fig. 9. And the coefficient C_l is approximated by $C_l = 10^a = 10^{-0.36} \approx 0.44$, where a = -0.36 is also given in Fig. 9. Therefore, the temperature rise ΔT may be approximated by $\Delta T = 0.44\ \Delta T_0\ (1/2)^{x/130.88}$, when $x > 50$m. Similarly, for the other two regions, two different equations of ΔT can be obtained with different constants a and b. Then, the temperature decay along the transport passage can be concluded in the forms as follows:

$$x \le 10, \ \frac{\Delta T}{\Delta T_0} = 1.48(\frac{1}{2})^{x/8.6} \qquad ...(11)$$

$$10 < x < 50, \ \frac{\Delta T}{\Delta T_0} = 0.74(\frac{1}{2})^{x/44.27} \qquad ...(12)$$

$$x \ge 50, \ \frac{\Delta T}{\Delta T_0} = 0.44(\frac{1}{2})^{x/130.88} \qquad ...(13)$$

To validate the exponential fitting, the temperature decays of the three FDS simulation cases under different heat release rates and the results of Eq. 11-13 are plotted against the distance from the fired main transformer hall in Fig. 10. It can be seen that the exponential fitting agrees well with the FDS simulated data.

Dimensionless smoke layer height, defined as $h(\hat{t}) = z(\hat{t}) / H$ (the ratio of predicted or measured smoke layer height to height of the transport passage model), are plotted against the dimensionless time $\hat{t} = t/(H/g)^{½}$ in Fig. 11. Time has been scaled up from the experiments as it is being compared with full scale simulations. It can be seen that the predicted smoke layer height changes agree well with the experiment.

CONCLUSIONS

In this paper, Fire Dynamics Simulator v5.0 is selected to compare with smoke experiments of an underground transport passage of the main transformer of the hydropower station under the adjacent main transformer hall fire. Three numerical simulations with different heat release rates have been carried out to study the characteristics of spill plume movement in the transport passage. Results show that the numerical model can give relatively accurate predictions of ceiling jet temperature and smoke layer height.

The simulated and experimental ceiling jet temperature decays along the transport passage are compared with the exponential equation obtained by Bailey et al. (2002) used in CFAST. Suitable adjustment of the constants of the exponential equation has given better agreement between the calculated results and the FDS predicted data. Thus, temperature distribution along the transport passage of the spill plume from fired main transformer hall can fall into exponential decays in the forms similar to the equation of Bailey et al. (2002).

The FDS predicted smoke layer height in the transport passage is also compared with the experiment in the dimensionless form. Good agreement is found between the numerical and experimental results.

Finally, as pointed out before, fire models are developing rapidly, and CFD models are widely used in the industry. But CFD results should be validated by experimental data even when used for design purposes. Therefore, more efforts should be made on carrying out larger-scale fire tests, and the results can be applied for improving CFD models.

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