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## Comparative Study of Point Supply/Exhaust Ventilation Systems of Road Tunnel using Numerical Simulation

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### Abstract:

This study presents a numerical simulation, using FLUENT ver. 6.3, for a point supply ventilation system (PSVS) of full-scale road tunnel. The conducted simulations are used to evaluate the effectiveness of the ventilation system by analyzing the numerical predictions of temperature, visibility and CO concentration fields for different sizes of tunnel fire namely; 5, 10, 20 and 40 MW. Numerical simulations predicted the overall flow field and gave valuable estimates of the temperatures, visibility and CO distribution throughout the tunnel. The hazard areas are determined according to environmental limitations established by National Fire Protection Association (NFPA) of United States. A comparison of PSVS and point exhaust ventilation system (PEVS) is also carried out to predict the hazard areas in the tunnel for both systems. The PEVS accomplishes NFPA limitations almost for all fire sizes. While, PSVS fails to do at fire sizes higher than 5 MW. These conclusions are true for the range of fire sizes and tunnel configuration considered in this study. The results of the study suggest the use of multiple openings at different locations on the tunnel ceiling and according to the fire location; one or more opening (the closest to the fire location) can be chosen to operate.

### Keywords:

Road tunnel, Ventilation, Point supply, Point exhaust, and Numerical simulation

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## 1. Introduction:

Ventilation systems are essential in the design of all road tunnels. The role of ventilation systems is to maintain acceptable levels of contaminants produced by vehicles during normal traffic operation (normal ventilation), and to control heavy smoke in event of fire (emergency ventilation). In the early years of tunneling, ventilation engineers were mainly concerned with normal operation. In the last two decades however their attention has been increasingly focused on the fire case. This is due to a significant reduction of motor-vehicle emissions and to a growing concern related to safety. This trend increased dramatically owing to number of recent tragic tunnel fires [1].

In the event of fire in road tunnel and due to its confining geometry, smoke generated from the fire could severely impede visibility and evacuation. Mechanical ventilation systems such as longitudinal, transverse and semi-transverse ventilation systems are commonly employed. The effectiveness of the ventilation system in event of fire is determined by its capability to maintain a tenable environment for occupants to escape. Ventilation requirements are specified by national codes and international standards. A code compliant ventilation system design may, in some circumstances, result in being over sized or poor performance. Therefore, designing the system on performance basis may achieve cost reductions and design benefits.

In performance-based design, three different approaches can be cited: reduced-scale models, full-scale tests and numerical models. In the first, significant contributions can be found in the literature [2-4], though their results are difficult to extrapolate to different operating conditions or configurations. In the second, fire tests are carried out to assess the smoke removal capacities of the tunnel ventilation systems. It is not practical to investigate every configuration experimentally after being constructed. Also, the tests are limited to fires of lower capacity to avoid damaging the tunnel ceiling or the tunnel itself. Full-scale tests are really expensive and only two of them have been conducted recently: EUREKA Project [5] and Memorial Tunnel Fire Ventilation Test Program (MTFVTP) [6]. They require of large experimental facilities, that are difficult to operate and maintain in order to obtain good results. The literature review of the last method (numerical modeling) explored different approaches of numerical models.

### a. Network Models

A tunnel, or network of tunnels and passageways, is divided into a circuit of one-dimensional ventilation pathways. Solving for the conservation of mass and energy at each junction, a network model predicts the time dependent movement of air (and smoke) through the network. The strength of these models is their ability to predict air movement within the entire network at short computing time-scales. Their weakness is the missing details at the fire source and the absence of any three-dimensional effects. However, used in combination with a zone or CFD model in the vicinity of the fire source, they provide potentially a very powerful design tool. TRANSIT [7] and RABBIT [8] are recent examples of one-dimensional network models.

### b. Zone Models

In a zone model the tunnel is divided into a number of zones, in which conditions at each zone are assumed to be uniform. Whilst widely used in the study of building fires, zone modeling has enjoyed less application in tunnel fires. FASIT [9] is an example of a time dependent zone model, where the fire source is represented as a Gaussian thermal

plume. Zone models provide some of the information missing in the network models. However, the assumptions required in the plume shape, ventilation flow pattern etc, means that care must be taken not to be used out of context.

### c. Computational Fluid Dynamics (CFD) Models

Based on first principles, CFD models solve the underlying conservation equations for mass, momentum, energy and species concentrations (e.g. fuel mixture fraction). This allows the important physical and chemical processes and their interactions, describing the production and movement of smoke and heat, to be simulated realistically. Physical sub-models describe the complex physical processes of turbulence, combustion and thermal radiation. In addition to general purpose commercial codes such as, JASMINE [10], Flow 3D[11], PHOENICS [12], and FLUENT [13], there are a number of special purpose CFD codes for application to tunnel fire such as SOLVENT [14], FDS [15], TUNFIRE [16]. The fire specific codes may employ simpler meshes and numerical schemes. In order to be completely reliable, the CFD codes must be calibrated and validated through comparison with experimental data. Skilful users are necessary; otherwise the obtained results may be quite misleading.

As summary, all models are potentially useful. Thus the simpler models are ideal for repeated applications, such as would be required in risk assessment. The details of geometry and ventilation system can be represented, taking advantage of 3-dimensional prediction capability of CFD codes. The main advantage of the CFD models is to allow the study of cases for which no experimental data are available. The major restriction is the time needed for the calculation and the complex utilization.

A previous study [17] has been conducted which validated the use of general purpose commercial CFD code (FLUENT ver. 6.3) for modeling flow field in full-scale road tunnel incorporating a ventilation system under fire incident. The objective of this study is to assess tunnel emergency ventilation system, utilizing the validated CFD model in the previous study. PSVS and PEVS have been selected here. They are much similar to longitudinal ventilation system but more simple in construction, operation and control. They apply a unidirectional airflow through a single opening located in the ceiling of the tunnel. They represent a competitive alternative especially where natural ventilation is not recommended for long tunnels in event of fire.

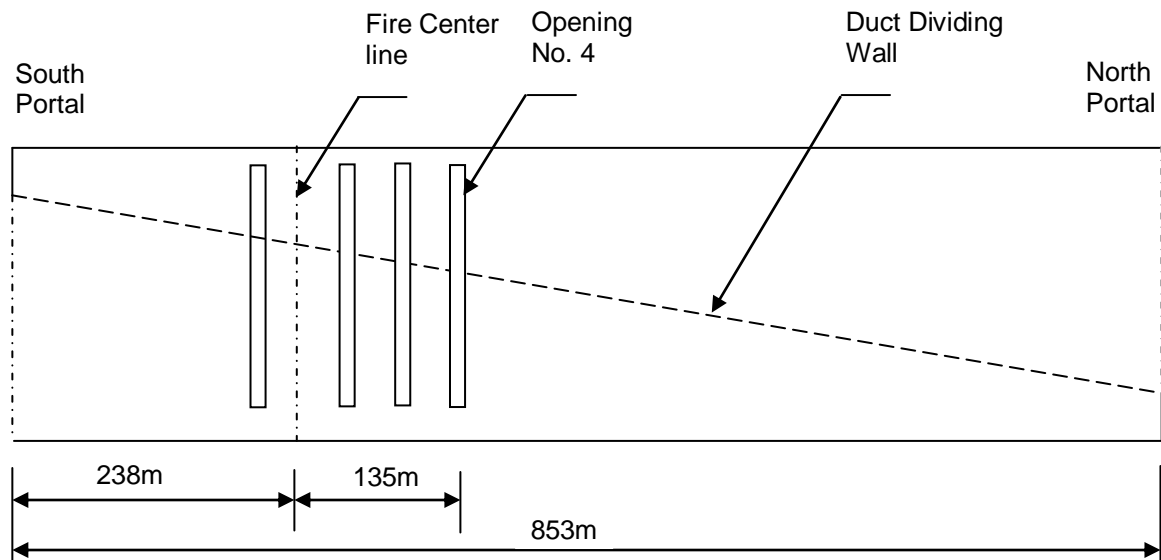
The performance assessment is conducted by analyzing the CO concentration, temperature, and visibility fields for different operating conditions. The numerical results are cross-checked against environmental limitations of NFPA [18] to obtain knowledge about the hazard areas in the tunnel for both systems. Also, a comparative study between PSVS and PEVS is carried out.

## 2. CFD Simulation Technique

CFD simulation was used to predict the thermal environment of the Memorial Tunnel for test cases 320A and 321A of the MTFVTP, [6]. Simulations were made using FLUENT ver. 6.3 with its pre-processor GAMBIT [19].

The Memorial Tunnel has a two-lane, 853 meter long road tunnel. It is a part of the West Virginia Turnpike near Charlestown, West Virginia, USA. The tunnel is 3.2% upgrade from south to north portal. The cross-sectional area of the tunnel is 60.4 m<sup>2</sup> without ceiling and 36.2 m<sup>2</sup> when the ceiling is in place. Test 320A investigates PEVS, while Test 321A investigates PSVS. Fire source is located at the approximate quarter

point of the tunnel (238m) from the south portal. Ventilation air passes through a 28m<sup>2</sup> opening on the ceiling located 135 m north of the fire source centre line, opening no. 4, figure (2).



**Fig (2):** Memorial Tunnel duct configuration for point supply / exhaust operation, [6]

The details of the numerical model are presented in previous paper, [17]. For validation purpose, the critical velocities during a fire incident were predicted and compared with published experimental data [6]. As a result, good agreement was achieved in all the tested cases. The numerical results were obtained using PC (3.0 GHz Pentium 4), 2 GB RAM, and 120 GB HD. Generally 800-1200 initiations were required to obtain a suitable level of solution convergence, while each calculation required about 8 hours of CPU time and 40-50 MB of HD memory.

### 3. Results and Discussions

Steady-state simulations were carried out with design volumetric flow rate of 84m<sup>3</sup>/s of ventilation air for different fire sizes namely 5, 10, 20 and 40 MW which simulates the HRR results from firing different types of vehicles. Simulation results make it possible to detect a priori the maximum level of toxicity, visibility conditions and threshold of human resistance to high temperatures in a fire incident. This information may determine if the design of the ventilation system is correct. If it is not, it may be useful to define corrective actions in order to improve the rescue plans.

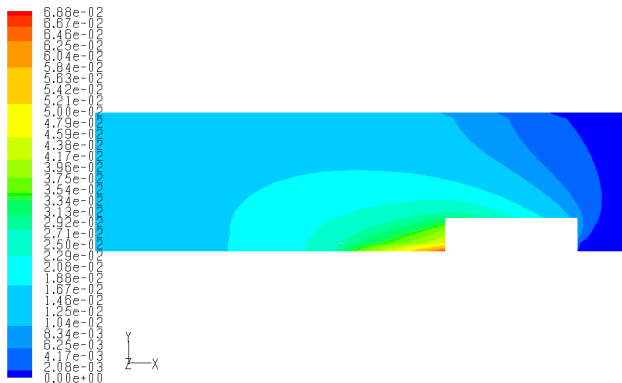
Simulation results are presented as contours of CO<sub>2</sub> and temperature on the symmetry plane. The real affection zone comprises 2m height from the road for the standing people trapped inside and 1m height for people inside vehicles. Therefore, the CO and temperature are plotted against longitudinal distance through the tunnel at two levels of 1 and 2m. The visibility, which is obtained mainly from the axial velocity distributions, is plotted against the longitudinal distance through the tunnel for the same levels.

In PEVS, the smoke produced from the fire is exhausted from the opening in the ceiling and fresh air is drawn from the south portal. The same geometry and dimensions are used but the flow direction is inverted. The boundary conditions are modified to suit this change.

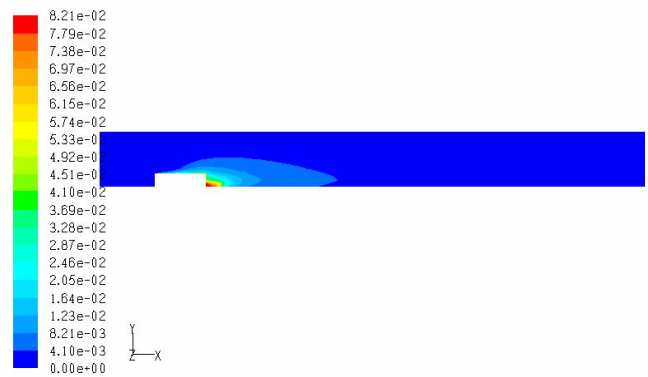
### 3.1 CO Concentration Distributions

While CO<sub>2</sub> is basically a contamination gas, the CO is a toxic gas. Thus large concentrations of CO<sub>2</sub> may lead to suffocate but a relative small proportion of CO is lethally poisonous. The severe toxicity of CO implies that large concentrations of the gas should not be accumulated inside the tunnel for a long period. The maximum tolerable rate of CO which may be used as a criterion for considering a smoke free zone can be established as 800 ppm, NFPA [18]. The CO concentration is directly obtained from the CO<sub>2</sub> results of the model. Approximately, there is 1ppm of CO for every 20 ppm of CO<sub>2</sub> for non-stoichiometric combustion, [20]. Figure (3) shows CO<sub>2</sub> contours in the tunnel symmetry plane at different fire sizes for both PSVS and PEVS.

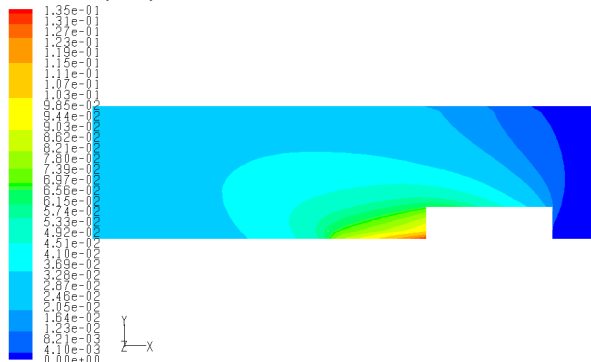
For PSVS, CO<sub>2</sub> concentration inside the tunnel ranges from 0 to 2500 ppm (corresponds to CO<sub>2</sub> mass fraction of 0.085) at 5 MW fire. CO propagation is assured towards the south portal and a large CO-free region is established along the tunnel. For moderate HRR (10 and 20 MW) there is a relatively small production of smoke and a balance between the production of toxic gases and its transport due to air movement which avoids the presence of high CO concentration. The CO concentration is quite acceptable. In case of 40 MW fire, due to a major heat release, maximum values of concentration reaches 0.135 mass fraction of CO<sub>2</sub> corresponds to 6500 ppm CO. The CO fills all the section between the fire location and the south portal where the CO concentration is more than 800 ppm as shown.



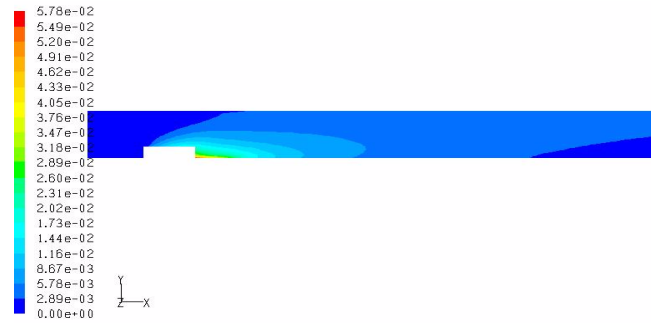
(A1): 5 MW fire size - PSVS



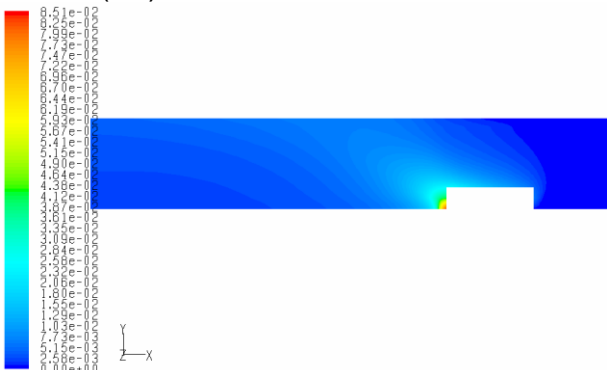
(A2): 5 MW fire size - PEVS



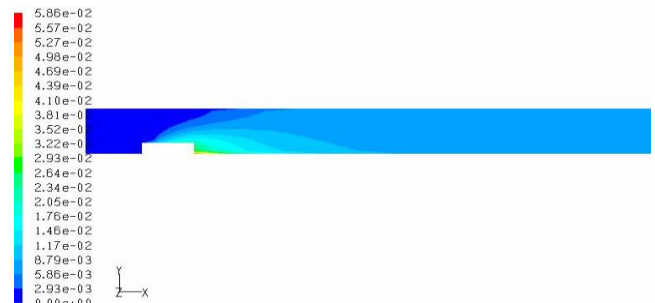
(B1): 10 MW fire size - PSVS



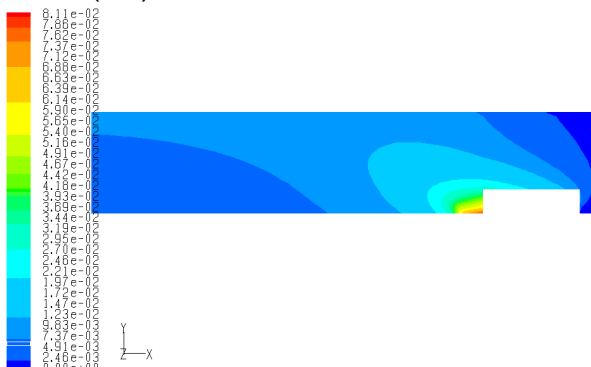
(B2): 10 MW fire size - PEVS



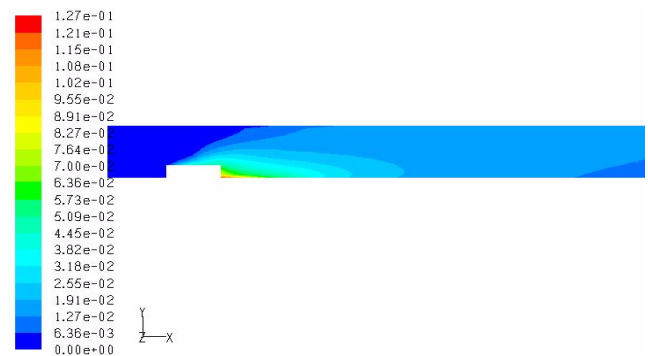
(C1): 20 MW fire size - PSVS



(C2): 20 MW fire size - PEVS



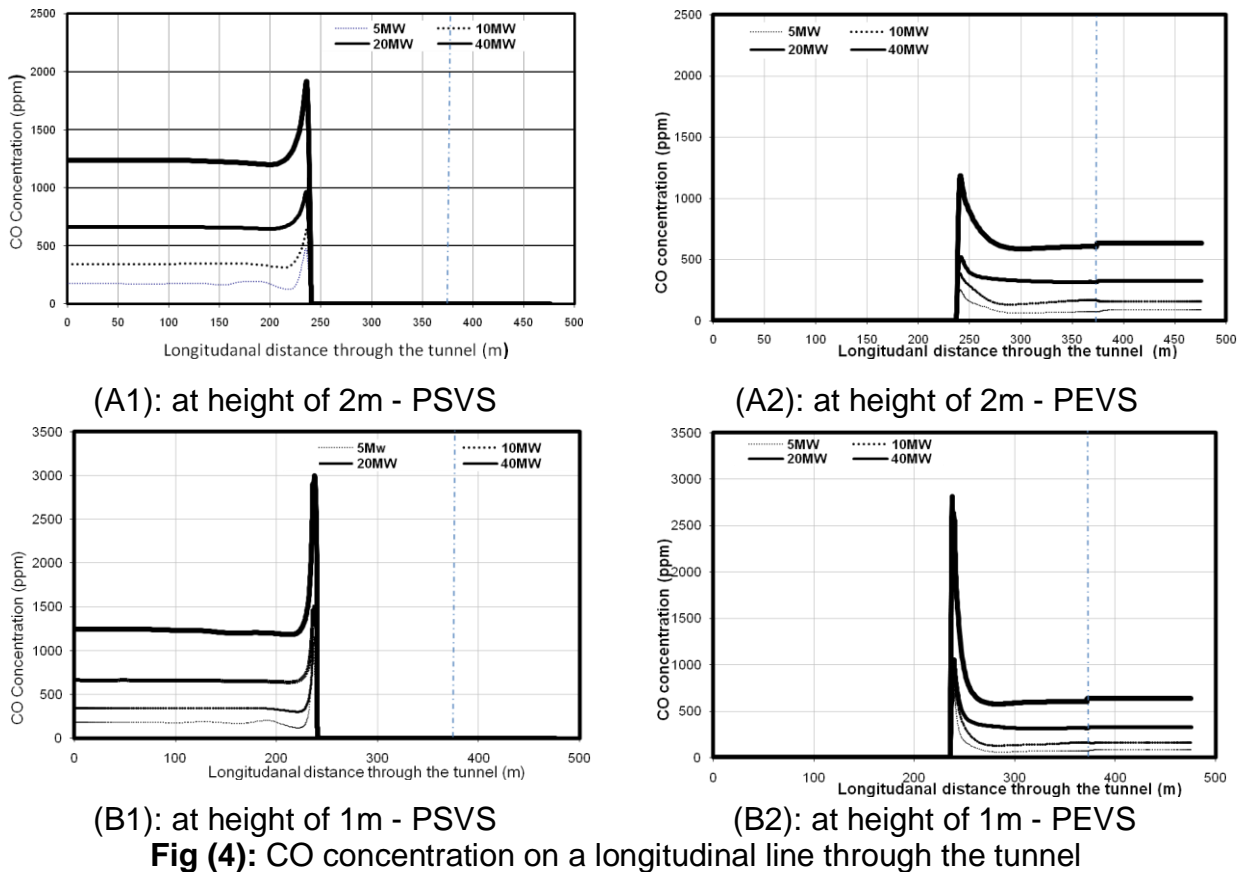
(D1): 40 MW fire size - PSVS



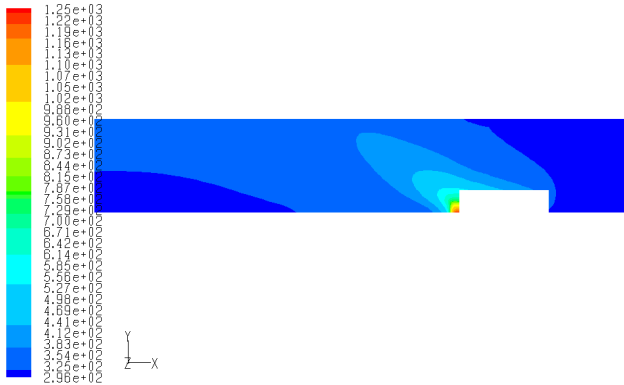
(D2): 40 MW fire size - PEVS

**Fig (3):** CO<sub>2</sub> concentration in the symmetry plane

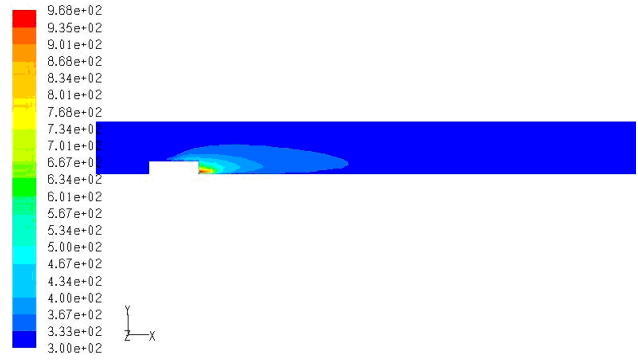
Concerning the PEVS, the maximum value of CO<sub>2</sub> which corresponds to maximum value of CO concentration is almost the same as PSVS. However, the distribution of CO<sub>2</sub> indicates a significant reduction on its concentration compared with PSVS. This can be attributed to the relative location of exit port from the fire source which is approximately half of the distance between the south portal and the fire location in PSVS. This situation make the sweeping of the combustion gases toward the exit port by the air current is easier. This sweeping action reduces the pollution of the air inside the tunnel.



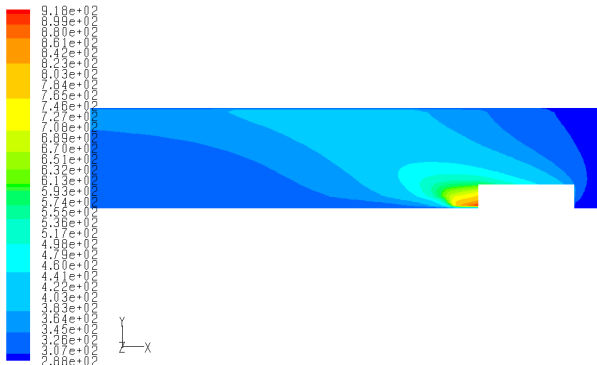
To quantify the above results, CO concentrations were plotted against the longitudinal distance through two lines located in the symmetry plane (2m and 1m height, respectively) as shown in figure (4). Generally, the CO concentration increases as the fire size increases due to the increase in amount of fuel consumption. Also, PEVS has smaller asymptotic values of CO concentration compared with PSVS. However, PSVS reaches asymptotic values at shorter distance from fire source compared with PEVS. Concerning the maximum values of CO concentration, PEVS has improved performance compared with PSVS especially at 2m level, where the induced effect due to the exhaust fan is more significant. Concerning the hazard area extension, the PEVS performs better than PSVS for all studied cases.



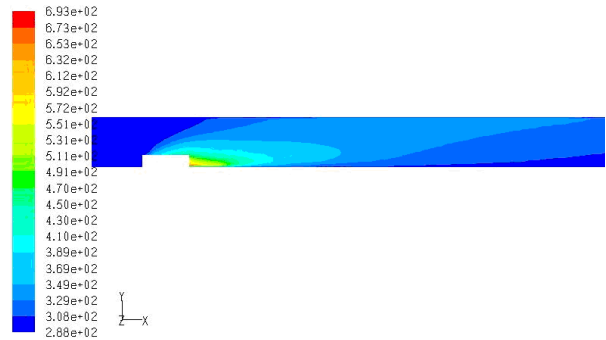
(A1): 5 MW fire size - PSVS



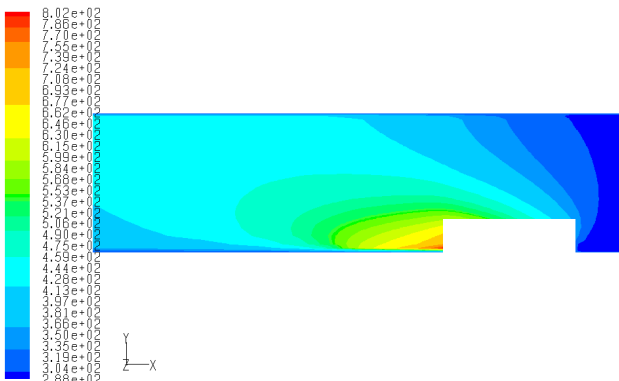
(A2): 5 MW fire size - PEVS



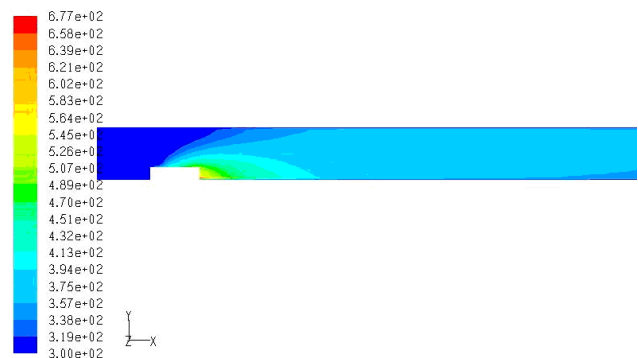
(B1): 10 MW fire size - PSVS



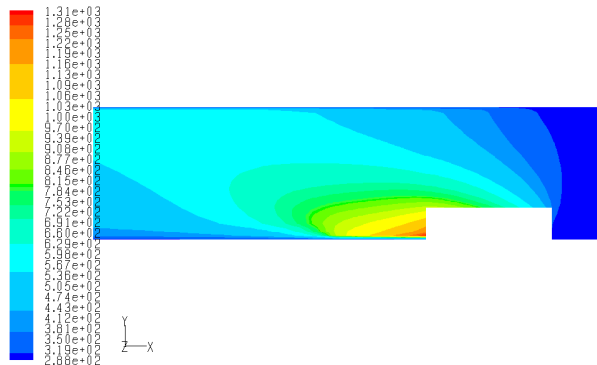
(B2): 10 MW fire size - PEVS



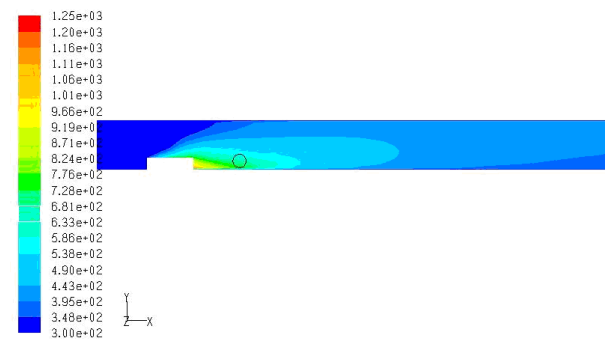
(C1) :20 MW fire size - PSVS



(C2) :20 MW fire size - PEVS



(D1) : 40 MW fire size - PSVS



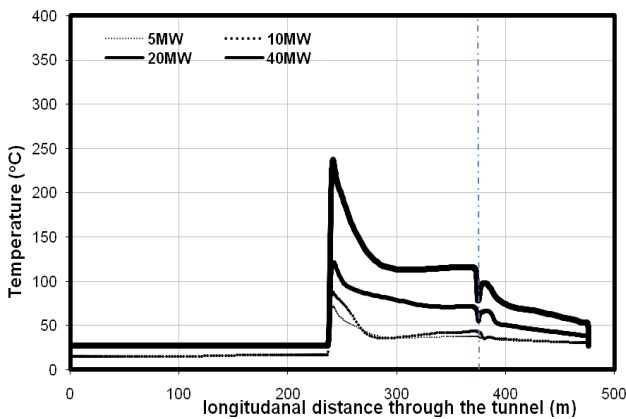
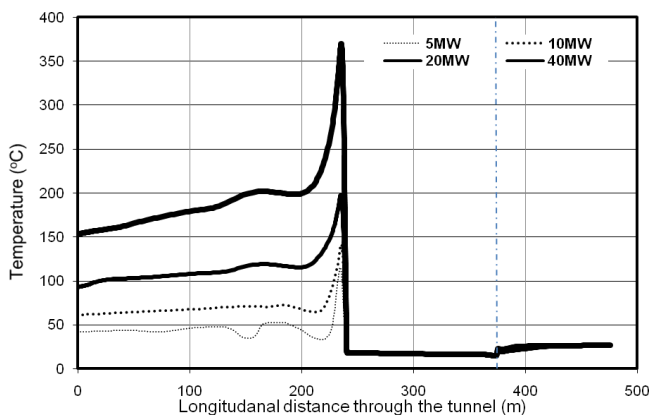
(D2) : 40 MW fire size - PEVS

**Fig (5):** Temperature distribution in the symmetry plane



### 3.2 Temperature Distributions

The ventilation system introduced fresh air that contributing to reduce the thermal map inside the tunnel. The ventilation system must keep a bearable temperature in the affection zone of the people. The maximum tolerable temperature which may be used as a criterion for considering a safe zone can be established as 60 °C, NFPA [18]. Figure (5) shows the temperature distribution in the symmetry plane for fire sizes of 5, 10, 20 and 40 MW, respectively. The maximum temperature is found beside the fire location in the downstream direction in the regions of small air movement. The area affected by the fire is shown to increase as fire size increases. The stratification of the air is more obvious at smaller fire sizes. The temperature in upstream direction is quiet low compared with the temperature in downstream direction. The above statements are valid for both ventilation systems. However, the temperature distribution through the symmetry plane indicates a significant reduction of temperature throughout the tunnel for PEVS compared with PSVS.

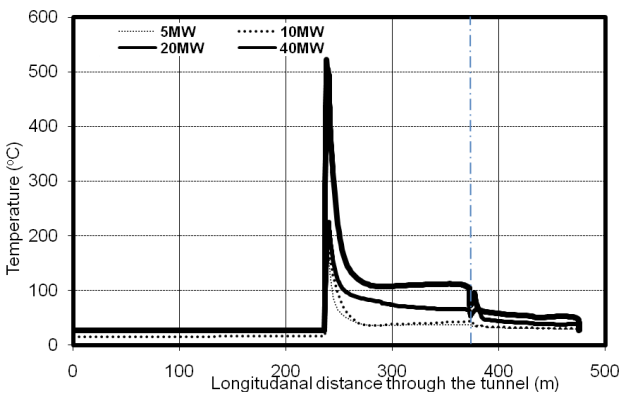
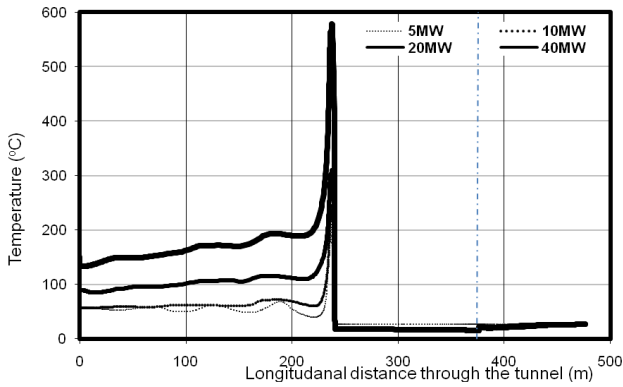


(A1): at height of 2m - PSVS (A2): at height of 2m - PEVS

(A1): at height of 2m - PSVS (A2): at height of 2m - PEVS

(A1): at height of 2m - PSVS (A2): at height of 2m - PEVS

(A2): at height of 2m - PEVS



(B1): at height of 1m - PSVS (B2): at height of 1m - PEVS **Fig (6):**

(B1): at height of 1m - PSVS (B2): at height of 1m - PEVS **Fig (6):**

(B1): at height of 1m - PSVS (B2): at height of 1m - PEVS **Fig (6):** Temperature

3

(B2): at height of 1m - PEVS **Fig (6):**

**Fig (6):** Temperature distribution on a

**Fig (6):** Temperature distribution on a longitudinal line through the tunnel

Figure (6) illustrates the temperature distribution along the tunnel symmetry plane at 1m and 2m heights for both ventilation systems. Compared with PSVS, the maximum temperature, at fire source, and minimum temperature, far downstream

direction, for PEVS was found to decrease about 100°C for all studied cases. It is shown that, the effect of opening port is more significant for PEVS compared with PSVS. Also, the steady state conditions prevail at shorter distance for PEVS compared with PSVS.

The hazard areas based on data in figures (4) and (6) are summarized in table (1). For PSVS, the hazard area concerning CO concentration extends all the downstream zone of the tunnel at 40 MW fire size. Also, the hazard areas concerning high temperature prevail throughout the downstream zone of the tunnel for 20 and 40 MW fire sizes. For 5MW fire size; the extension of hazard area is 7m and 10m at height of 1m and 2m, respectively. For 10 MW fire size; at a height of 1m the temperature decreases to less than 60°C at 170m from the fire centre line. While, at a height of 2m the temperature does not decrease below 60°C at all.

Concerning the PEVS, all the downstream direction of the tunnel is considered as a hazard area for 20 and 40 MW fire sizes. As indicated, the results show that the extension of the hazard area concerning CO concentration and temperature decreases with using PEVS than using PSVS.

**Table (1): The extension of the hazard area for different fire sizes**

Fire size (MW)	CO concentration	Temperature
5	7m	10m
10	170m	170m
20	170m	170m
40	170m	170m
5	Height of 2m	Height of 2m
10	Height of 2m	Height of 1m
20	Height of 1m	Height of 2m
40	Height of 2m	Height of 1m
5	Height of 1m	Height of 1m
10	PS	PS
20	PS PE	PS PE
40	PE PS	PE PS
5	PS PE	PS PE
10	PE PS	PE PS

	PS PE
	PE PS
	PS PE
	PE
5	
	5 None
	None None
	None 3
	3 None
	None 10
	10 9
	9 7
	7 12
	12
10	
	10 None
	None None
	None 3.5
	3.5 2
	2 All
	All 21
	21 170
	170 18
	18
20	
	20 8
	8 None
	None 9.5
	9.5 3
	3 All
	All 149
	149 All
	All 96
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	40 All
	All 18
	18 All
	All 19
	19 All
	All 211
	211 All
	All 177
	177

### 3.3 Visibility Conditions

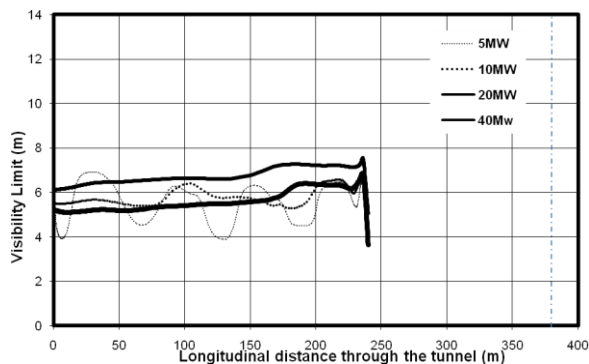
Unlike temperature or toxic gases, obscured visibility is not, itself, lethal. A hazard

results only if the reduced visibility prevents required action of escape activity. Visibility is often determined as the distance at which an object is no longer visible. Visibility limit can be calculated from the following correlation [21]

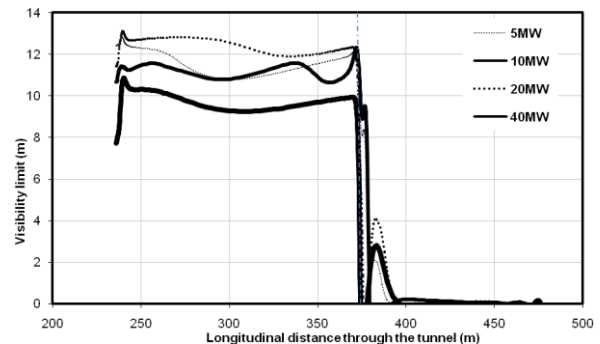
$$VI = \frac{k_v}{Ln10} \frac{uAH_l}{QD_m} \tag{1}$$

Where  $k_v$  is a constant. For objects such as walls, floors and doors in an underground arcade or long corridor  $k_v = 2$ , while  $k_v = 6$  for illuminated signs. The values of  $D_m$  for different types of vehicles are given based on experimental data [22]. The minimum tolerable visibility which may be used as a criterion for considering a safe zone can be established as 9 m, NFPA [18]. The extension of hazard area can be determined as the distance from the fire centre line that has a visibility limit lower than 9m for illuminated objects ( $k_v = 6$ ).

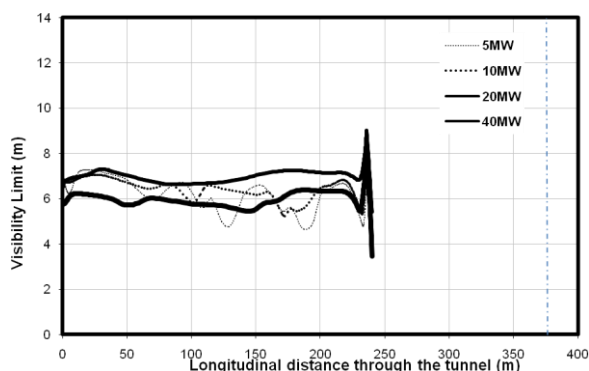
Figure (7) shows the visibility limit in the downstream direction of fire for both of ventilation systems in the tunnel symmetry plane at heights of 2m and 1m, respectively. The results of PSVS show that the visibility limit always less than 9m downstream the fire location for all fire sizes. While, the visibility limit always higher than 9m downstream the fire location for PEVS at all fire sizes. This is true, until the location of the exhaust opening where the visibility limit drops suddenly due to the decrease in air/smoke axial velocity. Generally, these above results indicate that PSVS is not suitable from the point of view of escape activity.



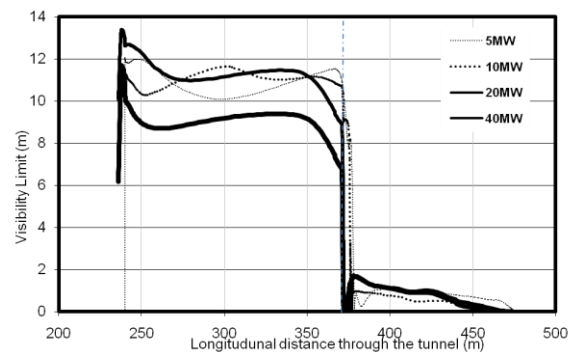
(A1): at height of 2m - PSVS



(A2): at height of 2m - PEVS



(B1): at height of 1m - PSVS



(B2): at height of 1m - PEVS

**Fig (7):** Visibility limit on a longitudinal line through the tunnel

4. Conclusions:

CFD technique is now reaching a mature state and gaining acceptance for tunnel applications. It has the potential both in design phase and as a design-verification tool. It could be used as a predictive tool of detailed parametric studies that would be too expensive to undertake by full-scale experiment. In this study, numerical simulation using commercial general purpose CFD software (FLUENT ver. 6.3) was used to predict the overall tunnel flow field under fire conditions and to give estimates of the temperatures, visibility and CO distribution throughout the tunnel. Simulation results enabled to determine the hazard areas in each studied case. PEVS accomplishes the thermal environment limitations established by NFPA standard almost at all fire sizes, namely; 5, 10, 20, and 40 MW. While, PSVS fails to do at fire sizes higher than 5 MW. These conclusions are true for the range of fire sizes and tunnel configuration considered in this study. However, it is recommended to use multiple openings at different locations on the tunnel ceiling according to the fire location; one or more opening (the closest to the fire location) can be chosen to operate.

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#### Nomenclatures

A	The cross-sectional area of the tunnel ( $m^2$ )
$D_m$	Mass optical density for materials ( $m^2/kg$ )
$H_l$	Lower heating value of fuel (kJ/kg)
$\dot{Q}$	Heat release rate from the fire (MW)
u	The longitudinal velocity (m/s)
VI	Visibility through irritant smoke (m)

#### Abbreviations

CFD	Computational Fluid Dynamics
HRR	Heat Release Rate
MTFVTP	Memorial Tunnel Fire Ventilation Test Program
NFPA	National Fire Protection Association
PEVS	Point Exhaust Ventilation System
PSVS	Point Supply Ventilation System