CFD SIMULATION ON DIFFUSION OF LEAKED HYDROGEN CAUSED BY VEHICLE ACCIDENT IN TUNNELS

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ABSTRACT

Hydrogen fuel cell vehicles are expected to come into widespread use in the near future. Accordingly, many hydrogen carrying vehicles will begin to pass through tunnels. It is therefore important to predict whether risk from leaked hydrogen accidents in tunnels can be avoided. CFD simulation was carried out on diffusion of leaked hydrogen in tunnels. Three areas of tunnels were chosen for study. One is the typical longitudinal and lateral areas of tunnels, and the others are underground ventilation facilities and electrostatic dust collectors which were simulated with an actual tunnel. The amount of hydrogen leaked was 60m^3 (approximately 5.08 kg), which corresponds to the amount necessary for future fuel cell vehicles to achieve their desired running distance. Analytical periods were the time after leaks began until regions of hydrogen above the low flammability limit had almost disappeared, or thirty minutes. We found that leaked hydrogen is immediately carried away from leaking area under existing ventilation conditions. We also obtained basic data on behavior of leaked hydrogen.

INTRODUCTION

In recent years fuel cell vehicles that use hydrogen as an energy source and exhaust only water have attracted much attention as clean cars. As hydrogen fuel cell vehicles come into more widespread use, we may predict accidents involving these vehicles inside tunnels. However, the equipment in current tunnels was designed with consideration of accidents involving mainly gasoline fuel vehicles. Moreover, to date there are few examples that can be used to predict damage from hydrogen leaks in tunnels [1]. Therefore, it is needed to predict the behavior of hydrogen leaked in tunnels and to obtain data for safety assessments.

1.0 SUBJECTS OF ANALYSIS

1.1 Main tunnel

The present analysis model adopted two representative tunnel shapes: a long model tunnel and an underwater model tunnel [2]. The long model tunnel had a height of 7.0m and was horseshoe shaped with a 2% longitudinal gradient (slope rising toward center of tunnel). The underwater model tunnel had a rectangular cross section with a height of 4.5 m and a 5% longitudinal gradient (trough slope). The space analyzed in both model tunnels has a width of 10 m and was one-way road with 2 lanes, with a length limited to 50 m. The hydrogen leaking vehicle was in the passing lane, with 4 trailing vehicles. Ventilation air speed within the tunnel was taken as a parameter. Fig. 1 shows cross sections of the 2 model tunnels.

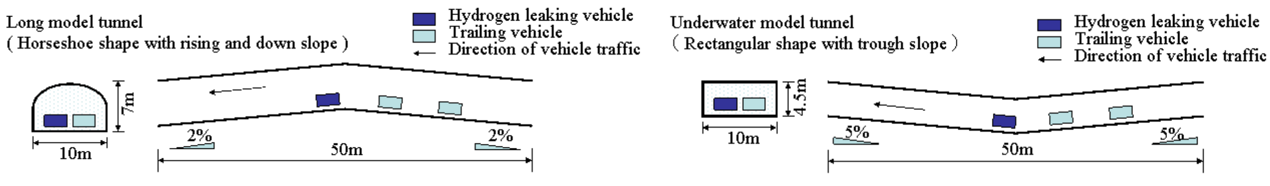


Figure 1. Vehicles arrangement in main tunnel

1.2 Electrostatic dust collector

The model for analysis was the longest road tunnel in Japan, Kanetsu Tunnel. In this tunnel, air in main tunnel is sent to an electrostatic dust collector located in a branch off main tunnel. The air is then cleaned and sent back into main tunnel. The space analyzed in this study was one section of the length of tunnel, plus the branch tunnel from main tunnel out to the location of electrostatic dust collectors. The actual cross-section and longitudinal gradient of both main and branch tunnels were simulated. Hydrogen leak in the simulations occurs at a point of 0 m in the passing lane where main and branch tunnels intersect, and at a point of 25 m to rear. The leaking vehicle and 2 other vehicles are arranged in main tunnel. Fig. 2 shows the tunnel configuration including electrostatic dust collector and the position of the vehicles. For ventilation air velocity, 3 m/s at normal times was adopted.

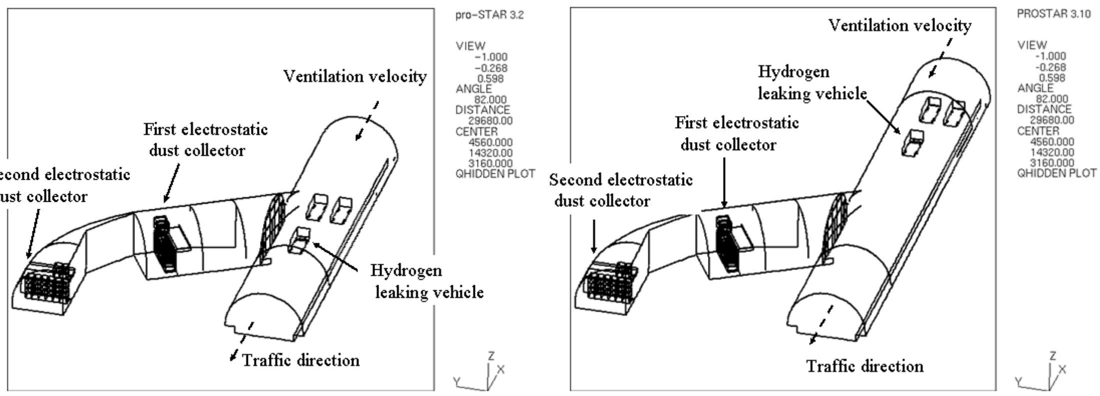


Figure 2. Electrostatic dust collectors and vehicles arrangement

1.3 Exhaust fan (underground ventilation facility)

The simulation model for exhaust fan, similar to that of electrostatic dust collector, was Kanetsu Tunnel. This tunnel is structured so that air inside tunnel is sent to an exhaust fan located in a branch off main tunnel and then released through a vertical shaft opening to outside. The space analyzed in this study, as shown in Fig. 3, is one section of tunnel from its overall length plus branch tunnel from main tunnel out to the position of exhaust fan. Hydrogen leak occurs at point of 0 m in the driving lane in main tunnel where it intersects branch tunnel leading to the underground ventilation facility, and a point 25 m to rear. The leaking vehicle and 2 other vehicles are arranged in main tunnel. Figure 3 shows tunnel configuration including the exhaust fan and the position of vehicles. As above, 3 m/s at normal times was adopted for ventilation velocity.

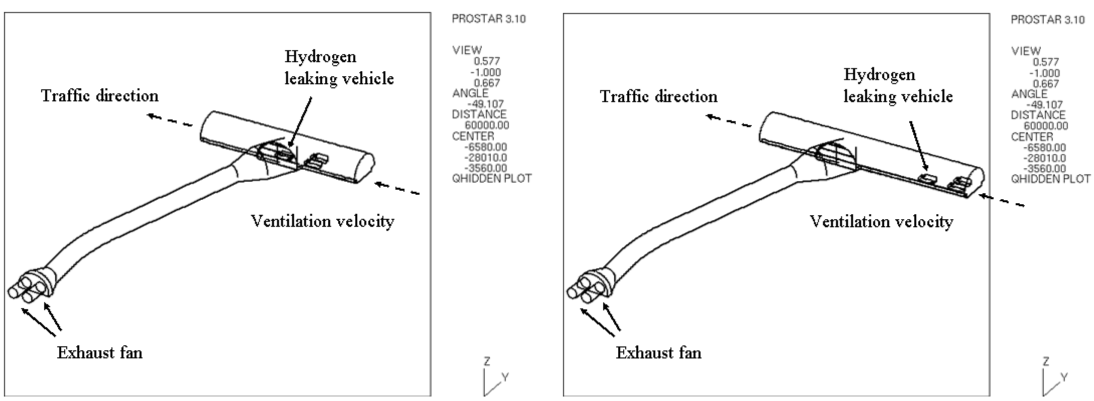


Figure 3. Underground ventilation facility and vehicles arrangement

2.0 NUMERICAL SIMULATION METHOD

2.1 Simulation scenario

In all cases one vehicle was the hydrogen-leaking vehicle, and this hydrogen fuel cell vehicle was fully charged with 60 m^3 of hydrogen. Hydrogen leak occurs in the center of tunnel as a result of accident or another cause. All vehicles are stopped, and hydrogen does not enter the passenger compartments. Hydrogen leak is finished after about 52 sec. This setting was established with consideration of hydrogen release rate from tanks in cases when the pressure release device (PRD) attached to current fuel cell vehicles' high pressure tank is activated. However, although most PRDs are the fusible plug type, for which the ambient temperature around the PRD must reach about 105°C for activation, this condition for this study did not include the presence of fire or other heat source. Simulation cases are shown in Table 1.

Table 1. Simulation cases

Case	**A-1**	**A-2**	**A-3**	**A-4**	**A-5**	**A-6**
Tunnel configuration	Long	Underwater	Long		Underwater	
Ventilation velocity (m/s)	Zero	Zero	1m/s	2m/s	1m/s	2m/s
Case	**B-1**	**B-2**	**C-1**	**C-2**	-	
Tunnel configuration	Electrostatic dust collector		Underground ventilation facility		-	
Leaking vehicle position (m)	Point 0	Point 25	Point 0	Point 25	-	
Ventilation velocity (m/s)	3m/s				-	

2.2 Calculation model

The general flow modeling software code STAR-CD was used in the calculation model. The governing equation for flow was taken to be a 3-dimensional non-steady Navier-Stokes equation (continuous, kinetic momentum; including gravitational items). For concentration fields hydrogen and air were applied to a preservation formula expressed with mass fractions. The working fluids were air and hydrogen in standard states. Temperature was constant. The property values of air and hydrogen used are shown in Table 2. The analysis continued 30 min after start of hydrogen leak, or until the concentration reached a steady state (the state when it was judged that the spatial distribution of hydrogen concentration was no longer changing). The turbulence model and other factors used in calculations are shown below [3].

・Turbulence model: Standard k-ε model (high Reynolds number, combined with wall law)

・Difference scheme: Third-order scheme (QUICK) for convection term

・Time integral: Standard implicit method (primary)

・Time step: $\Delta t=0.005$ sec (during leak), $\Delta t=0.2$ sec (after leak is ended)

・Solution: Pressure implicit split operator method (PISO)

Table 2. Property values of hydrogen and air

Air	Density	1.204	[kg/m^3]
	Kinematic viscosity	1.50E-05	[m^2/s]
Hydrogen	Density	8.38E-02	[kg/m^3]
	Kinematic viscosity	1.05E-04	[m^2/s]
Mutual molecular diffusion coefficient [4]		7.77E-05	[m^2/s]

2.3 Boundary conditions and calculation conditions

The area of hydrogen leak was established as a high pressure hydrogen stream underneath the hydrogen vehicle, and separated calculations were made for that stream. Hydrogen stream model for the separated calculations was a cylindrical space with a radius of 0.5 m and height of 0.3 m. An assumed hydrogen tank is adopted for that model and was located above the cylindrical space. The amount of 60m3 hydrogen is stored at 35 MPa in the tank. A diameter of 5.5 mm was selected for size of hydrogen leak hole. Fig. 4 shows schematic diagram of the separated calculation model. From the results of this separated calculation, Hydrogen flow rate and concentration at the sides of this cylinder were obtained. And then these were provided as hydrogen inlet boundary for the overall tunnel calculations. Thus, in tunnel overall, hydrogen was released radially from the surface of a cylinder that was perpendicular to road surface. The results of calculations for hydrogen stream model are shown in Appendix.

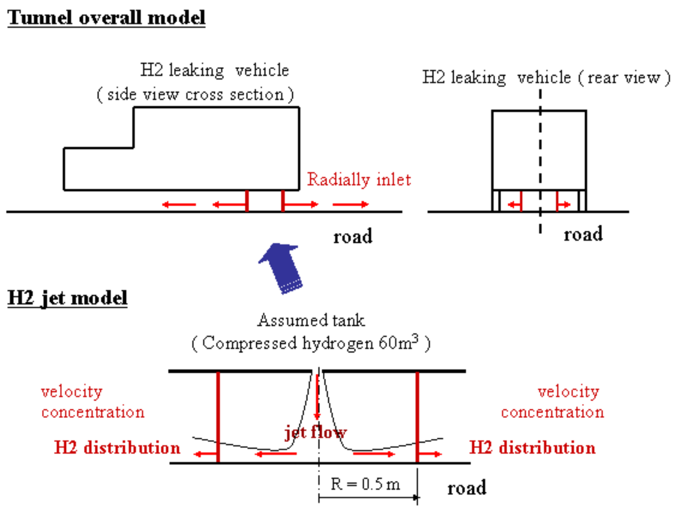


Figure 4. Schematic diagram of separated calculation model

Since the ventilation air velocity in main and branch tunnel was a steady-state flow, hydrogen leak was started at time zero. The ventilation air velocity in main tunnel was uniform from rear of the direction of vehicle travel. The forward end of main tunnel was fixed at atmospheric pressure. In the side tunnel respective inflow boundary conditions were established for the surfaces with electrostatic dust collectors and exhaust fan.

3.0 RESULTS AND DISCUSSION

3.1 Main tunnel

Two respective tunnel cross sections were selected for the results of hydrogen concentrations inside tunnel obtained from the simulation. These were a cross section including the leaking vehicle seen from the side (cross section A), and a cross section including the leaking vehicle seen from above (cross section B). Both are shown in Fig. 5.

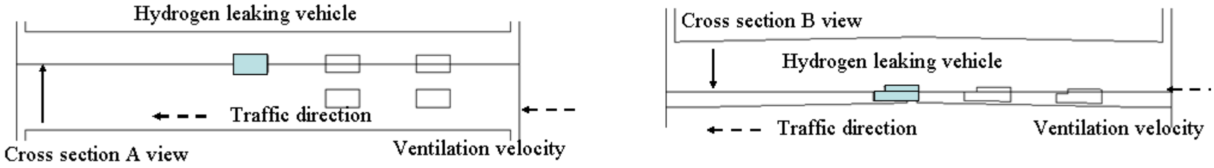


Figure 5. Cross sections for showing results in main tunnel.

3.1.1 Influence of tunnel shape

Hydrogen concentration distribution during the leak (52 sec) in long model tunnel is shown in Fig. 6. Gray indicates areas with concentrations above the low flammability limit (4 vol%). The diffusion direction of hydrogen leaking into main tunnel from beneath the leaking vehicle gradually shifted upwards. Hydrogen moving upwards diffused toward main tunnel exits, but in long model tunnel with a rising slope hydrogen near the ceiling remained at a concentration of above 4% for a relatively long time after hydrogen leak had stopped. In comparison, in underwater tunnel with trough slope hydrogen accumulated near ceiling disappeared in about 412 sec (about 7 min). Fig. 7 shows the results after stop of leak. Red indicates concentrations above the low flammability limit.

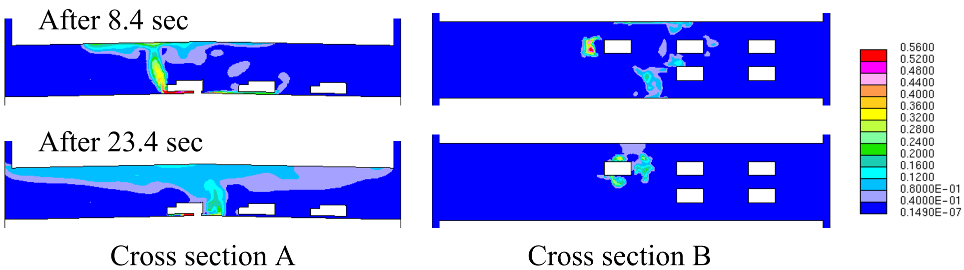


Figure 6. Hydrogen concentration distribution in long model tunnel (during leak)

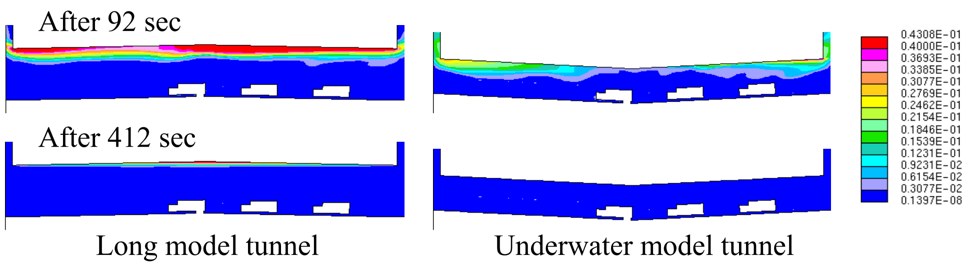


Figure 7. Hydrogen concentration distribution in model tunnels (after leak is ended)

3.1.2 Influence of tunnel ventilation

Since there is ventilation in an actual tunnel, the influence of ventilation air velocity on hydrogen diffusion within tunnel was investigated. Ventilation air velocities were set at 1 m/s and 2 m/s. It is expected that two layers were maintained when fire occurs during times of emergency, an upper layer consisting of smoke, and an air layer that forms beneath the smoke. A velocity of 2 m/s was applied for those two layers [5]. Results for the time during a hydrogen leak are shown in Fig. 8. Gray indicates regions with a hydrogen concentration above the low flammability limit.

In cases when there is no ventilation, nearly the entire upper layer in the longitudinal direction of the tunnel is above the low flammability limit at 23 sec after hydrogen leak started. In contrast, when there is ventilation it was found that nearly all of leaked hydrogen was removed toward the downstream ventilation flow. This is because hydrogen jetting radially from beneath the leaking vehicle has a considerably lower density than the air in tunnel, so that even if hydrogen initially has a large flow rate it loses kinetic momentum after repeatedly colliding with air, and is carried by the ventilation flow.

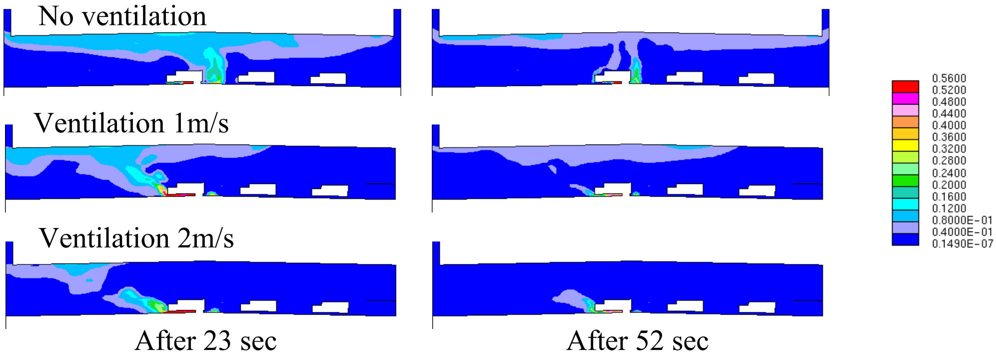


Figure 8. Influence of ventilation in long model tunnel (cross section A)

3.2 Electrostatic dust collector

The positions of results for direction considered to be representative and cross section are shown in Fig. 9.

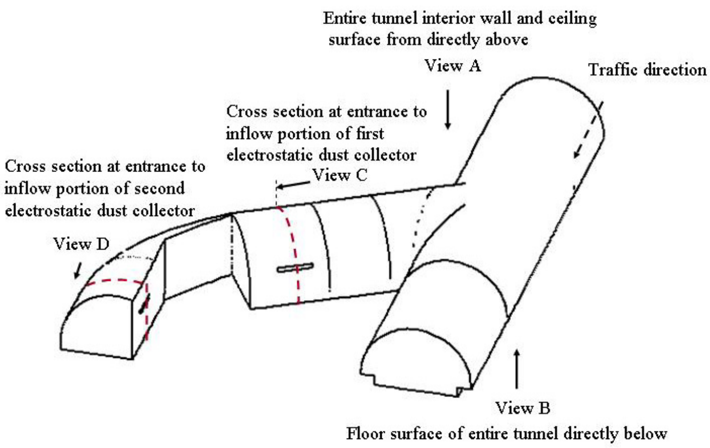


Figure 9. Positions of results shown for electrostatic dust collector

Fig. 10 shows hydrogen concentration distributions at a representative time in main tunnel and branch tunnel containing electrostatic dust collectors during the hydrogen leak in Case B1. Red indicates regions with hydrogen concentrations above 9 vol%, and green indicates concentrations at the low flammability limit. Leaked hydrogen rises as it is carried along the flow in tunnel. Fluid in most of main tunnel is suctioned into the branch tunnel containing electrostatic dust collectors. Hydrogen at concentrations above the low flammability limit (4 vol%) was found to flow into first electrostatic dust collector from about 6 to 21 sec after leak started, and into the second electrostatic dust collector from about 15 to 30 sec. The minimum hydrogen concentration for combustion to propagate downward is 9 vol% [6], and this concentration appears at first electrostatic dust collector from 6 to 13 sec after leak started.

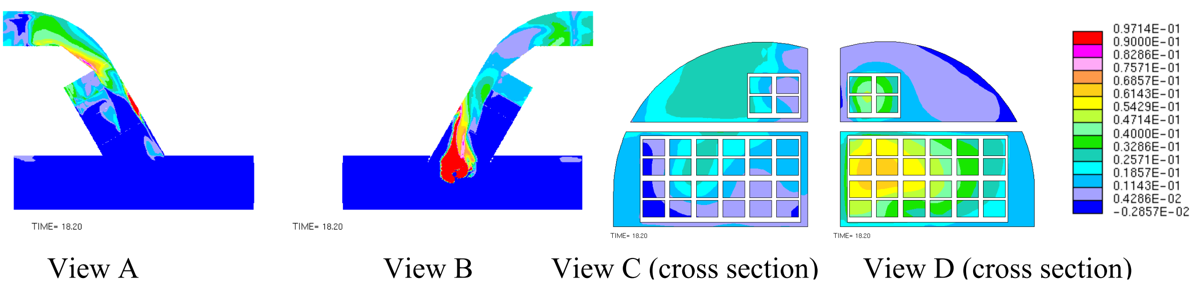
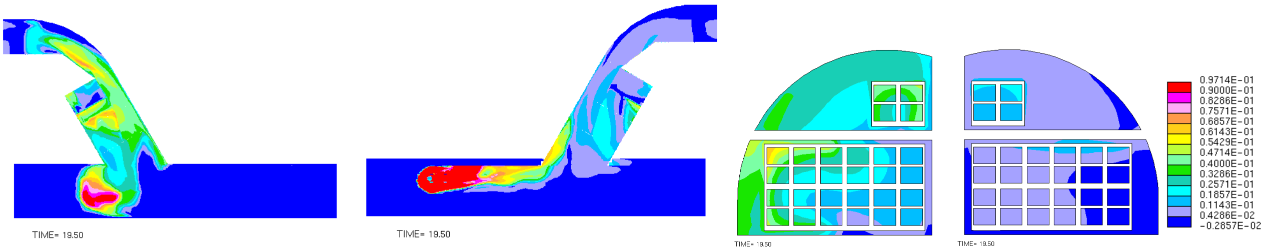


Figure 10. Hydrogen concentration distribution in electrostatic dust collector (after 18.2 sec)

Hhydrogen concentration distribution in electrostatic dust collectors during the leak in Case B2 is shown in Fig. 11. Red indicates hydrogen concentrations above 9 vol%, and green indicates concentrations at the low flammability limit. Leaked hydrogen rises and diffuses while being carried on the flow in tunnel. Most fluid in tunnel flows into the branch tunnel containing electrostatic dust collectors. Hydrogen above the low flammability limit (4 vol%) reaches the intake port of first electrostatic dust collector after about 14 sec, and there is an inflow of hydrogen above 4 vol% until 23 sec. In contrast, hydrogen above 4 volume % is present at the intake port of second electrostatic dust collector from 22 to 28 sec. The inflowing hydrogen concentration did not exceed 9 vol% at either of electrostatic dust collectors at any time throughout the entire analysis period. This is thought to be because the leaking vehicle is located more distant from branch tunnel than in Case B1, so leaked hydrogen arriving at the electrostatic dust collectors is thinned by diffusion.



View A View B View C (cross section) View D (cross section)

Figure 11. Hydrogen concentration distribution at electrostatic dust collector (after 19.5 sec)

3.3 Exhaust fan (underground ventilation facility)

Figure 12 shows the positions of results for direction considered to be representative and cross section.

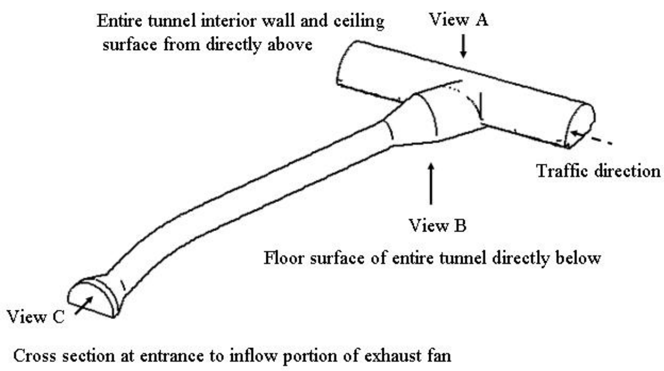


Figure 12. Positions of results shown for exhaust fan (underground ventilation facility)

Fig. 13 shows hydrogen concentration distribution in underground ventilation facility and main tunnel during leak are shown for Case C1. Areas shown in red indicate hydrogen concentrations of above 9 vol%, and those in green indicate concentrations at the low flammability limit. After hydrogen leak started, leaked hydrogen rises as it is carried by the flow in tunnel. Most of the fluid within tunnel flows into branch tunnel. Swirling flows occur in the interior of branch tunnel, and regions with slightly higher hydrogen concentrations carried on these swirling flows appear on both the upper and lower surfaces of branch tunnel. Hydrogen at concentrations above the low flammability limit (4 vol%) is found at the exhaust fan from 15 to 17 sec. Hydrogen concentration did not exceed 9 vol% at any time throughout the analysis.

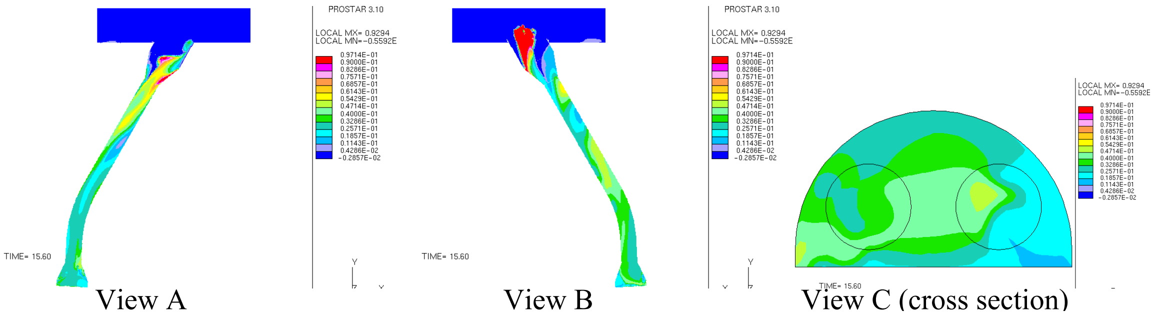


Figure 13. Hydrogen concentration distribution at underground ventilation facility (after 15.6 sec)

Fig. 14 shows hydrogen distribution at underground ventilation facility during leak for Case C2. Red indicates areas with hydrogen concentrations above 9 vol%, and green shows hydrogen concentrations at the low flammability limit. As in Case C1, leaked hydrogen rises as it is carried by the flow in tunnel. Also as in Case C1, swirling flows occur in the branch tunnel with exhaust fan. Hydrogen concentrations above the low flammability limit (4 vol%) were present at the exhaust fan intake from 22 to 25 sec. Hydrogen concentration never exceeded 9 vol% at the exhaust fan intake at any time throughout the analysis.

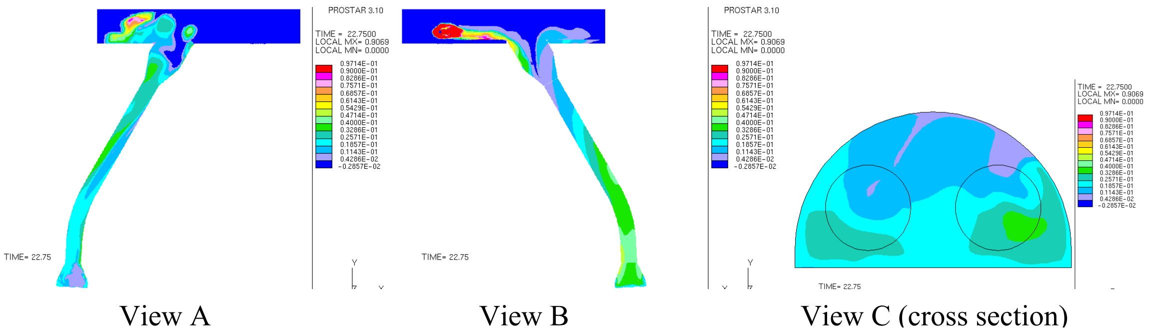


Figure 14. Hydrogen concentration distribution at underground ventilation facility (after 22.75 sec)

4.0 Summary

Simulation of hydrogen diffusion was carried out assuming a case in which 60 m^3 of hydrogen was leaked in tunnel at a jet rate which was the same as that when released by PRDs used in current high pressure gas tanks. The following findings were obtained with regard to diffusion and retention behaviors of leaked hydrogen.

- Because leaked hydrogen has a low density, its kinetic energy is low even if it is released at a high velocity. It therefore decelerates with repeated collisions with air in tunnel, and moves upward as it diffuses.

- When there is no ventilation in tunnel, it is predicted that in tunnels with rising slopes toward the center, such as long model tunnel in this study, Hydrogen at concentrations above the low flammability limit will remain at tunnel ceiling for several dozens of minutes. In tunnels with trough slopes in which the gradient rises toward exits, such as underwater model tunnel here, hydrogen is rapidly cleared from tunnel.

- In cases when ventilation flow exists in a tunnel in ordinary or emergency times, leaked hydrogen will be removed by the ventilation within several dozens of seconds.

- In the power collection portions of electrostatic dust collectors located approximately 15 m and 35 m from the point of confluence with main tunnel (in the present tunnel model), there is a possibility of inflow of hydrogen above the low flammability limit. However, because the hydrogen inflow to power collection portion has a high velocity, the time during which hydrogen above the low flammability limit flows into the power collector is short. Moreover, while there is concern about inflow of hydrogen at the downward propagation concentration of 9 vol% or greater, the time of inflow is even shorter than that of hydrogen above the low flammability limit.

- There is a possibility of inflow of hydrogen above the low flammability limit at the exhaust fan located approximately 87 m from the point of convergence with main tunnel (in the present tunnel model), but the inflow time and volume are small. The distance between main tunnel and exhaust fan is sufficient for the hydrogen to diffuse and mix with the surrounding air; moreover, there are swirling currents in branch tunnel that hasten the diffusion of hydrogen. There is no concern about inflow of hydrogen at concentrations greater than the downward propagation concentration of 9 vol%.

5.0 ACKNOWLEDGMENTS

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6.0 APPENDIX

Steady-state calculations were made for an axisymmetric model of cylindrical shape (radius 0.5 m, height 0.3 m, the diameter of exhaust nozzle 5.5 mm) near outlet of a hypothetical high pressure hydrogen tank (35 MPa, 60 m^3) [7]. The jet velocity was calculated from the high pressure hydrogen tank outlet choke flow (one-dimensional adiabatic expansion). The jet was considered to have stopped after the mass equivalent inside the tank had blown out. Conditions were established to calculate 3 steady flows: that at the time immediately after the outflow started (0% outflow time), 50% outflow time, and 90% outflow time. The results of the flow distributions obtained are shown in Fig. 15. Supersonic flow at the outlet of the tank was slowed by strong percussion waves, then collided with wall and formed a radial jet flow on wall surface [8]. The qualitative aspects of the flow were similar and independent of the hydrogen gas pressure (time) within the tank. The jet flow edge position in radial flow distribution was not time-dependent, and the flow distribution and hydrogen concentration distribution showed similar relations with time.

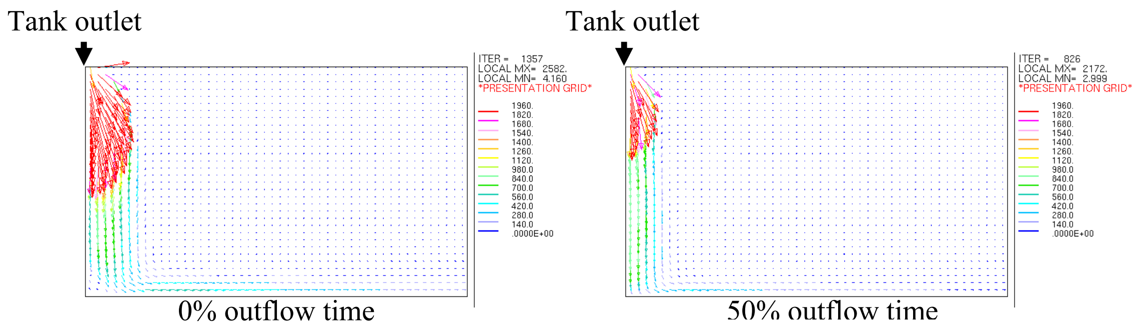

Figure 15. Flow vectors in hydrogen jet model

Using baseline flow distribution (here, t=0, 0%, i.e., distribution at start of outflow), flow distribution V(r, t) changing with time was approximated for t>0. The flow distribution on the outer surface of the cylinder is shown in Fig. 16, but the height of hydrogen jet from road surface is made non-dimensional on the transverse axis Z/Z max.

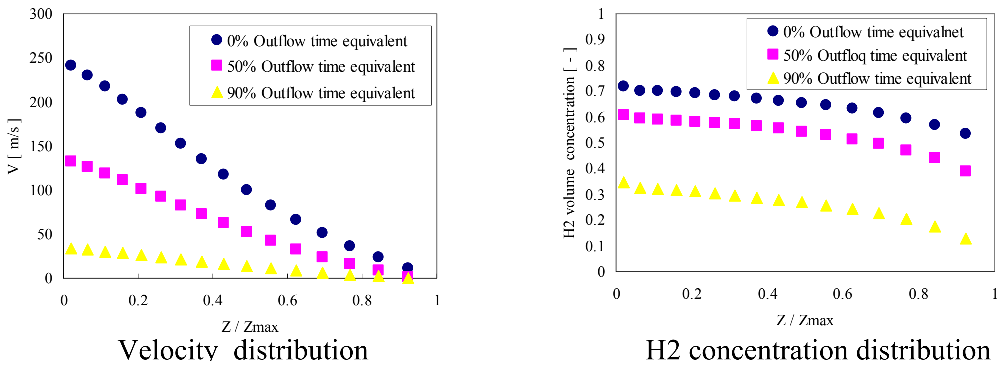

Figure 16. Velocity and hydrogen concentration distribution on cylinder surface in hydrogen jet model