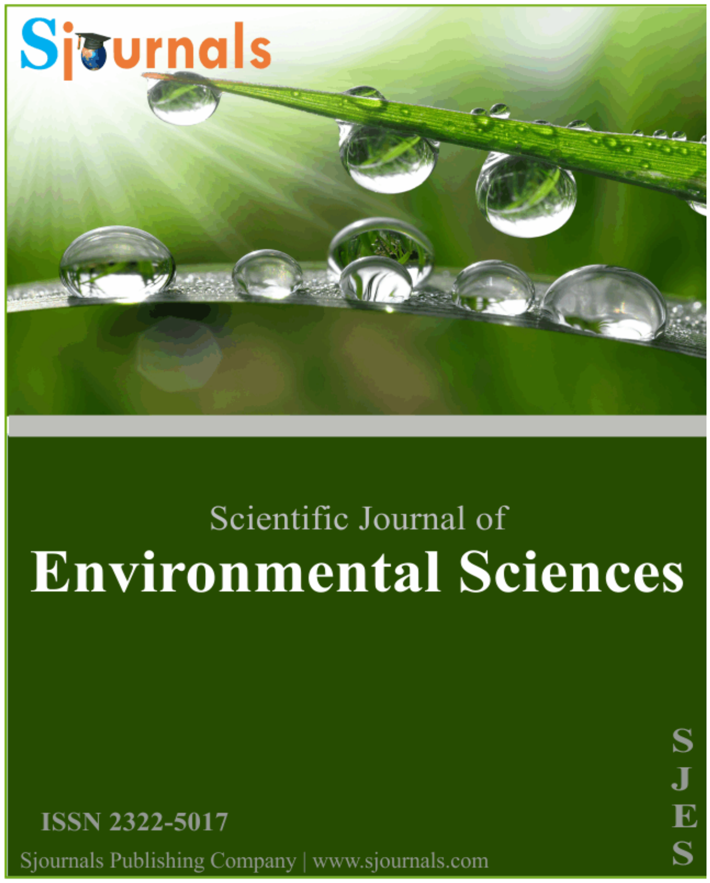
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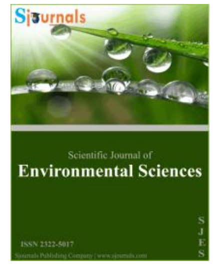

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Case study

Analysis of smoke control models at long tunnel: A case study on the Hsueh-shan tunnel

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A B S T R A C T

This study used the Fire Dynamics Simulator (FDS) to simulate a fire in a 5000 meters long section of the Hsuehshan tunnel (12.9km in total length). Actual distances were considered in jet fan simulations and steady-state velocity profiles were simulated in tunnel portals. A worst-case analysis was performed for the area between two vertical shafts in the tunnel. To prevent the smoke from becoming an obstacle in the Hsuehshan tunnel, fans located 250 meters upwind and 500 meters downwind of the fire source were deactivated. The smoke control system currently used in the Hsuehshan tunnel includes activation of four jet fans upwind of the fire and intermittent operation of jet fans downwind of the fire. This system was examined in this study as benchmark model Eva1 and compared with the alternative evacuation plans Eva2, Eva3 and Eva4. The results indicated that, regardless of fan activation, the downwind area of the fire remained dangerous. With regard to upwind safety, it was calculated that adults with an average walking speed of 1.2m/s and weak evacuees with an average walking speed of 0.64m/s would need 205 and 227 seconds respectively to traverse 30 meters. In Eva1 and Eva2, for 15MW, 30MW and 65MW heat release rates (HRRs), tunnel users situated within 30 meters from the fire source would not be able to escape safely.

1. Introduction

The Hsuehshan tunnel is the fifth longest tunnel in the world and a representative example of a road tunnel. It has often been selected as a subject for research due to its 12.9km length and because during fires inside the tunnel. It is extremely difficult to remove smoke naturally in the event of fires in confined spaces such as road tunnels. As a result, dense smoke and heat produced by a tunnel fire cannot be released into the external environment and instead spread along the entire tunnel, causing high temperatures and difficulties associated with evacuation, urgent disaster relief, and rescue work. In order to examine whether the smoke control system employed in the Hsuehshan tunnel during fire hazards enables tunnel users to escape safely and contains smoke and heat within a safe range, this study examined past literature to explore tunnel smoke control systems and the mechanism of the Hsuehshan tunnel smoke control system.

- ✓ This study determined the sizes of fires that occurred in past incidents based on the available heat release rate (HRR) information in past literature. Then, the times needed for temperatures, radiation, and concentration of carbon monoxide and carbon dioxide levels upwind and downwind to reach critical levels were estimated and escape times were analyzed to determine whether they were sufficient for a safe escape.
- ✓ This study investigated the present emergency evacuation model for the Hsuehshan tunnel, tested worst-case scenarios for fires with different HRRs and measured the model performance in terms of meeting safety criteria for various parameters.
- ✓ While previous studies on the Hsuehshan tunnel have based their simulations of the smoke control system on short distances and one portal cross-sectional areas, this study used parameters available in FDS to recreate the tunnel ventilation fans based on their real structure and positions in order to obtain valid results regarding smoke extraction.
- ✓ This study applied quantitative research methods to analyze which cases endangered evacuee lives. It is hoped that the results can serve as references for tunnel users and firefighters.
- ✓ This study aimed to build an FDS simulation of the smoke control system currently used in the Hsuehshan tunnel to examine the smoke flow resulting from using the system and to investigate the correct evacuation direction.

Longitudinal ventilation system uses longitudinal air flow, produced by jet fans which installed in tunnel, to blow smoke out of tunnel. The key point of longitudinal ventilation is the longitudinal wind velocity should be able to effectively prevent backflow, and ensure the smoke layer in downstream would not be destroyed. This longitudinal wind speed which can prevent smoke backflow is called the critical wind velocity. Many researchers have studied on the influences of tunnel geometry and heat release rate (HRR) on the through theoretical analysis (Kunsch, 2002), experimental studies (Vauquelin and Wu, 2006) and numerical simulations (Hua et al., 2008a; Hua et al., 2008b). To investigate possible air flow from the downstream, CFD software, FDS (Fire Dynamics Simulator) developed by NIST was utilized (Tetzner et al., 1999). Other aspects of smoke control have also been investigated. Lin and Chuah (2008) studied smoke extraction strategies for a long tunnel by numerical simulations.

2. CFD with FDS applied in the study

2.1. FDS (Fire Dynamics Simulator)

2.1.1. Raster analysis

To ensure the validity and accuracy of the FDS model, this study determined the optimal grid size based on the estimated fire diameter and the largest fire heat release rates (HHRs). The principle is explained below. Baum and McCaffrey (1989) presented the smallest length scale of a fire source as a characteristic fire diameter (D*) of a fire hazard that can be calculated with the following formula.

$$D^* = \left[\frac{Q^*}{\rho_0 \cdot C_p \cdot T_o \cdot \sqrt{g}} \right]^{2/5}$$

Where Q* is the HRR (kW), ρ0 is the air density (kg/m3), Cp is the air specific heat (kJ/kg K), To is the ambient temperature (K) and g is the gravity acceleration (m/s2). A number of studies have shown that 0.1D* is the most appropriate grid size for predicting smoke movement and combustion in the event of a fire, provided that the time-average axial velocity and temperature in the large eddy simulation (LES) model comply with MaCaffery's regression formula when the grid size is 0.1D*. The above formula was therefore the basis for calculating optimal grid size.

According to the method proposed by McGrattan et al. (1998), the largest HRR (Q) was 65000kW, which corresponds to a D* of 4.8m; therefore, 0.1D* was approximately 48cm. Thus, the optimal grid size for the fire source size was set at 50cm × 50cm × 50cm. A total of 3.12 million 0.5m × 0.5m × 0.5m grid points were planned to be included into the simulation model. However, since these grid points failed to appear in smokeview, simulation analysis was performed for 0.5m, 1.0m and 2.0m grid points (Table 1). An error value between 1m and 0.5m was within 3-5%, and this study simulated a model using 1.0m x 1.0m x 1.0m grid dimensions.

Table 1
Analysis of 0.5 m, 1 m and 2 m grid points.

	Grid size			
Seconds	**0.5m**	**1.0m**	**2.0m**	**Error value (%)**
326.00	30.40	31.40	72.10	3.29
327.00	30.60	31.40	75.20	2.61
328.00	31.00	31.50	74.90	1.61
329.00	31.00	31.80	72.70	2.58
330.00	31.30	32.00	72.90	2.24
330.00	31.40	32.10	76.90	2.23
331.00	31.60	32.50	82.60	2.85

2.2. PyroSim

PyroSim was applied before FDS. This modeling software provides instant feedback and guarantees an accurate import of FDS files. Measurement systems can be changed by the user from metric to English units and back. PyroSim allows the building of both 2D and 3D models and provides rotation, copying, and removal functions which facilitate the procedure of model creation.

3. Emergency management model

The Hsuehshan tunnel emergency response plan describes two operation modes for the smoke control ventilation system.

3.1. Evacuation model

After evacuation, the tunnel's self-closing fire doors close and fan relays are deactivated so that people can safely escape and in order to prevent smoke from affecting traffic in the adjacent tunnel. This model is used to facilitate tunnel users' evacuation in the event of a fire, and the jet fans and axial flow fans are used to maintain the in-tunnel air velocity at 2-4m/s. The smoke control system utilizes the principle that no fans are allowed to be activated within 250 meters upwind and 500 meters downwind of the fire location to avoid turbulence in smoke flows. Steady air velocity can be reached by locating jet fans at more than 200 meters from the fire source.

3.2. Smoke ventilation model

After tunnel users escape from dangerous areas via sidewalks and the side tunnels, Traffic Control Center personnel activate the smoke extraction system. In order to allow fire brigades to provide disaster relief as fast as possible and to avoid damage to the facilities, all jet fans and axial flow fans are activated to increase the wind speed inside the tunnel.

4. Results and discussion

To explore the possibility of decreasing the harm caused to tunnel users by high-density smoke, this study compared the Traffic Control Center's two-mode ventilation system with other smoke extraction models. A model was built to simulate a real tunnel fire. The first 200 seconds of the model simulated a tunnel before the outbreak of a fire, with jet fans set to maintain a steady air velocity of 2-4m/s. After 200 seconds, a fire was simulated with a fire source HHR of 30MW, which is the maximum allowed fire load for the Hsuehshan tunnel. It was supposed that, it would take 60 seconds for the Traffic Control Center to detect the fire, after which the smoke extraction model would be activated. Consequently, four different smoke extraction models were simulated at 260 seconds into the simulation model. The characteristics of each simulation are described below:

- ✓ Evacuation plan 1 (Eva1): the present evacuation model of the tunnel. The tunnel was ventilated as usual, but after 260 seconds of the simulation, the fans located within 250 meters upwind and 500 meters downwind of the fire were deactivated. Four jet fans upwind of the fire and none downwind of the fire were kept active. With regard to vertical axial flow fans (the tunnel has one vertical shaft), one inlet fan and two outlet fans were activated. The distance between the fire source and the nearest axial flow outlet fan was 150 meters.
- ✓ Evacuation plan 2 (Eva2): the present evacuation model of the tunnel. The tunnel was ventilated as usual, but after 260 seconds of the simulation, the fans located within 250 meters upwind and 500 meters downwind of the fire were deactivated. Four jet fans upwind of the fire and none downwind of the fire were kept active. With regard to vertical axial flow fans (the tunnel has one vertical shaft), no inlet fans or outlet fans were activated. The distance between the fire source and the nearest active jet fan was 300 meters.

While the total length of the Hsuehshan tunnel is 12.9km, this study used an FDS simulation of a 5000 meters long section with the fire source located at 2500 meters. The simulated fires had a fire area of 2 x 2.5m^2 and simulated, respectively, a crash involving three mini-buses (HRR=15MW), a crash involving one passenger bus (HRR=30MW), and the largest fire to have occurred historically in the Hsuehshan tunnel (HRR=65MW). Empirical calculation results of t-squared ultrafast fire growth were integrated into FDS to simulate real fires.

Real tunnel fires were simulated using full fan models built with the FDS. Optimized smoke extraction systems were compared to those that are currently employed during fires. Fan models were simulated based on measurements of actual distances and actual air velocity generated by fans. Fig. 1 illustrates the tunnel system fans; the jet fans are marked with numbers from 1 to 10 and active and inactive fans are indicated by red and white squares, respectively. Active and inactive vertical axial flow fans are marked in the figure using red and white stripes respectively, located under the blue oval indicating inlet fans and the pink oval indicating outlet fans. The FDS simulation of the tunnel exterior structure is shown in Fig. 2 where the dark blue frames numbered 1 to 10 indicate fan locations. The lower part of the figure provides a top view of the tunnel vertical shaft. Jet fans are located 100 meters from the vertical shaft in both directions and at 100 meters intervals. An improved outlet of the longitudinal ventilation system is located 50 meters downwind from the vertical shaft.

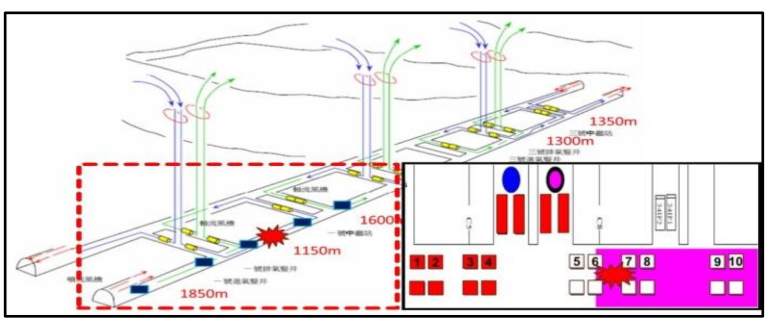

Fig. 1. Active axial flow fans and jet fans.

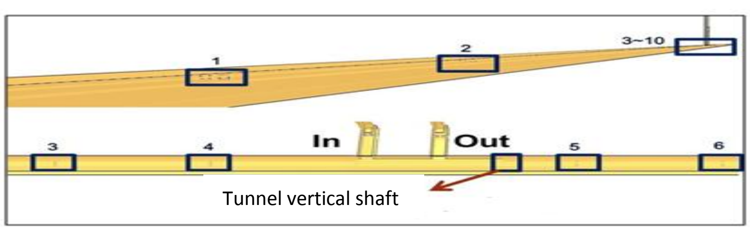

Fig. 2. Top overview of FDS-simulated tunnel vertical shaft.

4.1. Analysis of smoke back-layering

Under constant conditions, the length of a back-layered smoke flow is directly related to the HRR. Nevertheless, it can be reduced by increasing the number of active fans. Below are the analysis results for each evacuation plan:

- ✓ Eva1: The present evacuation model for the tunnel. Four jet fans upwind of the fire and none downwind of the fire were kept active. One axial flow inlet fan and two axial flow outlet fans were activated. The relatively short distance (150 meters) between the fire source and the nearest axial flow fan combined with the strong wind force led to back-layering of smoke with more uncontrollable smoke movement at higher HRRs.
- ✓ Eva2: The present evacuation model for the tunnel. Four jet fans upwind of the fire and none downwind of the fire were kept active. Neither axial flow inlet fans nor axial flow outlet fans were activated. The relatively long distance (300 meters) between the fire source and the nearest jet fan combined with the small wind force led to smoke back-layering distances of 110 meters (15MW), 123 meters (30MW) and 129 meters (65MW). The figures illustrating the back-layering are provided (Fig. 3 and 4).

Table 2
Time and length of smoke back-layering in the four evacuation models.

	15MW		30MW		65MW	
Model	**Time (s)**	**Distance (m)**	**Time (s)**	**Distance (m)**	**Time (s)**	**Distance (m)**
Eva1	-	-	-	-	-	-
Eva2	220	-110	232	-123	309	-129

Time refers to time between outbreak of the fire and the beginning of smoke back-layering.
Distance refers to the back-layering length upwind from the fire source.

Fig. 3. Smoke back-layering distances in Eva1 and Eva2.

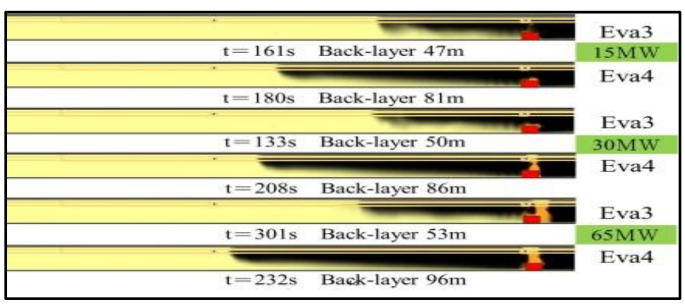

Fig. 4. Smoke back-layering distances in Eva3 and Eva4.

4.2. Analysis of visibility in Eva1 and Eva2

In Eva1, when the vertical axial flow fans were active, visibility in the area 30 meters upwind from the fire source was reduced to 10 meters 96 seconds after the fire outbreak. In Eva2, when the vertical axial flow fans were inactive, visibility was reduced to 10 meters 153 seconds after the fire outbreak. In Eva1, when the vertical axial flow fans were active, visibility in the area 30 meters downwind from the fire source was reduced to 10 meters 131 seconds after the fire outbreak due to ultra-fast fire growth rates. In Eva2, when the vertical axial flow fans were inactive, visibility was reduced to 10 meters 106 seconds after the fire outbreak due to ultra-fast fire growth rates.

The Eva1 and Eva2 models were compared in terms of the effect of vertical axial flow fan activation on the flow of smoke. The results indicated that critical visibility conditions within 30 meters upwind from the fire source were reached faster when the vertical axial flow fans were active (Eva1) than when they were inactive (Eva2). In Eva 1, smoke movement caused by air flow produced by outlet fans resulted not only in a stronger back-layering effect, but also in a reduced escape time. Based on escape time calculations for an evacuation route 30 meters in length, adults and weaker evacuees would need 205 and 227 seconds respectively, which is not sufficient for both upwind and downwind directions in the event of a 15MW fire (Fig. 5).

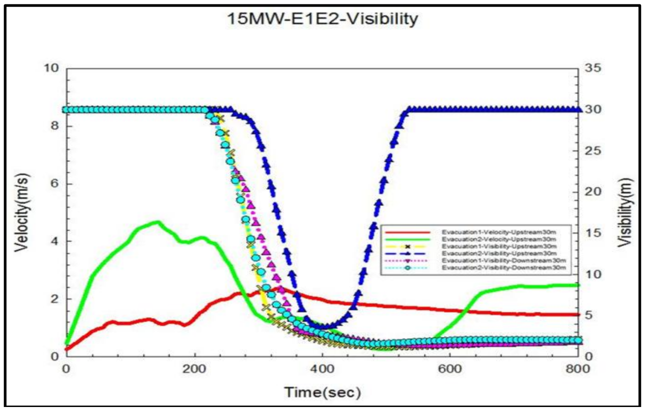

Fig. 5. 15MW: Analysis of visibility in Eva1 and Eva2.

In Eva1, when the vertical axial flow fans were active, visibility in the area 30 meters upwind from the fire source was reduced to 10 meters 100 seconds after the fire outbreak. In Eva2, when the vertical axial flow fans were inactive, visibility was reduced to 10 meters 155 seconds after the fire outbreak. In Eva1, when the vertical axial flow fans were active, visibility in the area 30 meters downwind from the fire source was reduced to 10 meters 121 seconds after the fire outbreak due to ultra-fast fire growth rates. In Eva2, when the vertical axial flow fans were inactive, visibility was reduced to 10 meters 105 seconds after the fire outbreak due to ultra-fast fire growth rates.

The Eva1 and Eva2 models were compared in terms of the effect of vertical axial flow fan activation on the flow of smoke. The results indicated that critical visibility conditions within 30 meters upwind from the fire source were reached faster when the vertical axial flow fans were active (Eva1) than when they were inactive (Eva2). In Eva 1, smoke movement caused by air flow produced by outlet fans resulted not only in a stronger back-layering effect, but also in a reduced escape time. Based on escape time calculations for an evacuation route 30 meters in length, adults and weaker evacuees would need 205 and 227 seconds respectively, which is not sufficient for both upwind and downwind directions in the event of a 30MW fire (Fig. 6).

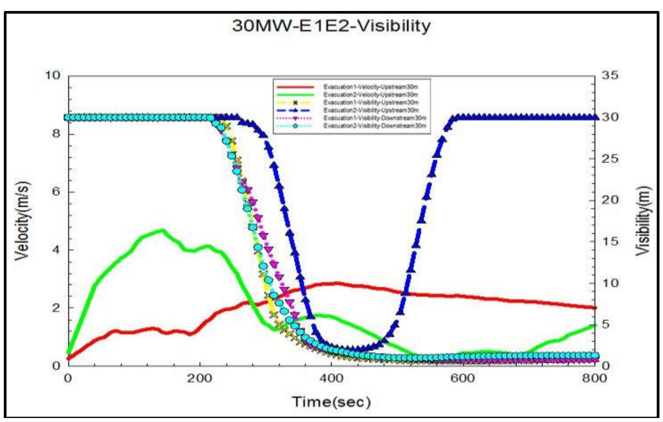

Fig. 6. 30MW: Analysis of visibility in Eva1 and Eva2.

In Eva1, when the vertical axial flow fans were active, visibility in the area 30 meters upwind from the fire source was reduced to 10 meters 105 seconds after the fire outbreak. In Eva2, when the vertical axial flow fans were inactive, visibility was reduced to 10 meters 153 seconds after the fire outbreak. In Eva1, when the vertical axial flow fans were active, visibility in the area 30 meters downwind from the fire source was reduced to 10 meters 123 seconds after the fire outbreak due to ultra-fast fire growth rates. In Eva2, when the vertical axial flow fans were inactive, visibility was reduced to 10 meters 105 seconds after the fire outbreak due to ultra-fast fire growth rates.

The Eva1 and Eva2 models were compared in terms of the effect of vertical axial flow fan activation on the flow of smoke. The results indicated that critical visibility conditions within 30 meters upwind from the fire source were reached faster when the vertical axial flow fans were active (Eva1) than when they were inactive (Eva2). In Eva 1, smoke movement caused by air flow produced by outlet fans resulted not only in a stronger back-layering effect, but also in a reduced escape time. Based on escape time calculations for an evacuation route 30 meters in length, adults and weaker evacuees would need 205 and 227 seconds respectively, which is not sufficient for both upwind and downwind directions in the event of a 65MW fire (Fig. 7).

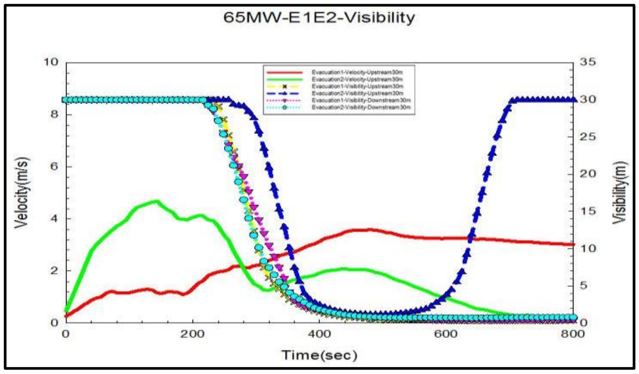

Fig. 7. 65MW: Analysis of visibility in Eva1 and Eva2.

4.3. Analysis of temperature in Eva1 and Eva2

In Eva1, when the vertical axial flow fans were active, the temperature in the area 30 meters upwind from the fire source increased to 60°C 228 seconds after the fire outbreak. In Eva2, when the vertical axial flow fans were inactive, the temperature increased to 44.14°C 192 seconds after the fire outbreak. In Eva1, when the vertical axial flow fans were active, the temperature in the area 30 meters downwind from the fire source increased to 60°C 228 seconds after the fire outbreak. In Eva2, when the vertical axial flow fans were inactive, temperature increased to 60°C 203 seconds after the fire outbreak.

The Eva1 and Eva2 models were compared in terms of the effect of vertical axial flow fan activation on the flow of smoke. The results indicated that critical visibility conditions within 30 meters upwind from the fire source were reached faster when the vertical axial flow fans were active (Eva1) but not when they were inactive (Eva2); thus, Eva2 was safe. In Eva 1, smoke movement caused by air flow produced by outlet fans resulted not only in a stronger back-layering effect, but also in a reduced escape time. However, since only the axial flow fans that moved the heated air in the downwind direction were active, tunnel users upwind from the fire were not affected. Based on escape time calculations for an evacuation route 30 meters in length, adults and weaker evacuees would need 205 and 227 seconds respectively. This time is sufficient to avoid critical temperatures when not all axial flow fans are activated. However, due to poor visibility, the tunnels remain unsafe (Fig. 8).

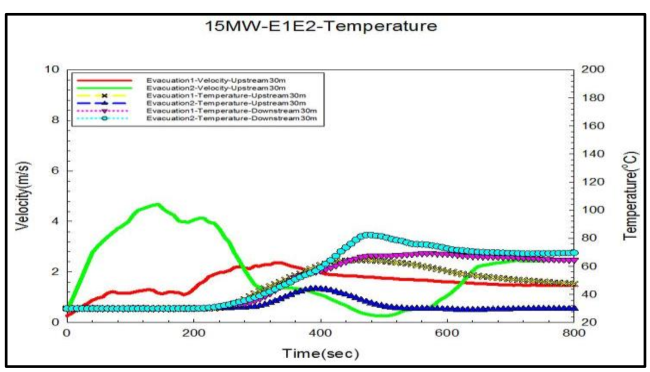

Fig. 8. 15MW: Comparison of temperatures in Eva1 and Eva2.

In Eva1, when the vertical axial flow fans were active, the temperature in the area 30 meters upwind from the fire source increased to 60°C 164 seconds after the fire outbreak. In Eva2, when the vertical axial flow fans were inactive, the temperature increased to 53.2°C 216 seconds after the fire outbreak. In Eva1, when the vertical axial flow fans were active, the temperature in the area 30 meters downwind from the fire source increased to 60°C 167 seconds after the fire outbreak. In Eva2, when the vertical axial flow fans were inactive, temperature increased to 60°C 164 seconds after the fire outbreak. The Eva1 and Eva2 models were compared in terms of the effect of vertical axial flow fan activation on the flow of smoke. The results indicated that critical visibility conditions within 30 meters upwind from the fire source were reached faster when vertical axial flow fans were active (Eva1) but not when they were inactive (Eva2); thus, Eva2 was safe. In Eva 1, smoke movement caused by air flow produced by outlet fans resulted not only in a stronger back-layering effect, but also in a reduced escape time. However, since only the axial flow fans that moved the heated air in the downwind direction were active, tunnel users upwind from the fire were not affected. Based on escape time calculations for an evacuation route 30 meters in length, adults and weaker evacuees would need 205 and 227 seconds respectively. This time is sufficient to avoid critical temperatures when not all axial flow fans are activated. However, due to poor visibility, the tunnels remain unsafe (Fig. 9).

In Eva1, when vertical axial flow fans were active, the temperature in the area 30 meters upwind from the fire source increased to 60°C 164 seconds after the fire outbreak. In Eva2, when vertical axial flow fans were inactive, the temperature increased to 60°C 238 seconds after the fire outbreak. In Eva1, when the vertical axial flow fans were active, the temperature in the area 30 meters downwind from the fire source increased to 60°C 164 seconds after the fire outbreak. In Eva2, when the vertical axial flow fans were inactive, temperature increased to 60°C 164 seconds after the fire outbreak. The Eva1 and Eva2 models were compared in terms of the effect of vertical axial flow fan activation on the flow of smoke. The results indicated that critical visibility conditions within 30 meters upwind from the fire source were reached faster when the vertical axial flow fans were active (Eva1), but not when they were inactive (Eva2); thus, Eva2 was safe. In Eva 1, smoke movement caused by air flow produced by outlet fans resulted not only in a stronger back-layering effect, but also in a reduced escape time. However, since only the axial flow fans that moved the heated air in the downwind direction were active, tunnel users upwind from the fire were not affected. Based on escape time calculations for an evacuation route 30 meters in length, adults and weaker evacuees would need 205 and 227 seconds respectively. This time is sufficient to avoid critical temperatures when not all axial flow fans are activated. However, due to poor visibility, the tunnels remain unsafe (Fig. 10).

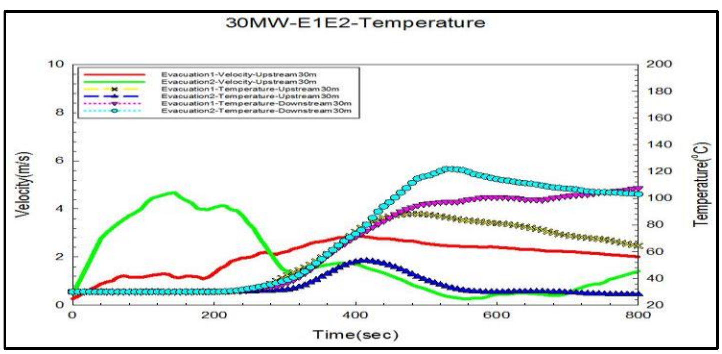

Fig. 9. 30MW: Comparison of temperatures in Eva1 and Eva2.

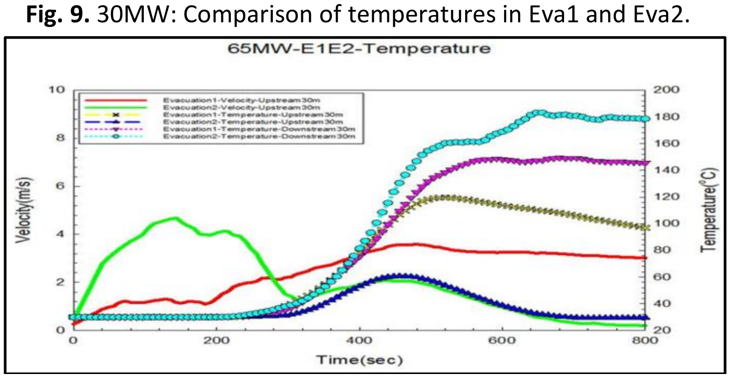

Fig. 10. 65MW: Comparison of temperatures in Eva1 and Eva2.

4.4. Eva1 and Eva2: Summary

Eva1 is the evacuation plan currently used in the Hsuehshan tunnel, in which no fans are activated 250 meters upwind and 500 meters downwind of the fire, four jet fans upwind of the fire and no jet fans downwind of the fire are activated, and one inlet fan and two outlet fans are activated. Eva2 differs from Eva1 in that no vertical air flow fans are activated. Similar to Eva1, no fans are activated 250 meters upwind and 500 meters downwind from the fire, while four jet fans upwind of the fire and no jet fans downwind from the fire are activated. The two models were compared for visibility and temperature conditions in the event of a tunnel fire.

4.4.1. Analysis of visibility in Eva1 and Eva2 (Table 3)

- ✓ In Eva1, activation of two outlet axial flow fans installed 150 meters downwind from the simulated fire source generated large air volumes which resulted in smoke back-layering.
- ✓ In contrast, no fans were activated 250 meters upwind and 500 meters downwind from the fire source in Eva2. As a result, smoke back-layering was minimized; however, visibility remained insufficient to allow safe escape.
- ✓ Based on the escape time calculations for an evacuation route 30 meters in length, adults and weaker evacuees would need 205 and 227 seconds respectively to escape the fire. Neither Eva1 nor Eva2 provided the necessary visibility conditions for safe escape.
- ✓ Critical visibility conditions were reached regardless of whether vertical axial flow fans were active (Eva1) or not (Eva2). Visibility analysis results are summarized below.

Table 3
Summary of visibility results in Eva1 and Eva2.

		Upwind		Downwind	
Situation	Visibility in Eva1 and Eva2	Fire duration	Minimum visibility	Fire duration	Minimum visibility
15MW	Eva1	96	10	131	10
	Eva2	153	10	106	10
30MW	Eva1	100	10	121	10
	Eva2	155	10	105	10
65MW	Eva1	105	10	123	10
	Eva2	153	10	105	10

4.4.2. Analysis of temperature in Eva1 and Eva2 (Table 4)

- ✓ Areas upwind of the fire were found to be less dangerous when vertical axial flow fans were not activated, whereas areas downwind of the fire source remained unsafe under both conditions.
- ✓ The critical temperature in areas downwind of the fire source could be delayed by deactivating vertical axial flow fans.
- ✓ Activation of vertical axial flow outlet fans located 150 meters from the fire source caused smoke back-layering.
- ✓ The present evacuation plan failed to fulfill the requirements for safe escape for the fires with three different HHRs. Temperature analysis results are summarized below.

Table 4
Summary of temperature results in Eva1 and Eva2.

		Upwind		Downwind	
Situation	Temperature in Eva1 and Eva2	Fire duration	Maximum temperature	Fire duration	Maximum temperature
15MW	Eva1	196	60	228	60
	Eva2	192	44.14	203	60
30MW	Eva1	164	60	167	60
	Eva2	216	53.2	164	60
65MW	Eva1	164	60	164	60
	Eva2	238	60	167	60

5. Conclusion

The following conclusion can be drawn from the research results:

- ✓ In the current Hsuehshan tunnel evacuation model, only four jet fans are activated upwind of a tunnel fire. Because two of these fans are located at the tunnel entrance very far from the fire and the air velocity in front of the fire source is insufficient, areas 30 meters upwind and downwind of the fire are unsafe.
- ✓ The optimized models included four active jet fans upwind and downwind of the fire. Safe conditions were attained for areas upwind of the fire when vertical axial flow fans were activated. Downwind areas remained safe when vertical axial fans were not activated for a 15MW fire, but were dangerous during 30MW and 65MW fires.
- ✓ With constant jet fan exit velocities and numbers of jet fans, less back-layering was observed when vertical axial flow fans were activated.
- ✓ When a fire occurs, Traffic Control Center personnel first determine the location of the fire, then coordinate the movement of people and vehicles, and finally organize an evacuation as the fire spreads. The smoke control system must be initiated within 60 seconds after the fire starts in the Hsuehshan tunnel regardless of whether jet fans and axial flow fans are activated automatically or manually. This study indicated that a descending smoke layer can be delayed by the early activation of jet fans and the maintenance of a 2-4m/s air velocity; this may give people more time to escape from the fire zone.
- ✓ For the tunnel vertical shaft located between the fire source and jet fans, when the fire is located in the first fire zone downwind of the vertical shaft and is near the outlet vent, back-layering occurs if the fire is too close to the outlet vent. This may lead to a longer back-layer of smoke, and visibility conditions upwind of the fire may worsen rapidly.

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