CAPABILITIES AND LIMITATIONS OF TEMPEST'S MOBILE VENTILATION UNIT TO CONTROL THE SMOKE AND HEAT GENERATED BY A MAJOR TUNNEL FIRE
- A CFD Study -

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ABSTRACT

Steady state and the limiting case emergency ventilation analysis of an automobile fire in various road tunnel configurations were performed. The maximum Heat Release Rate (HRR) of 29.3MW inside various tunnel lengths (60.9m to 5.2km) with maximum 4% down grade was considered. The Mobile Ventilation Unit (MVU™) manufactured by Tempest Technology™ was used as the ventilation equipment. In particular, the 1.5m diameter MVU with 55 m^3/s capacity was chosen. In order to isolate the effect of various physical and geometrical parameters a series of steady state runs were made. Based on the preliminary steady state analysis of the chosen MVU the fire was located about 1.6 km from the nearest portal, down grade, as a limiting case scenario. Buoyancy driven flow and throttling effect due to the large amount of heat generated by the fire cause significant resistance to the downgrade ventilation flow. Development of emergency ventilation flow was simulated to examine the MVU's capability to provide sufficient airflow in order to allow a safe rescue and fire-fighting path. The results of this study indicate that the chosen MVU is a suitable emergency ventilation tool for majority of tunnel fires considered in this study. In the limiting case, however, larger (or multiple) MVU(s) should be used for full prevention of smoke backlayering.

1. INTRODUCTION

Fires in tunnels and in underground facilities represent a significant challenge for system operators and fire-fighting personnel who are required to ensure safe passenger evacuation and fire-fighting access. Tunnel fires may also cause severe structural damage, damage to tunnel joints and seals as well as severe damage to power, communication and signaling cables, and vehicles. The most damaging of them all is the loss of life, which in turn may lead to major lawsuits and litigations costing the owner or operating agency unaffordable compensation. Therefore, smoke and heat must be controlled and prevented from contaminating the evacuation route, while the fire should be prevented from spreading.

It is necessary to look for feasible and cost-effective alternatives to protect the passengers and operating personnel. Lacking such alternatives may create a negative safety image among the prospective users of the tunnel, with serious economic consequences. Generally the tunnel systems are provided with tunnel ventilation systems capable of controlling the smoke and heat by creating an air stream with a velocity past the fire higher than the velocity required to prevent smoke backlayering. However, there are numerous tunnels that do not have sufficient ventilation capacity in case of a tunnel fire. NFPA 130 *Standard for Fixed Guideway Transit and Passenger Rail Systems*, Edition 2000, recommends that all tunnels longer than 300 m have a mechanical ventilation system, while those between 61 and 300m should be subjected to an engineering analysis to determine how a fire can be ventilated, [1]. One of the requirements in fighting tunnel fires is to ventilate the tunnel in a manner that provides a safe and smoke free path for the fire-fighting crew and the emergency rescue personnel to reach the accident site. Tempest MVUs are designed to provide rapid emergency ventilation deployment for locations that would otherwise lack sufficient ventilation capacity to fight tunnel fires. Therefore, MVUs represent an economical alternative for costly upgrades to existing tunnel ventilation systems. A scientific investigation of the MVU system is valuable in predicting its performance under various operating conditions. The results of the scientific study can be used in selection and sizing of the MVU system in order to optimize its application in the field. In addition possible enhancements to the system can be identified. One approach to a comprehensive and cost effective scientific investigation of the MVU system is the use of Computational Fluid Dynamics

(CFD) simulations in conjunction with limited experiments to validate the CFD results. The results from these investigations will benefit both the consumers and the manufacturer of the MVU systems.

The MVU system consists of a relatively large, hydraulically driven axial fan powered by a diesel engine, with a fuel tank allowing up to 10 hours of operation and can be installed on a truck or trailer. The system has been demonstrated in several tunnels and the airflow measurements indicate that tunnels up to 10km in length can be ventilated by multiple MVUs [2], [3]. The system can also be used as a backup system for tunnels with jet fans that might be damaged by fire.

The scenario considered in this analysis consists of a generic 5.2km long road tunnel of semicircular cross-sectional area and a 4% down grade. A vehicle fire with HRR of 29.3MW was simulated inside the tunnel. A 1.5m diameter MVU with 55m^3/s capacity was used as the ventilation equipment. Various MVU positions were tested: 15.2m outside and 33.5m inside the tunnel portal, with the fan operated in supply towards the tunnel exit at full capacity. It was assumed that the tunnel has no permanent ventilation system and the MVU was the only means of moving air through the tunnel to ventilate the fire. It was further assumed that the nearest safe place of refuge is outside the tunnel through the upper portal. The necessary airflow to protect the evacuation and prevent the backlayering effect was calculated using "Critical Velocity" criterion recommended by NFPA 130 [1] and the calculated value was used for comparison with the CFD simulation results. As the first step in determining the limiting case, a series of steady state runs were performed.

In the following sections some available background data, the problem statement, details of a field test, the model, and discussion of results for this study are presented and concluding remarks are made. It should be noted that the uncertainty levels in this study are larger than what is necessary to make precise quantitative predictions and/or claims. The results should be viewed as qualitative, rather than exact quantitative representation of the flow phenomena considered.

2. AVAILABLE DATA

Several tunnel ventilation demonstrations were conducted in Europe by the Tempest Technology staff. Some of the results from these demonstration runs are presented in the Tempest Technology MVU catalog and other publications [2], [3]. In addition the Swedish National Testing and Research Institute (SP), Fire Technology is conducting a research work on the application of a mobile fan placed at the entrance of a tunnel with volume flow rate of 38m^3/s, [4]. A small tunnel (Manessetunnel) and a large tunnel (Käferbergtunnel) were used. Comparisons between experimental and computational results were made using CFD software, Fluent, and reasonable results were obtained when no combustion was considered. The research confirmed that the time required for establishing a steady flow inside a tunnel is closely linked to the size of the tunnel. Thus, according to the calculations performed with Fluent the flow supplied by the fan established in Manessetunnel and Käferbergtunnel reached final velocities of 3.75m/s and 2.24m/s within 4 and 10 minutes, respectively.

Small-scale fire tests were carried out at SP facilities with ventilation systems, which combine shafts and mobile fans. The tests allowed an evaluation of the accuracy of the solution given by Fluent for cases where fire is involved. The results appeared to be globally acceptable and showed that a fan could reverse the flow induced by the fire, make the access to the center of the fire much easier and significantly enhance the efficiency of the shafts. One of the research parameters was the time it takes for the fan to reverse the fire-induced buoyant flow. Simulations of two 15MW fires in the middle of two trains centered inside Manessetunnel and Käferbergtunnel were performed. The elevation differences between the ends of the tunnels were considered in order to account for the buoyant forces of the fire. It appeared that the flow supplied by the fan was established within 1 to 3 minutes. These results are the same as the case with no fire and with trains present. It was concluded that obstacles inside tunnels have a strong influence and shorten the time required for the flow to establish. However, the final velocities are lower in case of a fire, which opposes the flow supplied by the fan. Based on this observation it was concluded by the researchers that the use of mobile fans positioned at the entrance of a tunnel should allow a rapid intervention of the fire brigade directly at the heart of the fire and in a safer atmosphere. Considering the accuracy of the previous calculations by SP compared with the experimental data, the order of magnitude of time to reach steady flow (a few minutes) was reasonable. It was further concluded that MVUs will create a safer environment for the fire fighters and will shorten the time for access to the tunnel.

3. PROBLEM STATEMENT

A typical MVU consists of an axial fan, which is mounted on a mobile platform with several degrees of freedom for proper direction of the ventilation flow. The particular MVU modeled in this study has a 1.5 m diameter and 55 m^3/s volume rate capacity. Figure 1 shows a 1.2 m diameter, 37.7 m^3/s model of Tempest Technology MVU, which is similar to the one considered in this study.

Figure 1. The 1.2m diameter Tempest Technology MVU

This MVU is used to ventilate a 5.2km long road tunnel, which has a 29.3MW fire at 1.6 km from the closest portal. The tunnel is set at 4% down grade to create a limiting case scenario. The cross section of the tunnel is semicircular with a maximum height of 6.7 meter. The MVU was placed at 3.6m above ground level and centered at the tunnel width and at 18.2m outside of the tunnel portal. Other steady analysis cases were considered with the MVU at 15.2m outside and 33.5m inside tunnels of various lengths to evaluate the effects of the fan location and tunnel length on the flow characteristics.

3. MVU FIELD TEST

Background

The MVU flow spread data were not available for calibration of the CFD simulation runs. Therefore, upon discussion with the Tempest Technology staff it was agreed that Earth Tech would perform a field test of a 1.2m diameter MVU at the Tempest Technology headquarters in order to estimate the typical spread rate of the MVU flow.

Test Apparatus

The test was set up in an empty and unobstructed lot at Tempest Technology in Fresno, California. The test apparatus included a 1.2m diameter model MVU, 3 anemometers (NK Kestrel 2000), distance measuring and marking equipment, and optical magnifying equipment for remote observation of the anemometer display faces.

Test Procedure

The MVU was raised to approximately 3.6m at centerline and pointing horizontally. It was running at normal operating condition of nearly 2150 rpm. The three anemometers were mounted at fixed heights above ground level (0.9m. 3.6m, and 7.6m) on a steel tripod. The tripod was placed at various axial (x) and radial (y) coordinates from the MVU discharge face. The MVU discharge air velocity was measured in groups of three readings as time-averaged values measured over approximately 10 minutes periods in order to reach quasi steady state conditions. Ambient conditions were determined based on observation of local wind and visibility plus weather reports from Fresno airport Automated Terminal Information System (ATIS), which provided the temperature, dew point. and atmospheric pressure.

Test Results

A total of 27 data points were collected. Table 1 shows the ambient conditions at test time, and the measured data at each point.

Table 1. Tempest MVU field test data

MVU Model:	1.2m (48-inch) Diameter	Site contact:	Dexter and Leroy Coffman
Test Engineer:	Nader Shahcheraghi	Site address:	4645 Bendel Ave, Fresno, CA 93722
Test Date:	21-May-01	Test Time:	6:00 am to 9:00 am

Ambient Conditions:	Temp C (F)	Source	P (mmHg)	Source	
	27 (80.6)	FAT-ATIS	29.87	FAT-ATIS	
	Dew Pt. C (F)	Source	Wind km/h (mph)	Direction	Source
	12 (53.6)	FAT-ATIS	calm [<8 (5)]	variable	local observation

Test Pt.	X* m (FT)	Y* m (FT)	Z* m (FT)	Air Speed** m/s (fpm)	Notes
1	6.1 (20)	0 (0)	3.0 (10)	0 (0)	
2	6.1 (20)	0 (0)	3.6 (12)	23.4 (4600)	
3	6.1 (20)	0 (0)	7.6 (25)	0 (0)	
4	6.1 (20)	0.6 (2)	3.0 (10)	0 (0)	
5	6.1 (20)	0.6 (2)	3.6 (12)	16.8 (3300)	
6	6.1 (20)	0.6 (2)	7.6 (25)	0.51 (100)	
7	6.1 (20)	-9.1 (-3)	3.0 (10)	0 (0)	
8	6.1 (20)	-9.1 (-3)	3.6 (12)	10.9 (2155)	
9	6.1 (20)	-9.1 (-3)	7.6 (25)	0 (0)	
10	12.2 (40)	0 (0)	3.0 (10)	180	
11	12.2 (40)	0 (0)	3.6 (12)	14.5 (2850)	
12	12.2 (40)	0 (0)	7.6 (25)	0.89 (176)	
13	12.2 (40)	-3.0 (-10)	3.0 (10)	0.27 (53)	Unsteady
14	12.2 (40)	-3.0 (-10)	3.6 (12)	0.34 (68)	Unsteady
15	12.2 (40)	-3.0 (-10)	7.6 (25)	0.16 (31)	Unsteady
16	12.2 (40)	1.5 (5)	3.0 (10)	0 (0)	
17	12.2 (40)	1.5 (5)	3.6 (12)	1.62 (320)	
18	12.2 (40)	1.5 (5)	7.6 (25)	0 (0)	
19	18.3 (60)	0 (0)	3.0 (10)	2.44 (480)	
20	18.3 (60)	0 (0)	3.6 (12)	6.37 (1254)	
21	18.3 (60)	0 (0)	7.6 (25)	0.91 (180)	
22	18.3 (60)	-3.0 (-10)	3.0 (10)	1.1 (215)	
23	18.3 (60)	-3.0 (-10)	3.6 (12)	2.1 (410)	
24	18.3 (60)	-3.0 (-10)	7.6 (25)	1.0 (198)	
25	18.3 (60)	3.0 (10)	3.0 (10)	1.2 (240)	
26	18.3 (60)	3.0 (10)	3.6 (12)	2.8 (560)	
27	18.3 (60)	3.0 (10)	7.6 (25)	0.81 (160)	

* X is horizontal distance along MVU center line measured from MVU discharge face,
Y is horizontal distance from MVU center line in radial direction, Z is elevation above ground level.

** Air speed is a time-averaged value measured over a 10 minute interval at quasi-steady conditions.

4. MODEL

The governing equations of flow and heat transfer are the Navier-Stokes equations, thermal energy equation, and the k-ε transport equations for the modeling of turbulence. These equations are solved using the CFX-TASCflow version 2.10.0 CFD software package. Details of the governing equations are provided in the TASCflow Theory Documentation, [5], and are presented briefly here. Mass and momentum balance equations in terms of Cartesian flow velocity components, u_i, fluid density, ρ, effective fluid dynamic viscosity, μ_{eff}, fluid pressure, P, and other body forces, S_{ui}, are

$$\frac{\partial}{\partial t}\left(\int_v \rho dv\right) + \int_s \rho u_j dn_j = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}\left(\int_v \rho u_i dv\right) + \int_s \rho u_j u_i dn_j = -\int_s P dn_i + \int_s \mu_{eff}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) dn_j + \int_v S_{u_i} dv \qquad (2)$$

The thermal energy balance equation is derived from the first law of thermodynamics and for turbulence closure the well-known k-ε model is used. These equations result in scalars (ϕ) system of the unsteady convection-diffusion transport equations with effective diffusivity, Γ_{eff}, and their respective source (sink) terms

$$\frac{\partial}{\partial t}\left(\int_v \rho \phi dv\right) + \int_s \rho u_j \phi dn_j = \int_s \Gamma_{eff}\left(\frac{\partial \phi}{\partial x_j}\right) dn_j + \int_v S_\phi dv \qquad (3)$$

These equations involve volume, v, and surface, s, terms that are integrated over discrete control volumes in a finite volume scheme. The discretization of the physical domain was performed using the ICEM-CFD grid generation software, [6], which provided hexahedral control volumes. A typical grid is shown in Figure 3.

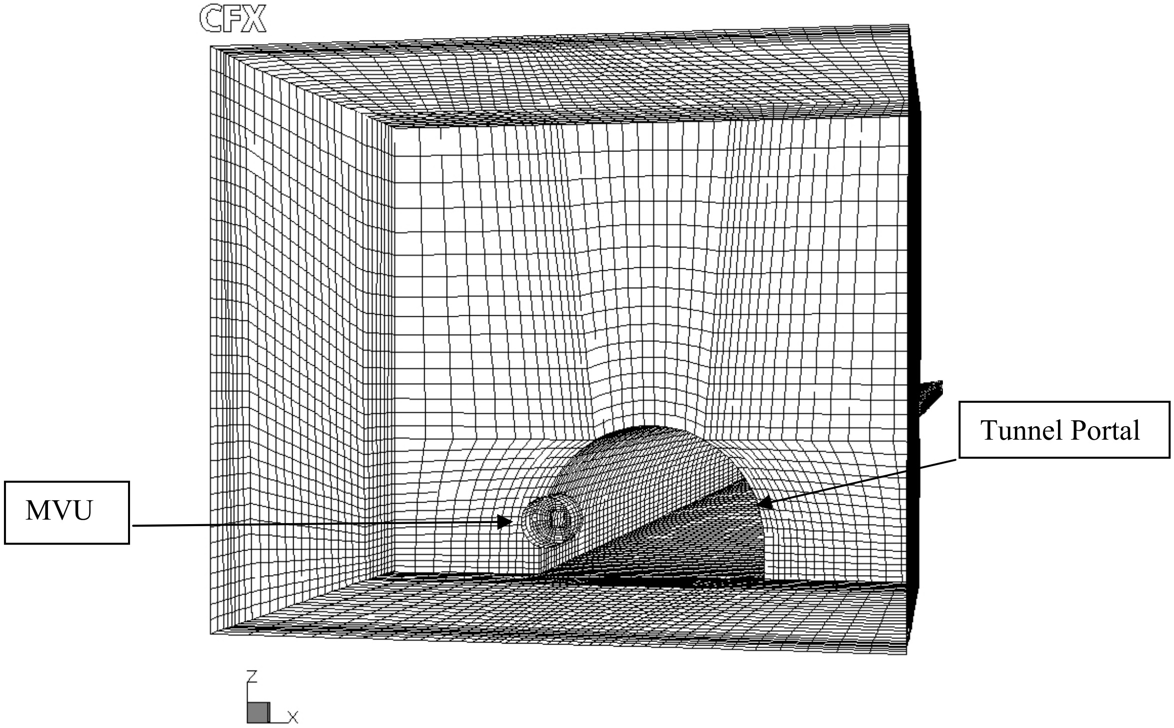


Figure 3. Typical computational grid

The computational domain included the tunnel plus a rectangular area “outside” the tunnel, within which the MVU is located. The open boundaries of the outside area were set far enough such that their effect on the MVU flow would be minimized. The typical outside area is approximately 36m wide (x-dimension) by 23m high (z-dimension) by 20m long (y-dimension), (see Figure 3), using a right-handed Cartesian coordinate system. The far field faces of the outside area were modeled as openings with a linear pressure profile, which decreases with increasing height (z), in order to accurately account for the hydrostatic pressure distribution at these boundaries. Similar pressure boundary conditions were specified at the tunnel exit face. The MVU discharge face was modeled as an inflow boundary with specified mass flow rate. Walls were model as no slip boundaries with estimated roughness values of 0.25cm. The number of nodes within the computational domain depends on the tunnel length. The total number of nodes ranged from about 110,000 for the short tunnel cases to approximately 380,000 for the longest tunnel.

5. RESULTS

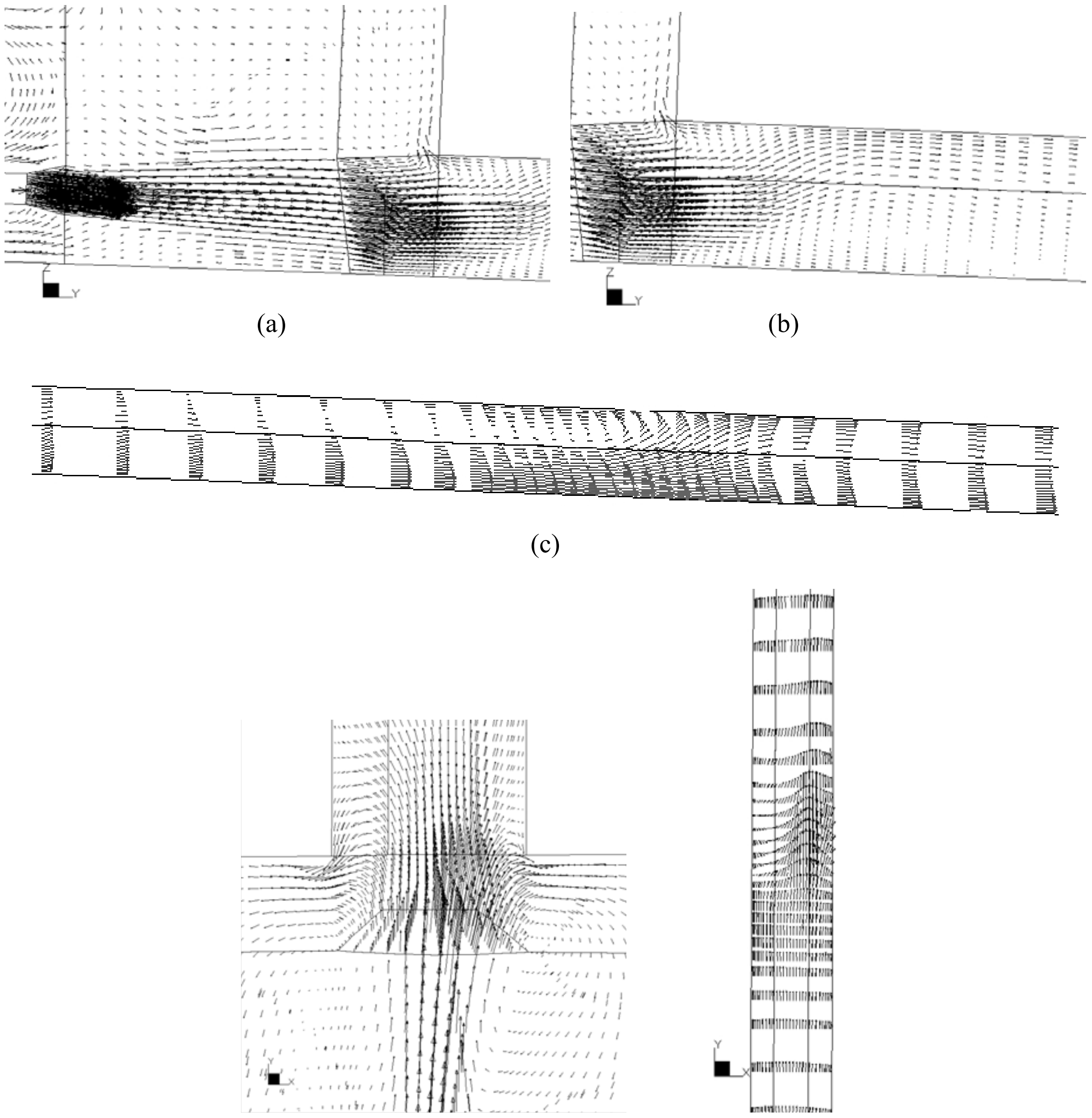
When air enters a tunnel from a portal, certain distance is required before the flow becomes “fully developed”. This distance is referred to as the “entrance flow development length”. In order to isolate the influence of entrance flow development length, tunnel length, and fan location several steady state runs were made. Based on these runs it was observed that in tunnels with length of below 60m the entrance effects dominate the flow characteristics inside the tunnel. In these short-tunnel cases the MVU air stream, which resembles a turbulent jet, encounters a small frictional resistance from tunnel walls. Therefore, negligible pressure gradient develops and entrance development pattern is observed over the entire tunnel length. Maximum tunnel pressure, $P_{max} = P - P_{ambient}$, is zero in this case. In a 137.2m tunnel there is enough length to establish a fully developed turbulent flow and to provide significant wall resistance such that a noticeable value of P_{max}= 1.4 Pa is observed at 82.3m from the tunnel entrance. As the fan is moved inside the 137.2m tunnel (at 33.5m from the portal) the entrance development length reduces the effective tunnel length and smaller flow resistance results in a smaller P_{max} = 0.72 Pa located at 106.7m from the tunnel portal (or 73.2m from the fan discharge location). A similar pattern is repeated for the longer (442m) tunnel. In this case P_{max} = 31.1 Pa at 45.1m for the MVU located at 15.2m outside the tunnel entrance, and P_{max} = 26.3 Pa at 75.3m for a fan located 33.5m inside the tunnel. The simulation results for the longest level tunnel (5.2km) resulted in a P_{max} = 39.3 Pa at 23.8m from the tunnel entrance. It should be noted that for longer tunnels the larger wall friction resistance not only increases P_{max}, but also results in a shorter entrance flow development length. The next task was to evaluate the grade effects. For this, the longest tunnel case was run with a negative 4% grade. In this case P_{max} = 2547 Pa at the tunnel exit (5.2km). By comparison with the level tunnel case it was concluded that the hydrostatic pressure, which is 11.4 Pa per vertical meter (at sea level and 20°C), dominates the pressure distribution and magnitude in tunnels with any significant change in elevation. Table 2 provides a summary of these cases.

Table 2. Tunnel length and grade effects on pressure distribution in the tunnel.

Case (run)	Tunnel Length (m)	Grade %	Fan Location[1] (m)	P_{max} (Pa)	P_{max} Location[1] (m)	$P_{Hydrostatic}$ (Pa)
1	60.9	0	-15.2	0.0	60.9	0
2	137.2	0	-15.2	1.4	82.3	0
3	137.2	0	33.5	0.72	106.7	0
4	442	0	33.5	31.1	45.1	0
5	442	0	33.5	26.3	75.3	0
6	5166	0	-15.2	39.3	23.8	0
7	5166	4%	-15.2	2547	5166	2508

1- Positive value indicates distance inside the tunnel from tunnel entrance. Negative value indicates distance outside the tunnel from tunnel entrance.

As the next step, the simulation involving a fire in the tunnel was performed to examine the buoyancy and throttling effects of the fire on the ventilation flow pattern. This particular case required small time steps in order to maintain the numerical stability of the simulation. The simulation was not carried to full convergence due to computational time constraints and the mass balance was within approximately 12% of the MVU mass flow rate. However, we feel that the basic features of the flow were developed sufficiently to provide qualitative representation of the flow characteristics. Figure 4 shows the velocity vectors in various Cartesian planes near the tunnel entrance and in the vicinity of the fire. Velocity vectors near the tunnel entrance show the spread of the air stream from the MVU as it approaches the tunnel entrance. Near the fire, transverse buoyancy driven flow interacts with the axial ventilation flow and causes circulation and some backlayering of the hot gases. The fire is located off center and this asymmetry results in three dimensional flow patterns near the fire.



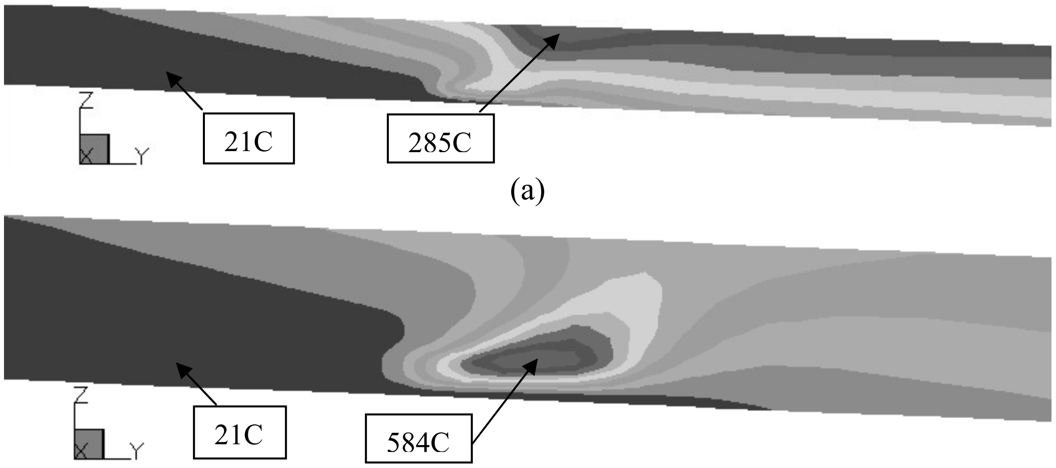
(a) (b)

(c)

(d) (e)

Figure 4. Velocity vectors in (a) vertical yz plane between the MVU and tunnel entrance, (b) vertical yz plane at the tunnel entrance, (c) vertical yz plane near the fire region, (d) horizontal xy plane near tunnel entrance, and (e) horizontal xy plane at the fire zone.

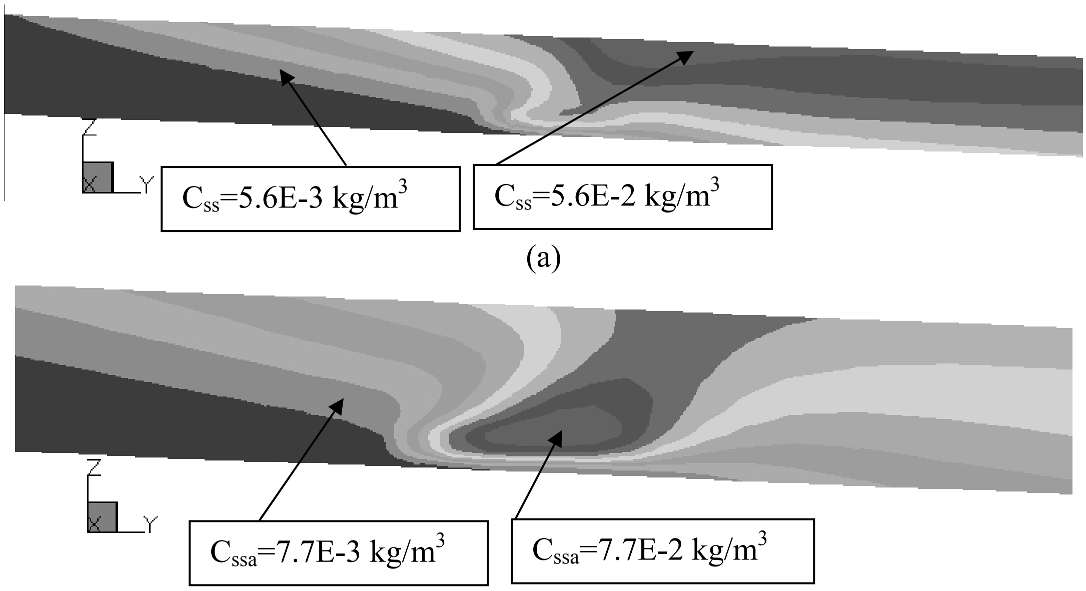
The temperature contour plot near the fire is shown in Figure 5. This figure shows the temperature contours in the vicinity of the fire in the yz plane at x=0 (a), and x=1.5m (b) planes. The temperature range is 21C to 285C in the x=0 (a) plane, and 21C to 584C in the x=1.5m (b) plane, which passes through the off centered fire. The majority of the hot gases from the fire are being pushed towards the exit portal of the tunnel. The large grade (4%) coupled with the relatively long tunnel (5.2km) causes limited backlayering of the hot gases. This is because the MVU produces an average speed of 1.1 m/s, which is less than half the calculated critical velocity (2.5 m/s) needed to completely prevent any backlayering. Therefore, this tunnel configuration can be considered as a limiting case for operation of a single 1.5m diameter MVU model. Despite limited backlayering the MVU was capable of providing a clearer path to the fire for the rescue and fire fighting operations than would be possible in its absence. However, it should be noted that upon full development of the steady flow hot gases would fill the entire tunnel volume downstream of the fire. The rise in the average air temperature in the large volume downstream of the fire would increase the buoyancy of the air and consequently could increase the backlayering. The contours of the smoke density, C_{ss}, have similar patterns as those of the temperature and are shown in Figure 6. The allowable smoke density (based on allowable visibility limits) is C_{ssa}=7.5E-3 kg/m^3, [7], [1].



(a)

(b)

Figure 5. Temperature contours in the yz plane and vicinity of the fire at (a) x=0m and (b) x=1.5m locations.



(a)

(b)

Figure 6. Smoke density contours in the vertical yz plane and in the vicinity of the fire at (a) x=0m and (b) x=1.5m locations.

6. FUTURE WORK

In order to better understand the performance characteristics of the Tempest MVU and to optimize its deployment a more detailed parametric study of the flow phenomena is needed. These parametric studies should consider the effects of MVU position relative to the tunnel portal, MVU flow direction, and combined effects of multiple MVUs. In addition, the use of the MVU is best represented in an unsteady flow model, where a fire-induced buoyant flow is established in the tunnel over a reasonable response time needed for the fire-fighting crew to reach the tunnel. After this response time the MVU is turned on and the unsteady development of fresh air in the tunnel is simulated. Therefore, the next step in a more accurate analysis of the MVU performance is unsteady simulation of the MVU flow development in a tunnel fire. This scenario involves long unsteady runs, which require larger computing resources, time, and effort.

7. CONCLUSIONS

1. The steady state results indicated that the MVU is suitable for emergency ventilation of the prescribed 29.3MW fire in level road tunnels as long as 5.2km. In these level tunnels the MVU was able to establish the critical velocity needed to prevent backlayering of hot gases and provide a clear path for the evacuation, rescue, and fire-fighting operations.
2. In the limiting case with a tunnel length of 5.2km and 4% down grade preliminary results show that the MVU can produce a clear and smoke free path to close vicinity of the fire for fire-fighting efforts. However, the calculated critical velocity of 2.5m/s was not met. The average air velocity at tunnel cross section was approximately 1.1m/s. Therefore, complete prevention of backlayering of the smoke and hot gases was not achieved.
3. In the limiting case maximum temperature of 585^{o}C was observed within the fire region along with a maximum smoke density of 7.7E-2kg/m^3. Both the temperature and smoke density levels quickly fall below the allowable limits of 60^{o}C and 7.5E-3kg/m^3 within one tunnel diameter upstream of the fire.
4. In order to better understand the flow characteristics, and for optimized deployment of the MVU in tunnel fire situations, more parametric studies of the ventilation flow are necessary. These parameters include the MVU position relative to the tunnel portal, flow direction, and multiple MVU operations. Also, for a more realistic simulation of the MVU operation unsteady runs should be performed.

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