INVESTIGATION ON COOLING EFFECT OF WATER SPRAYS ON TUNNEL FIRES OF HYDROGEN

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ABSTRACT

As one of the most promising renewable green energies, hydrogen power is a popularly accepted option to drive automobiles. Commercial application of fuel cell vehicles has been started since 2015. More and more hydrogen safety concerns have been considered for years. Tunnels are an important part of traffic infrastructure with a mostly confined feature. Hydrogen leak followed possibly by a hydrogen fire is a potential accident scenario, which can be triggered trivially by a car accident while hydrogen powered vehicles operate in a tunnel. Water spray is recommended traditionally as a mitigation measure against tunnel fires. The interaction between water spray and hydrogen fire is studied in a way of numerical simulations. By using the computer program of Fire Dynamics Simulator (FDS), tunnel fires of released hydrogen in different scales are simulated, coupled with water droplet injections featured in different droplet sizes or varying mass flow rates. The cooling effect of spray on hot gases of hydrogen fires is apparently observed in the simulations. However, in some circumstance, the turbulence intensified by the water injection can prompt hydrogen combustion, which is a negative side-effect of the spray.

Key Words: tunnel fire; hydrogen fire; hydrogen safety; water injection; water spray; hydrogen-powered vehicle.

1 INTRODUCTION

The improvement of living standards and the rapid development of technology are based on the consumption of energy resources. People relied on wood before the first industrial revolution. Later the age of fossil fuel began and human started to utilize coal and petroleum [1]. Nowadays the demand for energy is still increasing significantly, but conventional energy utilization cannot afford human's ambition. Meanwhile, global warming and air pollution force people to decrease excessive fossil energy consumption, eventually to phase it out.

Therefore, national governments and research institutions try to discover alternative resources and to obtain sufficient supplies of energy in the future, such as nuclear power, solar energy, wind power, hydrogen energy etc. The clean energies make it happened, that people turn more easily into low-carbon life. Among the renewable energies, hydrogen serves as zero-emission fuel [2], which is friendly to the environment. Hydrogen can be utilized in different domains of daily life, like household heating, transport and energy storage, which belong to essential sectors of the low-carbon energy system [3].

Moreover, the preference for transportation needs to be changed to a more sustainable way [4]. Up to now, internal combustion engine is the preferred drivetrain in automobile industry. Recently electric vehicles, including hydrogen fuel cell vehicle (HFCV), are attracting more attention from the whole society and serve as the alternative on sale.

The application of HFCVs brings new challenges to the provision of life safety and surrounding protection at an acceptable risk level [5]. The fuel for HFCV usually is compressed gaseous hydrogen (CGH2). Comparing to gasoline and diesel, different properties of hydrogen result in some new hazards. Hydrogen fire may also present different features from the conventional hydrocarbon fires.

Confined spaces, including traffics tunnel, underground car parks, garages and repair workshops, represent especially critical environment for hydrogen [6]. Increasingly tunnels are built as an essential infrastructure, especially to go through the rugged mountain as a city tunnel or beneath water ways. With the introduction of HFCVs, safety measures of prevention, management of incidents/accidents, fire and explosion protection need to be verified and updated [7]. This study focuses on the interaction between the traditional mitigation measure – water spray and hydrogen fires in traffic tunnels.

The Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) computer code developed by the National Institute of Standards and Technology (NIST). The code models thermally-driven flows by solving numerically a large eddy simulation form of the Navier–Stokes equations appropriate for low-speed, with an emphasis on smoke and heat transport from fires and the evolution of the fires. Therefore, the FDS is chosen to mimic numerically the tunnel fire of hydrogen supressed by water sprays.

2 GEOMETRICAL MODEL OF TUNNEL WITH HFCVS

2.1 Tunnel model

The accident scenario is assumed to take place in a two-way two-lane single-tube tunnel with a rectangular cross section. The shape is often seen for traffic tunnels, underpasses or underground carparks. The straight tunnel section is defined as 20 m long, 9 m wide and 5.8 m high, containing 3 vehicles in the tunnel.

Ventilation is an important measure to control the atmospheric contaminations in tunnels and to facilitate evacuations and firefighting operations in emergency. A forced longitudinal ventilation is assumed to the tunnel model as a boundary condition, with a ventilation flow velocity of 3 m/s from one end to other of the tunnel.

The spray nozzle is fixed on the ceiling of the tunnel. In an ideal case, the location of the nozzle is defined exactly above the hydrogen leakage location of the failed HFCV.

2.2 HFCV model and hydrogen source definition

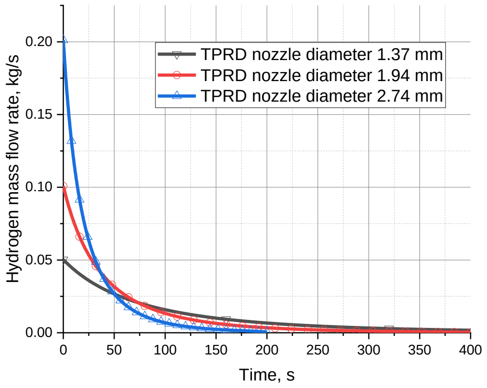


Figure 1. Hydrogen source definitions: blowdown hydrogen mass flow rates decaying along time, corresponding to TPRD diameter of 1.37 mm, 1.94 mm and 2.74 mm, respectively

According to the investigation of on-sale HFCVs, a general dimension of vehicle model is defined as 4.5 m long, 1.8 m wide and 1.6 m high, with a ground clearance of 0.4 m. Hydrogen inventory of each HFCV is 5 kg at a pressure of 70 MPa.

The starting mass flow rates of hydrogen blowdown from storage pressure tanks of HFCV are defined as 0.05 kg/s, 0.1 kg/s and 0.2 kg/s, respectively, which are the maximal flow rates at the beginning moment of blowdown. The three configurations are corresponding to different nozzle diameters of the thermally activated pressure relief device (TPRD) of the storage tank, 1.37 mm, 1.94 mm and 2.74 mm, respectively. The H_2 source is defined according to the EU HyTunnel-CS project descriptions [5, 6]. The mass flow rate decays along the time as the tank depressurizes. The hydrogen is released horizontally.

The adiabatic hydrogen blowdown mass flow rates are shown in Figure 1.

2.3 Numerical mesh

Adaptive mesh scheme is applied to the whole computation domain in the tunnel model. Refined mesh size is defined in the region of hydrogen fire close to the TPRD nozzle; course mesh in the farther region. The total cell number is 11,160 for the 20 x 9 x 5.8 m^3 domain with an average cell size of 0.454 m. The minimal cell size in the hydrogen fire region is 0.125 m, which is estimated based on the characteristic dimension of the hydrogen fire in the lower limit case of 0.05 kg/s of initial hydrogen blowdown mass flow rate. The mesh resolution satisfies the convergence criteria according to the numerical model definition in the FDS code. A grid sensitivity study also proved the claimed convergence of numerical solutions [8].

The geometrical model with mesh is shown in Figure 2, which presents the traffic tunnel with three vehicle models. The blue point on the ceiling stands for the spray nozzle; the red point beneath the vehicle model for the hydrogen release nozzle (TPRD).

It should be emphasized that the detailed structure of hydrogen jet flow is not simulated due to the coarse mesh scheme for computing efficiency consideration. However, this simplification does not influence the focus of the study on thermal effect of hydrogen fire and cooling effect of water spray, because the local complicated jet structure hardly influences the overall thermal effect of the hydrogen fire averaged in the whole domain.

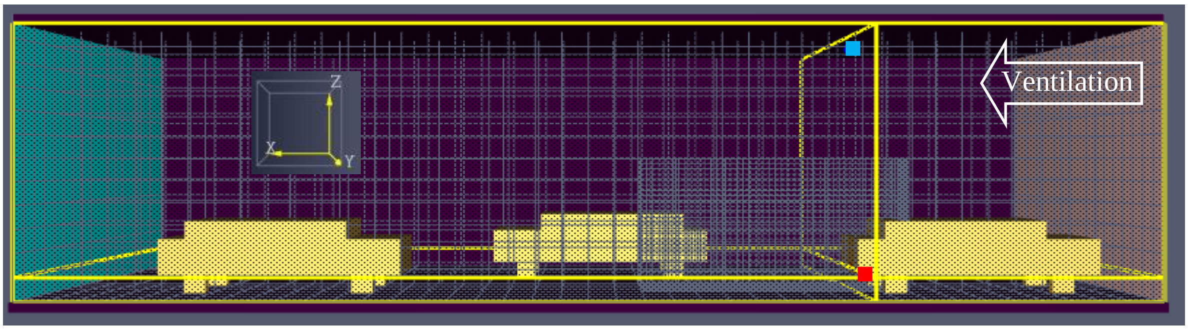


Figure 2. Tunnel geometrical model with adaptive mesh scheme with locations of hydrogen release and water injection

3 THEORETICAL MODELS

3.1 Lagrangian particle model

Liquid droplets of water spray are modelled as Lagrangian particles in the FDS code. Lagrangian particle model focuses on the bi-directional coupling between gas and liquid phases, specifically, on momentum, heat and mass transfers between the particles and the surrounding conveying gases. The three main governing equations are formulated as follows.

Momentum equation:

$$\frac{dm_d\overrightarrow{v_d}}{dt} = m_d\vec{g} - \frac{1}{2}\rho_g C_D \pi {r_d}^2 \|\overrightarrow{v_{rel}}\|\overrightarrow{v_{rel}} \tag{1}$$

where,

m_d: droplet or particle mass, kg,
$\overrightarrow{v_d}$: droplet velocity, m/s,
r_d: droplet radius, m,
ρ_g: surrounding gas density, kg/m^3,
C_D: drag coefficient, which is a function of Reynolds number of droplet,
$\overrightarrow{v_{rel}}$: droplet velocity relative to gas, m/s,

Mass equation:

$$\frac{dm_d}{dt} = -A_{p,s} h_m \rho_g (Y_{\alpha,l} - Y_{\alpha,g}) \tag{2}$$

where,

$A_{p,s}$: surface area of droplet, m^2,
h_m: mass transfer coefficient, m/s, which is relevant to Sherwood number and diffusion coefficient,
$Y_{\alpha,l}$: equilibrium vapor mass fraction,
$Y_{\alpha,g}$: vapor mass fraction.

Energy equation:

$$m_d c_d \frac{dT_d}{dt} = A_{p,s} h\left(T_g - T_d\right) + \dot{q}_r + \frac{dm_d}{dt} h_v \tag{3}$$

where,

c_d: specific heat of droplet liquid, J/(kg·K),
T_d: droplet temperature, K,
T_g: gas temperature, K,
h: heat transfer coefficient, W/(m^2·K), which is relevant to Nusselt number and gas thermal conductivity,
$\dot{q}_r$: thermal radiation rate of droplet, J/s,
h_v; vaporization latent heat of liquid, J/kg.

3.2 Combustion model

In the hydrogen release scenario, hydrogen and air are initially unmixed and the chemical kinetics are fast compared with mixing. Therefore, the turbulent combustion model of eddy dissipation concept (EDC) in the FDS code is applied in the simulations, which is based on a simple "burn on contact" approximation. The details of the combustion model refers to [10].

4 SIMULATION RESULTS

Common boundary conditions for simulations are: ambient temperature: 20 °C; ambient pressure: 101325 Pa; relative humidity in air: 40 %; gravity: 9.81 m/s^2; ventilation velocity (horizontal): 3 m/s.

General configurations for spray model are: operation pressure: 0.5 bar; droplet velocity: 5 m/s; spray angle: 60° to 75°; jet stream type: conical; injected particles per second: 10000.

The water mass flow rate for spray can be configured as 1.34 kg/s (*small*), or 2.74 kg/s (*large*). The droplet size can be configured as 100 μm (*small*), 200 μm (*medium*) or 300 μm (*large*).

As described in Section 2.2, the hydrogen release rate can be 0.05 kg/s (*small*), 0.1 kg/s (*large*) or 0.2 kg/s (*very large*).

By considering the variables, a simulation case matrix is summarized in Table 1.

Table 1 Simulation cases with variant hydrogen release rates, mass flow rates of spray water and spray droplet sizes

	Water spray						No spray
	Small mass flow rate of water (1.34 kg/s)			Large mass flow rate of water (2.74 kg/s)			
	Small droplet (100 μm)	Medium droplet (200 μm)	Large droplet (300 μm)	Small droplet (100 μm)	Medium droplet (200 μm)	Large droplet (300 μm)	
Small mass flow rate of H_2 (max.0.05 kg/s)	*sss*	*ssm*	*ssl*	*sls*	*slm*	*sll*	*alpha*
Large mass flow rate of H_2 (max.0.1 kg/s)	*lss*	*lsm*	*lsl*	*lls*	*llm*	*lll*	*beta*
Very large mass flow rate of H_2 (max.0.2 kg/s)	*xlss*	*xlsm*	*xlsl*	*xlls*	*xllm*	*xlll*	*epsilon*

The 21 simulation scenarios, listed in Table 1, are simulated by using the FDS code. Representative output parameters like gas temperature, absolute humidity and gas volume fraction in certain regions are computed as results to analyze suppression effect of water spray in different configurations.

4.1 Flow field

The flow field in the tunnel model is simulated by solving the compressible fluid dynamic governing equations of mass, momentum and energy. The spray droplet distribution is also simulated by solving the coupled Lagrangian particle dynamic equations. Figure 3 shows an example of flow field and spray droplet distributions in the case of initial max. 0.2 kg/s H_2 release rate and 2.74 kg/s water spray with 100 μm droplet (Case “xlss”) during 2 – 3 s. Six time moments are selected to show the typical distribution patterns of the spray droplets (in blue). In order to show the velocity vectors in the major volume of the model, the upper limit of the colour index for velocity is reduced.

The maximal velocity (in red) is in the vicinity of TPRD, where hydrogen leaks from the vehicle. Right above the location of TPRD, the origin of the spray droplets is on the ceiling. Apparently the ventilation flow is from right hand side to left, which entrains and disperses the spray droplet also from right to left.

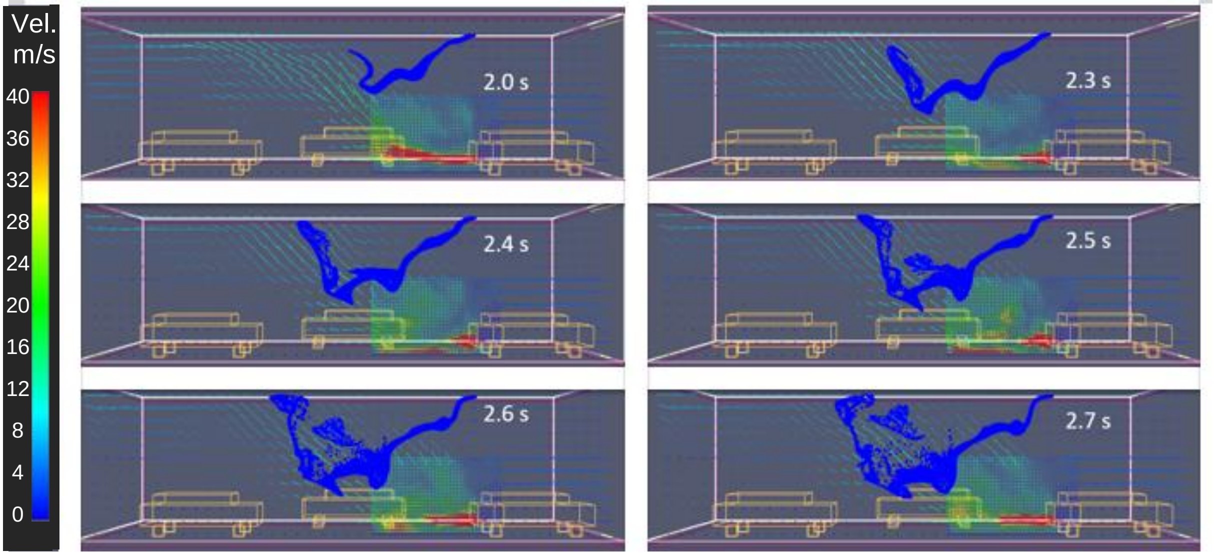


Figure 3. Velocity vector and spray droplet distribution in the computation domain of tunnel in case of initial max. 0.2 kg/s H_2 release rate and 1.34 kg/s water spray with 100 µm droplet (Case "*xlss*") during 2 – 3 s

4.2 Gas temperature

The main goal of the study is to investigate the cooling effect of spray. So concentrations are focused on the gas temperature in the tunnel, specially in the downstream region from the leaking place to the tunnel portal, and the temperature at the tunnel exit. As an example, the temporal evolution of gas temperature distribution in a longitudinal vertical cut of tunnel is shown in Figure 4 for the simulation case "*lls*". The peak temperature is presented in the contour plots because the view plane cuts through the core region of hydrogen fire around the activated TPRD. The decrease of fire dimension along time is mainly due to the decaying hydrogen release rate.

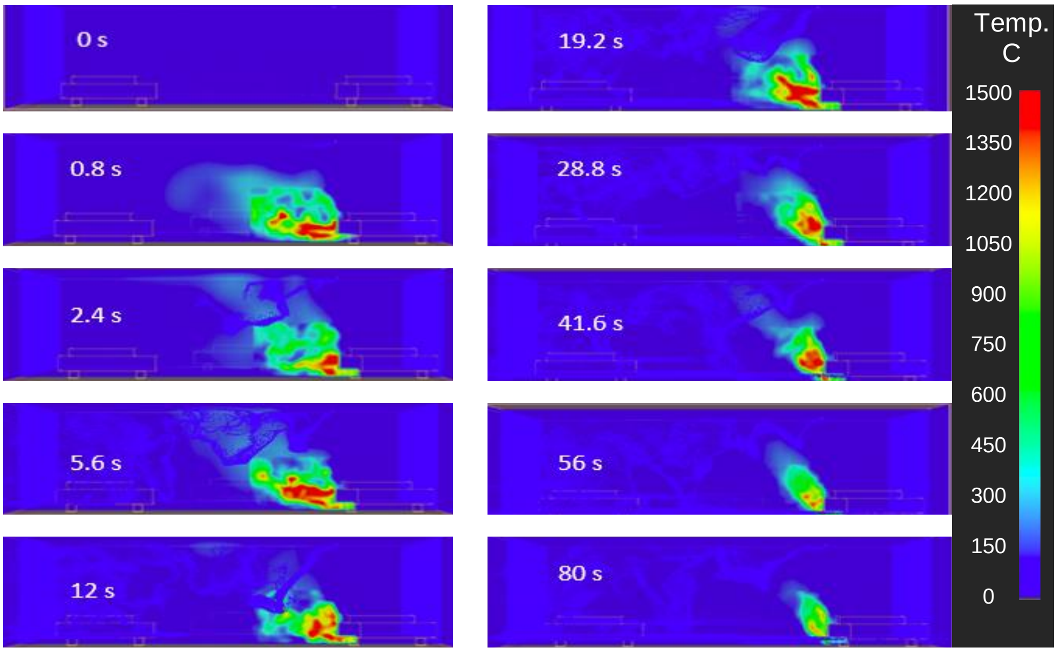
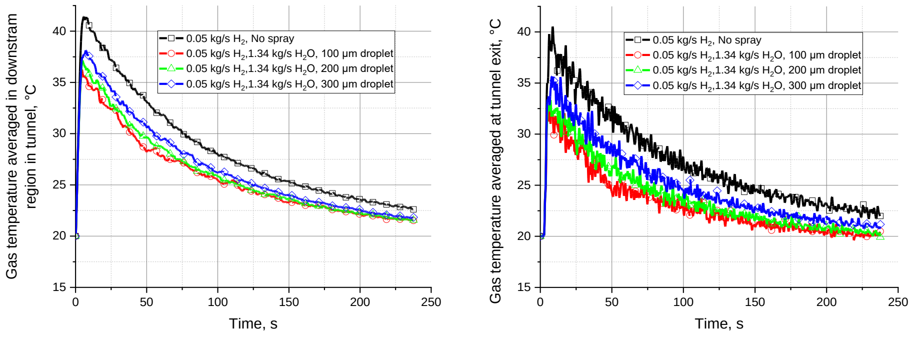


Figure 4. Temperature contour plots in a longitudinal vertical cut of tunnel through TPRD nozzle at different times in case of initial max. 0.1 kg/s H_2 release rate and 2.74 kg/s water spray with 100 µm droplet (Case "*lls*")

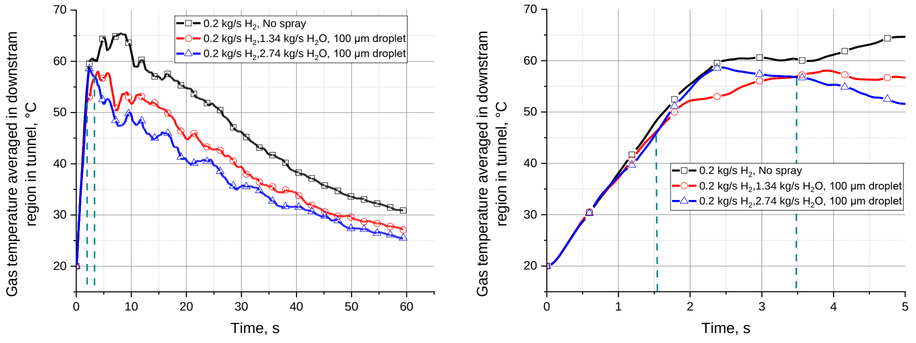
The gas temperatures in the downstream region are shown in Figure 5 (a) for the simulation cases, as an example, of 0.05 kg/s H_2 release rate and a spray water mass flow rate of 1.34 kg/s, with different droplet size configurations. Due to hydrogen combustion, the atmospheric temperature in tunnel climbs to a peak value, then decays along time, mainly because the hydrogen release rate decays. It is clear that the gas temperature (curve in black) without water spray is higher than that with water injection (curves in colour). It proves the cooling effect of water spray. Furthermore, the smaller droplet is, the lower the gas temperature becomes. It is rational that the fine droplet shows a better cooling effect due to the larger surface area to volume ratio of liquid phase.

Accordingly, the gas temperatures at the tunnel portal are recorded in Figure 5 (b). The curves show a similar evolution feature as those in (a), except the stochastic oscillations. By comparing (a) and (b), the temperature at the tunnel exit is lower than the corresponding temperature in the downstream region by 3 – 5 °C, because the portal is the farthest location from the hydrogen fire center.



(a) (b)

Figure 5. Average gas temperatures in the downstream region (a), and at tunnel exit (b), in case of 0.05 kg/s H_2 release rate without and with spray of different droplet sizes



(a) (b)

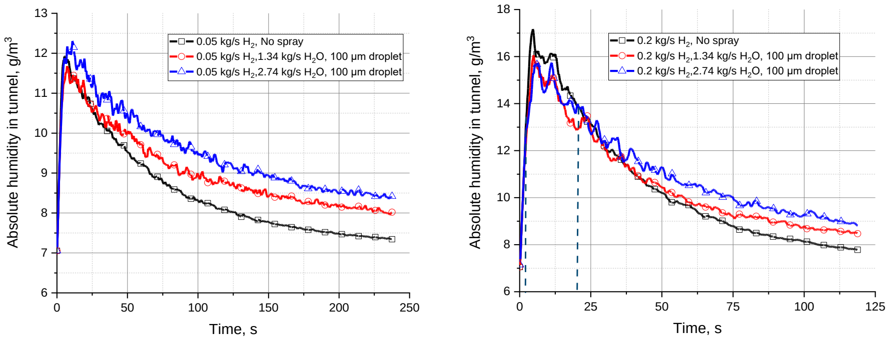
Figure 6. Average gas temperatures in the downstream region in case of 0.2 kg/s H_2 release rate without and with spray of different water mass flow rate: (a) whole view; (b) zoomed view during 0 – 5 s, showing the intensified turbulence effect caused by spray

In case of "*very large*" H_2 release rate 0.2 kg/s, as shown in Figure 6 (a), the suppression effects of different spray water mass flow rates are compared. The plot manifests that the larger water injection flow rate (2.74 kg/s) presents a better cooling effect than the smaller one (1.34 kg/s) in most time. It is certain that more droplets produces more chance to evaporate when they encounter hot gases of hydrogen fire, where explicit heat is converted into latent heat of vapour. Thus, it performs better to cool down the hot atmosphere. However, as shown in the zoomed view Figure 6 (b), there is uncertainty behind the certain fact. During 1.5 – 3.5 s, the gas temperature (in blue) in case of larger water mass flux is even higher than that of smaller flux (in red). A logical explain is that, the turbulence caused by spray intensified the hydrogen combustion in the case of 2.74 kg/s water flow rate. The phenomenon of spray enhanced hydrogen combustion is also formulated in the literatures [9].

4.3 Humidity

The absolute humidity in the tunnel atmosphere is computed in the interaction between hydrogen fire and water spray. Figure 7 (a) shows the humidity evolutions in the case of 0.05 kg/s H_2 release rate. Both hydrogen combustion and evaporation of spray droplets contribute vapour. Due to the two reasons, vapour content in air increases to a peak value then decreases gradually, as the available amount of hydrogen for combustion decays along time. As indicated in the plot, the humidity in the case with water sprays is higher than that in the dry case. It manifests that vaporization dominates the interacting process between fire and liquid water, in most time.

However, as shown in the Figure 7 (b) for the case of 0.2 kg/s H_2 release rate, the absolute humidity in air in the wet cases is even lower than the humidity in the dry case. It implies that the hot vapour generated by combustion is cooled down locally by the spray, and condensates into liquid, during the first 20 s of the simulation time. During this time being, condensation dominates the process. Inversion occurs at about 25 s, and vaporization takes over afterwards.



(a) (b)

Figure 7. Absolute humidity in tunnel atmosphere: (a) *small* H_2 release rate (0.05 kg/s); (b) *very large* H_2 release rate (0.2 kg/s), without and with spray of different water mass fluxes

5 CONCLUSIONS

Water spray can effectively decrease the temperature of hot products of hydrogen fire in tunnels. Spray with fine droplets has better cooling effect than that with larger droplets, due to the larger surface-to-volume ratio liquid phase. In some circumstances, spray induced turbulence may intensify hydrogen combustion, which is a potential disadvantage of water spray. The steam fraction in air increases due to the evaporation of the injected droplets and the production of hydrogen combustion. The humidity increase in the tunnel proves that the hydrogen combustion heat is transferred partially to liquid droplets or converted partially to latent heat of vapour. In a word, water spray can suppress hydrogen fires in tunnels in a sense of cooling, but it is not recommended as an effective distinguisher for hydrogen fires.

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REFERENCES

1. A, Züttel, et al. Hydrogen: the future energy carrier. Philos Trans A Math Phys Eng Sci 2010; 368(1923):3329–42. https://doi.org/10.1098/rsta.2010.0113.
2. S. Dunn. Hydrogen futures: toward a sustainable energy system. International Journal of Hydrogen Energy 2002; 27:235–67.
3. I. Staffell, et al. The role of hydrogen and fuel cells in the global energy system. Energy Environ. Sci. 2019; 12(2):463–91. https://doi.org/10.1039/C8EE01157E.
4. New Energy World Industry Grouping. FCH technologies in Europe: Financial and technology outlook 2014 - 2020. NEW-IG.
5. M. Pursell and M. Garcia. HyTunnel-CS_D1.3_Report on Selection and Prioritisation of Scenarios. Fuel Cells and Hydrogen Joint Undertaking, 2019.
6. Z. Xu, et al.. HyTunnel-CS_D1.1-Report on assessment of effectiveness of conventional safety measures in underground transportation systems and similar confined spaces. Fuel Cells and Hydrogen Joint Undertaking.
7. C. LaFleur, et al. Hydrogen Fuel Cell Electric Vehicle Tunnel Safety Study; 2017.
8. F. Jiang, Study on Effects of Water Sprays and Oxygen Depletion on Hydrogen Fire in Confined Spaces, Master Thesis, Karlsruhe Institute of Technology, May, 2020.
9. G.O. Thomas. On the Conditions Required for Explosion Mitigation by Water Sprays. Process Safety and Environmental Protection 2000; 78(5):339–54. https://doi.org/10.1205/095758200530862.
10. K. McGrattan, S. Hostikka, R. McDermott, J. Floyd, M. Vanella, Fire Dynamics Simulator Technical Reference Guide Volume 1: Mathematical Model, NIST Special Publication 1018-1, Sixth Edition, http://dx.doi.org/10.6028/NIST.SP.1018.