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Computational Fluid Dynamics Simulations of Hydrogen Jet Fires inside a Tunnel

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***Abstract*—Compared with the hydrogen jet fire from a pressure vessel in an open space, the hydrogen jet fire inside a tunnel has a different kind of risk because of the semi-enclosed space. In this study, computational fluid dynamics (CFD) simulations of the hydrogen jet fire from a hydrogen transport vehicle inside a tunnel were carried out. Several different factors, such as hydrogen leakage rate, leakage area, longitudinal ventilation, transverse ventilation and the volume of the tunnel, were considered to analyze the influence on the temperature and diffusion of hydrogen inside the tunnel during the jet fire. The results show that compared with an open space, the hazards of the hydrogen jet fire inside a tunnel lie in not only high temperature but also the accumulation of hydrogen, which may pose a secondary disaster inside the tunnel. In order to control the hazard and avoid a secondary disaster after the hydrogen jet fire happened, enough longitudinal and transverse ventilation is necessary inside the tunnel.**

Keywords—computational fluid dynamics simulations; hydrogen jet fire; tunnel fire; dangerous chemical transport

I. INTRODUCTION

Considering the various advantages of hydrogen fuel and the important role hydrogen plays in chemical industry, it is clear that hydrogen is being widely used in many areas [1-4]. With the wide application of hydrogen, it is unavoidable that a large amount of hydrogen transport vehicles, such as tube trailers, tank trucks and even hydrogen cylinders within vans, will be used in order to support the hydrogen transport [5-6].

As is well known, hydrogen has a low ignition energy suggesting that leaks have a high probability of ignition [7]. If hydrogen leaked from a hydrogen transport vehicle inside a tunnel, then a jet fire caused, it would be riskier than that of an open space [8-11]. In Wu's work, two computational fluid dynamics (CFD) simulations under different power of hydrogen jet fire inside a tunnel were carried out [12]. The work was innovative but the simulations were not comprehensive due to the limitations of calculational conditions.

In this study, one of CFD simulations software, fires dynamics simulator (FDS) was used to simulate the hydrogen jet fire inside a tunnel. FDS is an open source CFD code and is developed based on the Navier-Stokes equations appropriate to low Mach number applications. The code has been widely used in fire research field and its validity has been extensively verified [13-15]. Several different factors, such as hydrogen leakage rate, leakage area, longitudinal ventilation, transverse ventilation and the volume of the tunnel, were considered to analyze the influence on the temperature and diffusion of hydrogen inside the tunnel. The objective of this study is to indicate the hazard of the hydrogen jet fire inside a tunnel and provide some guidance for controlling the hazard and avoiding a secondary disaster after the fire happened.

II. THE PARAMETERS OF SIMULATIONS

In this study, models of the jet fire inside a tunnel were established by PyroSim, which can establish a fire-fighting simulation and invoke FDS to execute the calculation [16]. The tunnel was set as 102 m long and a hydrogen leakage source from a hydrogen transport vehicle located 40 m away from the tunnel entrance which meant there was a 40 m upstream and a 62 m downstream tunnel. The planform of the models was shown as Fig. 1, two slices were set in the middle of the tunnel, one was used to monitor temperature and the other to the diffusion of hydrogen inside the tunnel.

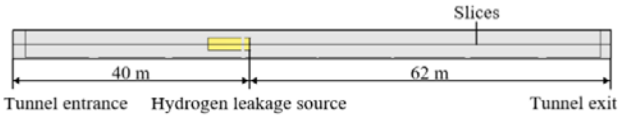

FIGURE I. THE PLANFORM OF THE MODELS

The initial pressure, temperature, mass fraction of oxygen and relative humidity inside the tunnel were set as a standard atmospheric pressure, 20 ℃, 0.232 and 40% respectively. The hydrogen transport vehicle was set as an inert surface which meant it would not be destroyed by jet fire, so the hydrogen leakage source would not change its location during the fire.

All the eight simulations with different parameters were shown as Table 1. Because all the hydrogen would participate in combustion immediately when it was released from the vehicle in these simulations, the prospective power of hydrogen jet fire was determined by hydrogen leakage rate and leakage area. Meanwhile, all the simulations had the same length of tunnel, so the bigger cross-sectional area meant the bigger volume of the tunnel.

TABLE I. ALL THE EIGHT SIMULATIONS WITH DIFFERENT PARAMETERS

No.	The cross-sectional area of tunnel	The speed of longitudinal ventilation [m/s]	The speed of transverse ventilation [m/s]	Leakage area [m^2]	Leakage rate [kg/ m^2·s^{-1}]	The prospective power of fire [MW]
1	5 m × 5 m	0	0	0.25	0.169	6
2	5 m × 5 m	2.5	0	0.25	0.169	6 [12]
3	5 m × 5 m	2.5	0	0.25	0.845	30 [12]
4	5 m × 5 m	2.5	0	0.125	1.69	30
5	5 m × 5 m	2.5	0	0.5	0.4225	30
6	7 m × 7 m	2.5	0	0.25	0.845	30
7	5 m × 5 m	2.5	2.5	0.25	0.845	30
8	5 m × 5 m	5	0	0.25	0.845	30

If a hydrogen transport vehicle was impacted by another car in a traffic accident, compared with the common structural failure of a pressure vessel in a factory, there would be a larger crevasse created on the pressure vessel of the vehicle. For this reason, the leakage areas of the simulations were set as 0.125, 0.25 or 0.5 m2, which was much larger in order to distinguish a traffic accident from a common structural failure in a factory.

III. THE SIMULATIONS OF THE TEMPERATURE INSIDE THE TUNNEL

A. The Influence of the Power of Fire and Longitudinal Ventilation on Temperature

The power of fire and longitudinal ventilation has a decisive influence on the development of disaster in a tunnel fire [17-18]. The shapes of flame in simulations 1 to 3 were shown as Fig. 2. These figures were generated by Smokeview (SMV) which can ensure the visualization of CFD simulations results [19]. Obviously because hydrogen is a known gas which has the minimum density in the world, when there wasn't any longitudinal ventilation, the flame spread vertically inside the tunnel in simulation 1. When there was longitudinal ventilation from the entrance of the tunnel, the flame spread to the downstream tunnel and the bigger power of hydrogen jet fire would lead to a more evident spread.

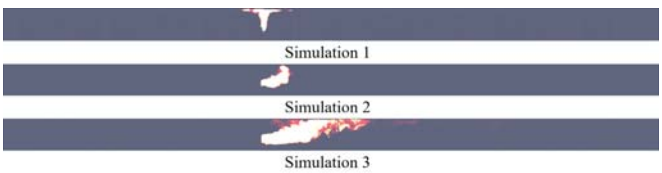

FIGURE II. THE SHAPES OF FLAME IN SIMULATIONS 1 TO 3

Fig. 3 showed the temperature on slices 10 seconds after the fire happened in simulations 1 to 8, Fig. 4 and Fig. 5 showed 30 and 60 seconds respectively. It could be seen that when there wasn't any longitudinal ventilation, temperature was symmetrically distributed inside the tunnel with the vertical direction of the leakage source as an axis in simulation 1. Under the influence of longitudinal ventilation, high temperature appeared in downstream tunnel and the upstream was almost unaffected in simulations 2 and 3. Obviously, a bigger power of fire would result in a faster spread of high temperature in the whole tunnel.

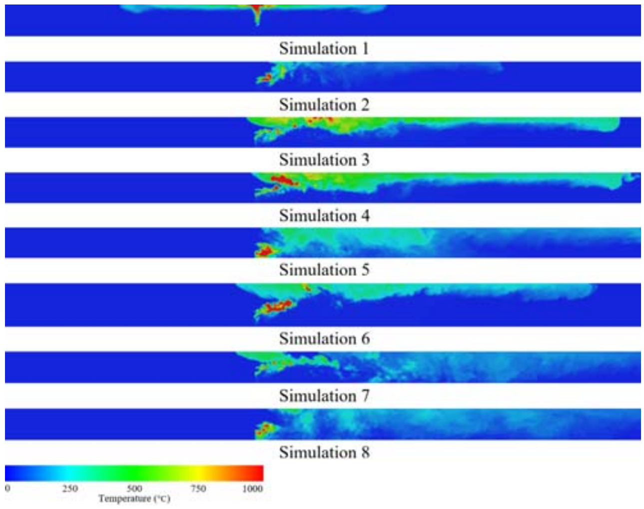

FIGURE III. THE TEMPERATURE ON SLICES 10 SECONDS AFTER THE FIRE HAPPENED IN SIMULATIONS 1 TO 8

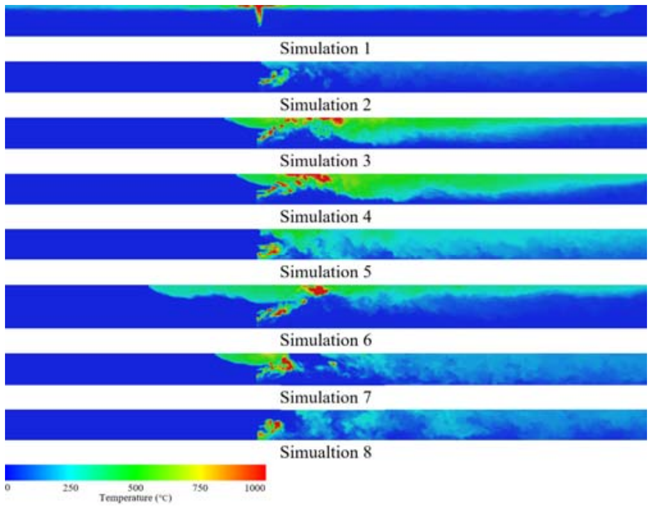

FIGURE IV. THE TEMPERATURE ON SLICES 30 SECONDS AFTER THE FIRE HAPPENED IN SIMULATIONS 1 TO 8

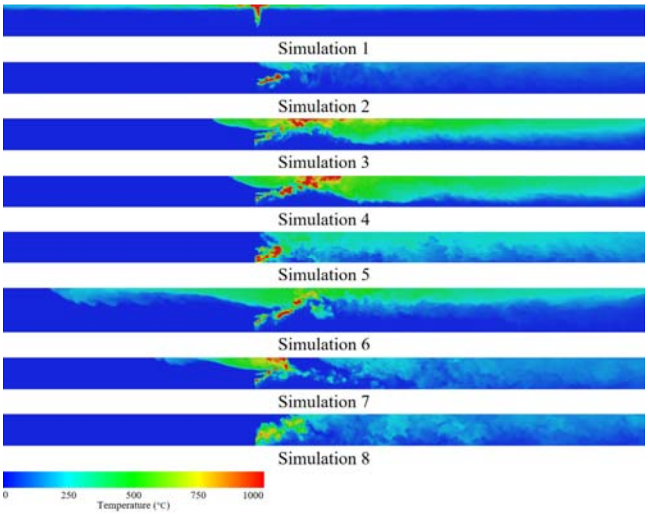

FIGURE V. THE TEMPERATURE ON SLICES 60 SECONDS AFTER THE FIRE HAPPENED IN SIMULATIONS 1 TO 8

As shown in Fig. 3 to Fig. 5, under the influence of the longitudinal ventilation with a faster speed, the temperature of the whole tunnel went down obviously in simulation 8. In fact, comparing the percentile maximum temperatures on slices which were shown as Table 2, the same conclusion can be confirmed which means that longitudinal ventilation is a useful measure to control the high temperature in hydrogen jet fire inside the tunnel, the faster the speed of longitudinal ventilation is, the lower the temperature becomes. As shown in Fig. 5, the temperature of the flame center even began to go down 60 seconds after the fire happened in simulation 8, which had a clear contrast with simulation 3.

TABLE II. PERCENTILE MAXIMUM TEMPERATURES ON SLICES IN ALL THE EIGHT SIMULATIONS

No.	The cross-sectional area of tunnel	The speed of longitudinal ventilation [m/s]	The speed of transverse ventilation [m/s]	Leakage area [m^2]	Leakage rate [$kg/m^2 \cdot s^{-1}$]	The percentile maximum temperature on slices [℃]
1	5 m × 5 m	0	0	0.25	0.169	1238.45
2	5 m × 5 m	2.5	0	0.25	0.169	945.11
3	5 m × 5 m	2.5	0	0.25	0.845	1249.67
4	5 m × 5 m	2.5	0	0.125	1.69	1344.15
5	5 m × 5 m	2.5	0	0.5	0.4225	997.06
6	7 m × 7 m	2.5	0	0.25	0.845	1221.31
7	5 m × 5 m	2.5	2.5	0.25	0.845	1207.14
8	5 m × 5 m	5	0	0.25	0.845	1026.67

B. The Influence of Leakage Area and Leakage Rate on Temperature

All the hydrogen would participate in combustion immediately when it was released from the vehicle in these simulations, so the prospective power of hydrogen jet fire was determined by hydrogen leakage rate and leakage area, which played an important role in the distribution of temperature inside the tunnel during the simulations.

Fig. 3 showed the temperature on slices 10 seconds after the fire happened in simulations 3 to 5, Fig. 4 and Fig. 5 showed 30 and 60 seconds respectively. Meanwhile, considering the percentile maximum temperature on slice in simulation 4 was higher than which in simulation 3 and simulation 3 was higher than simulation 5 as shown in Table 2, it can be concluded that a faster leakage rate will lead to a higher temperature inside the tunnel. The increase of temperature would become slow obviously when the leakage rate was too fast.

C. The Influence of the Volume of Tunnel on Temperature

Fig. 3 to Fig. 5 showed the temperature on slices 10, 30, and 60 seconds respectively after the fire happened in simulations 3 and 6. These two simulations had a same length but different cross-sectional areas of the tunnel which meant the different volumes of the tunnel. The results of these simulations show that a bigger volume can make the increase of temperature become slow inside the tunnel at the beginning of the jet fire, but the temperature can still rise to a high value as the fire goes on. So as shown in Table 2 the percentile maximum temperatures on slices in these two simulations were almost the same.

It could be seen that when the cross-sectional area of the tunnel was 5 m × 5 m, under the influence of longitudinal ventilation, high temperature appeared in downstream tunnel and the upstream was almost unaffected. But in simulation 6, the upstream tunnel was affected conspicuously under a bigger volume of the tunnel even there was longitudinal ventilation, this phenomenon may due to the heat transfer provided by sufficient oxygen.

D. The Influence of Transverse Ventilation on Temperature

Compared with simulation 3, transverse ventilation was given at the top of the downstream tunnel 5 m away from hydrogen leakage source in simulation 7. The area of transverse ventilation vent was set as 5 m × 5 m and the speed of transverse ventilation was 2.5 m/s which was same as the longitudinal ventilation.

As shown in Fig. 3 to Fig. 5, the temperature of the downstream tunnel went down obviously due to the transverse ventilation in simulation 7. It can be concluded that transverse ventilation is also a useful measure to control the high temperature in a hydrogen jet fire inside the tunnel.

However, a transverse ventilation vent couldn't control the high temperature of upstream tunnel in simulation 7, so as shown in Table 2 the percentile maximum temperature on slices in simulations 3 and 7 was almost the same. If transverse ventilation is taken to control the high temperature of a tunnel during a hydrogen jet fire, several vents are necessary to be set.

IV. THE SIMULATIONS OF THE DIFFUSION OF HYDROGEN INSIDE THE TUNNEL

A. The Influence of the Power of Fire and Longitudinal Ventilation on the Diffusion of Hydrogen

Fig. 6 showed the diffusion of hydrogen on slices 10 seconds after the fire happened in simulations 1 to 8, Fig. 7 and Fig. 8 showed 30 and 60 seconds respectively. The percentile maximum value of hydrogen mole fraction in contour diagrams was 0.04, meaning that the volume concentration of hydrogen was 4%, which was the lower explosive limit (LEL) of hydrogen.

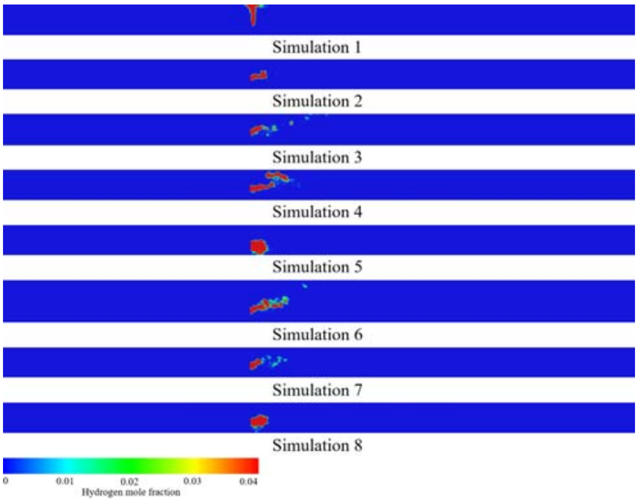

FIGURE VI. THE DIFFUSION OF HYDROGEN ON SLICES 10 SECONDS AFTER THE FIRE HAPPENED IN SIMULATIONS 1 TO 8

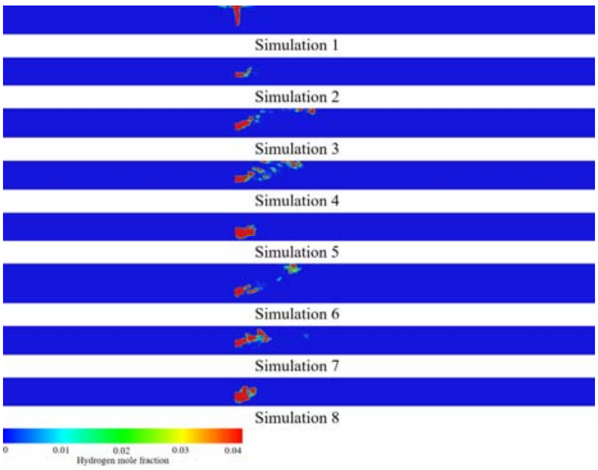

FIGURE VII. THE DIFFUSION OF HYDROGEN ON SLICES 30 SECONDS AFTER THE FIRE HAPPENED IN SIMULATIONS 1 TO 8

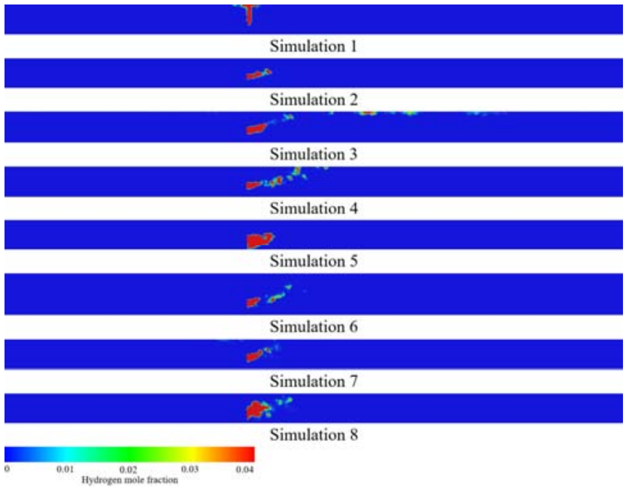

FIGURE VIII. THE DIFFUSION OF HYDROGEN ON SLICES 60 SECONDS AFTER THE FIRE HAPPENED IN SIMULATIONS 1 TO 8

Compared with simulation 2, because the environment of the tunnel could not provide sufficient oxygen into the combustion under a bigger prospective power of hydrogen jet fire, there was a hydrogen layer accumulating at the top of the downstream tunnel in simulation 3. It can be concluded that compared with the hydrogen jet fire in an open space, the hazards of the hydrogen jet fire inside a tunnel lie in not only high temperature but also the accumulation of hydrogen, which may pose a secondary disaster inside the tunnel.

When the longitudinal ventilation of tunnel was enough to provide sufficient oxygen into the fire, the accumulation of hydrogen could be avoided in simulation 8. Sufficient oxygen may lead to a big power of fire but as shown in Table 2 the longitudinal ventilation could also control the temperature inside the tunnel. It can be concluded that in the hydrogen jet fire inside a tunnel, longitudinal ventilation can not only control the high temperature, but also avoid the accumulation of hydrogen.

B. The Influence of Leakage Area and Leakage Rate on the Diffusion of Hydrogen

Fig. 6 to Fig. 8 showed the diffusion of hydrogen on slices 10, 30, and 60 seconds respectively after the fire happened in simulations 3 to 5. It can be concluded that a faster leakage rate will lead to a faster diffusion of hydrogen. However, as shown in Fig. 8, compared with simulation 3 if the leakage rate was too fast, hydrogen could not diffuse further to a far location away from leakage source inside the tunnel in simulation 4. The accumulation of hydrogen happened just near the leakage source, this phenomenon may because sufficient oxygen was involved into the combustion under a too fast hydrogen leakage rate and then hydrogen was consumed more compared with a slow leakage rate.

C. The Influence of the Volume of Tunnel on the Diffusion of Hydrogen

As shown in Fig. 6 to Fig. 8, under a bigger volume of the tunnel the further accumulation of hydrogen was avoided in simulation 6. Meanwhile, considering the simulations of temperature inside the tunnel, it can be concluded that the hydrogen jet fire inside a small tunnel is more dangerous than inside a big one.

D. *The Influence of Transverse Ventilation on the Diffusion of Hydrogen*

Fig. 6 to Fig. 8 showed the diffusion of hydrogen on slices 10, 30, and 60 seconds respectively after the fire happened in simulations 3 and 7. The results of these two simulations show that the further accumulation of hydrogen inside the downstream tunnel can be avoided under the influence of transverse ventilation.

It should be noted that if the transverse ventilation vent is far away from leakage source, once hydrogen has already accumulated to a dangerous concentration at the top of tunnel after jet fire happened and then hydrogen layer moves to the location near the vent, the transverse ventilation may provide oxygen into the hydrogen layer with a high temperature and cause a secondary disaster [20]. Therefore, several vents of transverse ventilation are necessary inside a tunnel in order to avoid the accumulation of hydrogen in a hydrogen jet fire.

V. CONCLUSIONS

In this study, CFD simulations of hydrogen jet fires inside a tunnel were carried out. According to the results of simulations, major findings include:

1. Compared with an open space, because a tunnel is a semi-enclosed space which cannot provide sufficient oxygen, once a hydrogen jet fire happened inside, the hazards of the fire lie in not only high temperature but also the accumulation of hydrogen, which may pose a secondary disaster inside the tunnel.

2. A faster leakage rate will lead to a higher temperature and a faster diffusion of hydrogen inside the tunnel during a hydrogen jet fire. But the increase of temperature will become slow obviously when the leakage rate is too fast. Meanwhile under the influence of a too fast leakage rate, hydrogen cannot diffuse further to a far location away from leakage source inside the tunnel which means the accumulation of hydrogen will happen just near the leakage source.

3. Because of the higher temperature and the faster diffusion of hydrogen, the tunnel with a smaller volume is easier to induce a secondary disaster than those with a bigger volume when a hydrogen jet fire happened inside.

4. Sufficient ventilation, including longitudinal and transverse ventilation is a useful measure to control the high temperature and the diffusion of hydrogen in hydrogen jet fires inside a tunnel.

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