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Numerical Simulation of the Protective Effect of Air Walls on Liquid Hydrogen Leakage

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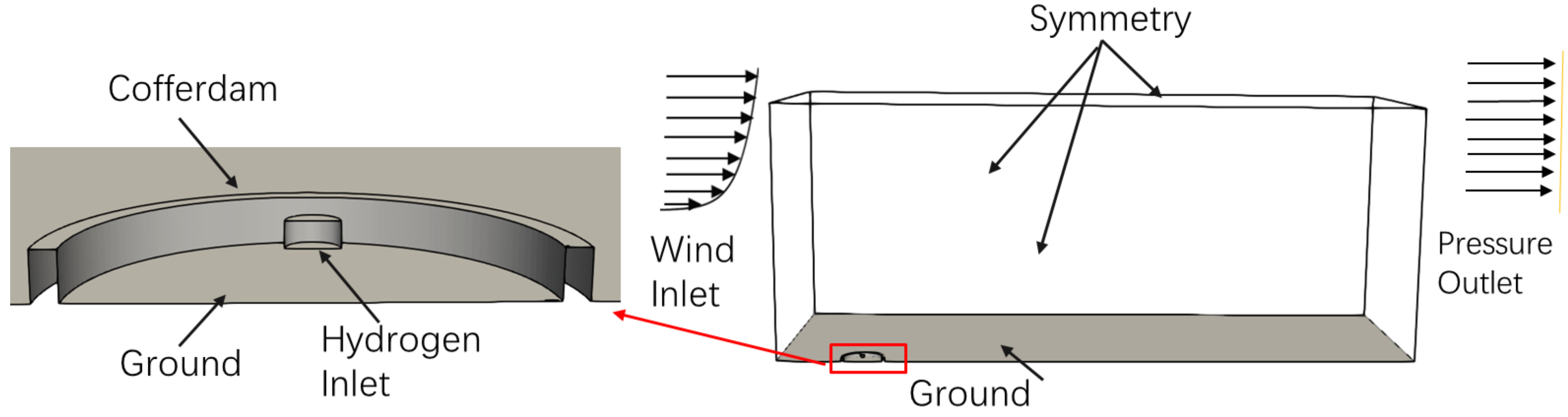
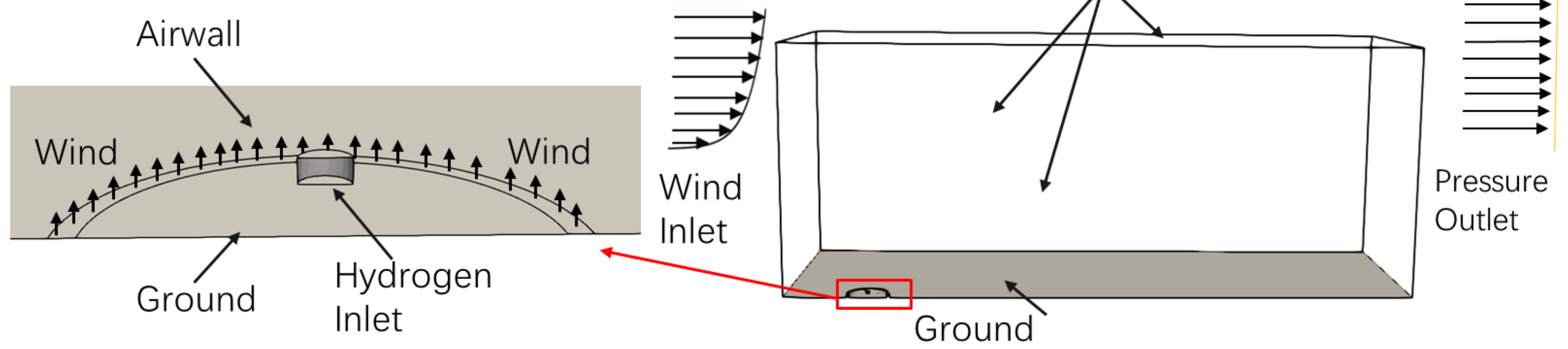
Abstract

An innovative approach called the "air wall" has been proposed as an enhanced safety measure alternative to conventional enclosure systems. The air wall consists of a series of upward air outlets designed to intercept the lateral diffusion of low-temperature, high-density hydrogen. Results show that air walls offer a safer option for mitigating the consequences of liquid hydrogen leaks.

Geometric schematic



(a) Schematic diagram of the geometric model with cofferdam



(b) Schematic diagram of the geometric model with air wall

Numerical Model

- **Conservation equations**

mass equation
$$\frac{\partial \bar{\rho}}{\partial t} + \nabla \cdot (\bar{\rho}\widetilde{U}) = 0$$

momentum equation
$$\frac{\partial(\bar{\rho}\widetilde{U})}{\partial t} + \nabla \cdot (\bar{\rho}\widetilde{U}\widetilde{U}) = -\nabla\bar{p} + \nabla \cdot (\tilde{\tau}_{eff}) + \bar{\rho}g$$

specie equation
$$\frac{\partial(\bar{\rho}\widetilde{Y}_\iota)}{\partial t} + \nabla \cdot (\bar{\rho}\widetilde{U}\widetilde{Y}_\iota) = \nabla \cdot (\mu_{eff}\nabla\widetilde{Y}_\iota) + \overline{\omega_\iota}$$

energy equation
$$\frac{\partial(\bar{\rho}\widetilde{h_s})}{\partial t} + \nabla \cdot (\bar{\rho}\widetilde{U}\widetilde{h_s}) = \nabla \cdot (\alpha_{eff}\nabla\widetilde{h_s}) + \sum_{i=1}^{np}(\nabla \cdot \{\overline{h_{s\iota}}[\rho D_i - \alpha]\})\nabla Y_i + \overline{\omega_h}$$

multiphase equation
$$\frac{\partial(\bar{\rho}\widetilde{\alpha_\xi})}{\partial t} + \nabla \cdot (\bar{\rho}\widetilde{U}\widetilde{\alpha_\xi}) = \tilde{\Gamma}_\xi \quad (\xi = l, g)$$

Lee model
$$\begin{cases} \dot{m}_{l\to v} = \mathrm{coeff}\cdot\alpha_l\rho_l(T_l - T_{sat})/T_{sat}, & \text{if } T_l > T_{sat} \\ \dot{m}_{v\to l} = \mathrm{coeff}\cdot\alpha_v\rho_v(T_v - T_{sat})/T_{sat}, & \text{if } T_v < T_{sat} \end{cases}$$

standard K-Epsilon model

Epsilon Equation
$$\frac{\partial}{\partial t}(\alpha\rho\epsilon) + \nabla\cdot(\alpha\rho\mathbf{u}\epsilon) - \nabla^2(\alpha\rho D_{\epsilon\mathrm{eff}}\epsilon) = C_1\alpha\rho G\frac{\epsilon}{k} - \left(\left(\frac{2}{3}C_1 - C_{3,RDT}\right)\alpha\rho\nabla\cdot\mathbf{u}\epsilon\right) - \left(C_2\alpha\rho\frac{\epsilon}{k}\epsilon\right)$$

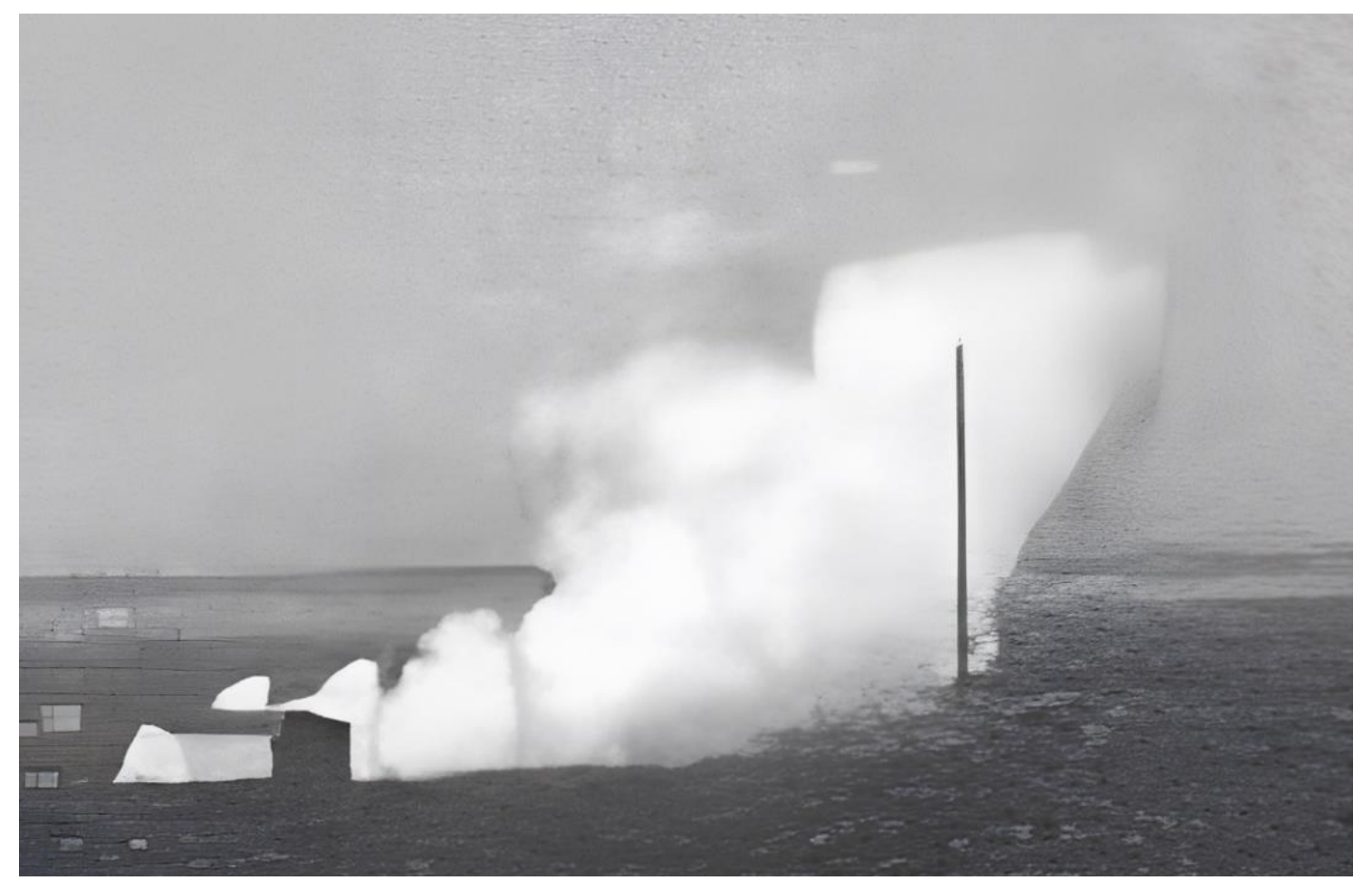
K Equation
$$\frac{\partial}{\partial t}(\alpha\rho k) + \nabla\cdot(\alpha\rho\mathbf{u}k) - \nabla^2(\alpha\rho D_{k\mathrm{eff}}k) = \alpha\rho G - \left(\frac{2}{3}\alpha\rho\nabla\cdot\mathbf{u}k\right) - \left(\alpha\rho\frac{\epsilon}{k}k\right)$$

VOF model
$$\rho = \alpha\rho_1 + (1-\alpha)\rho_2$$
$$\alpha_l = 1 - \alpha_v$$
$$\frac{\partial}{\partial t}(\alpha_v\rho_v) + \nabla\cdot(\alpha_v\rho_v\vec{V_v}) = \dot{m}_{l\to v} - \dot{m}_{v\to l}$$

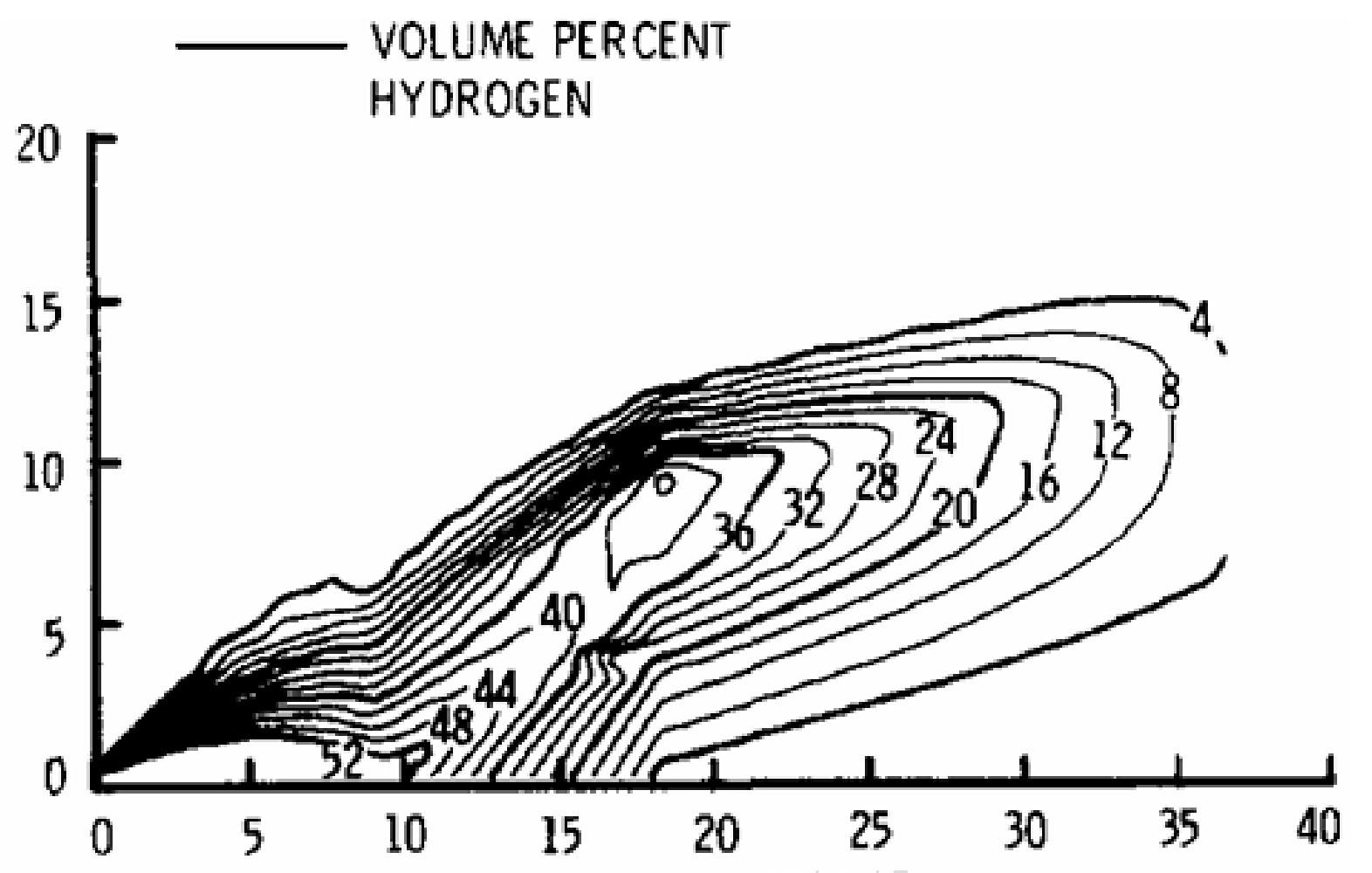
incompressible ideal gas model
$$\rho = \frac{p_{\mathrm{ref}}}{RT}$$

Exponential wind profile by **AIJ**
$$I(z) = 0.1\left(\frac{z}{z_G}\right)^{-\Phi-0.05} \quad (z \geq 5\mathrm{m})$$
$$l(z) = 100\left(\frac{z}{30}\right)^{0.5}$$
$$u(z) = u_0\left(\frac{z}{z_0}\right)$$
$$\varepsilon(z) = C_\mu^{3/4}k(z)^{1.5}/l(z)$$
$$k(z) = \frac{3}{2}[u(z)I(z)]^2$$

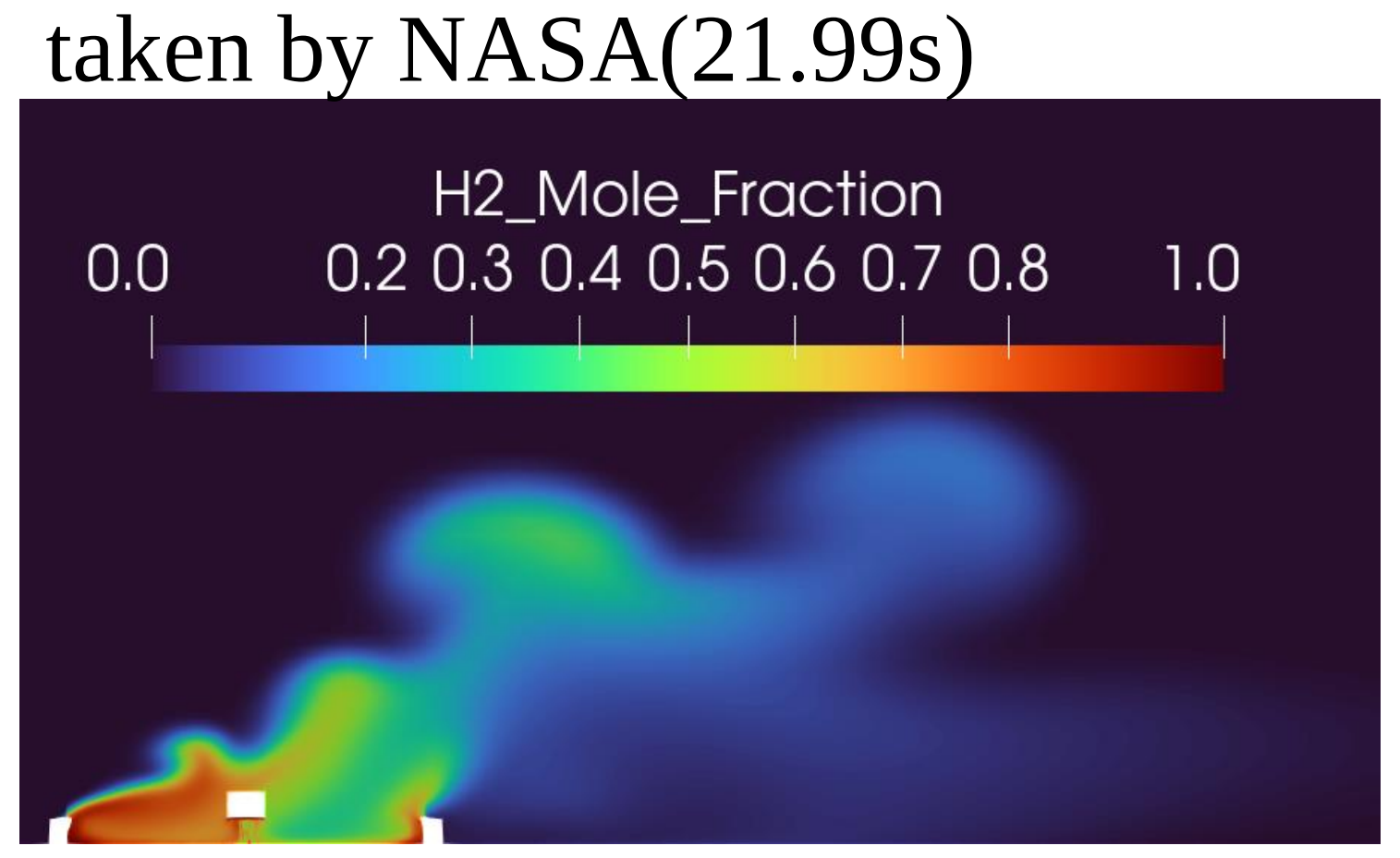
Model Validation and Comparison



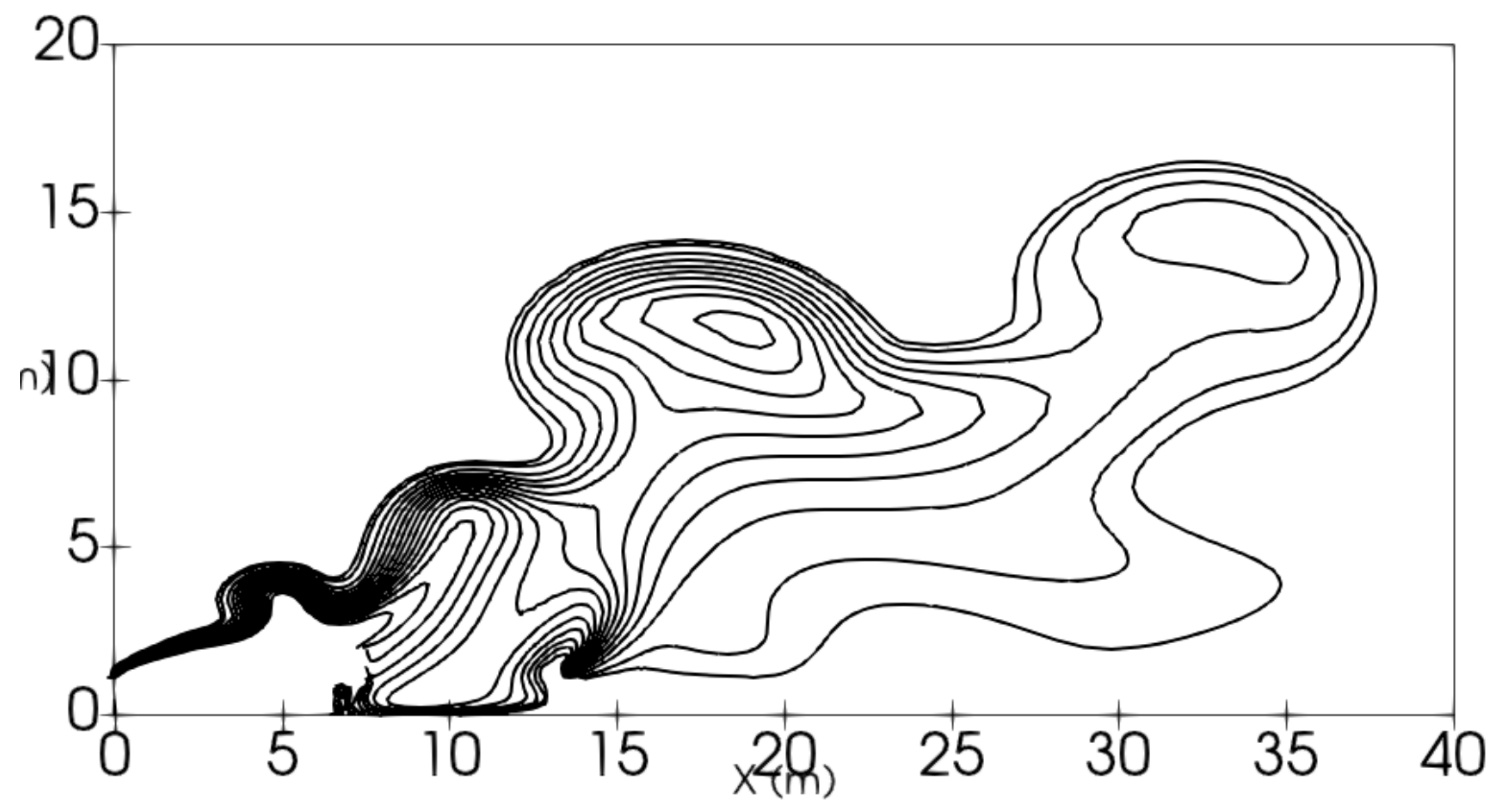
(a) Experimental record. Photo taken by NASA(21.99s)



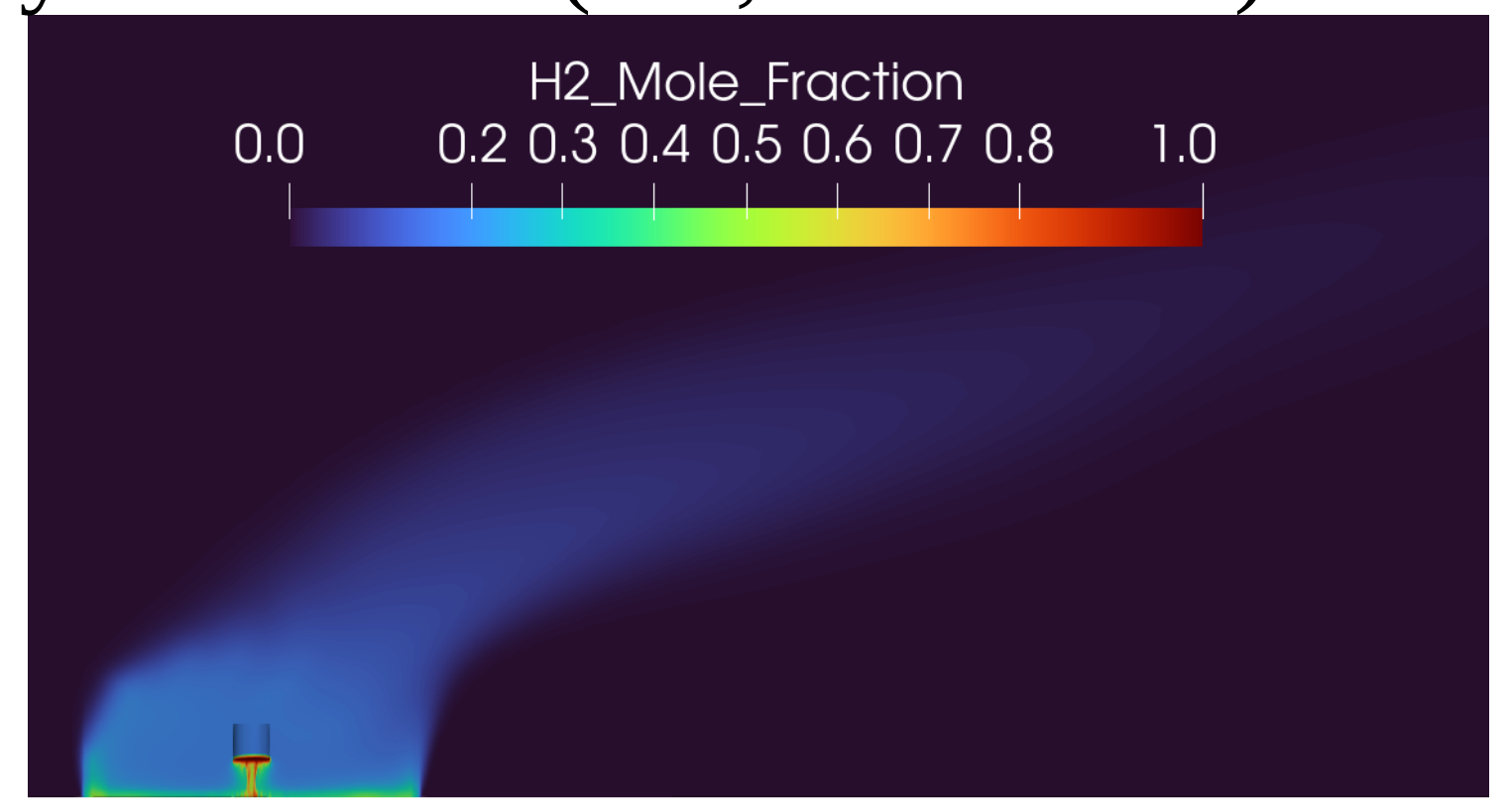
(a) Hydrogen concentration contours, NASA data (21.36s)



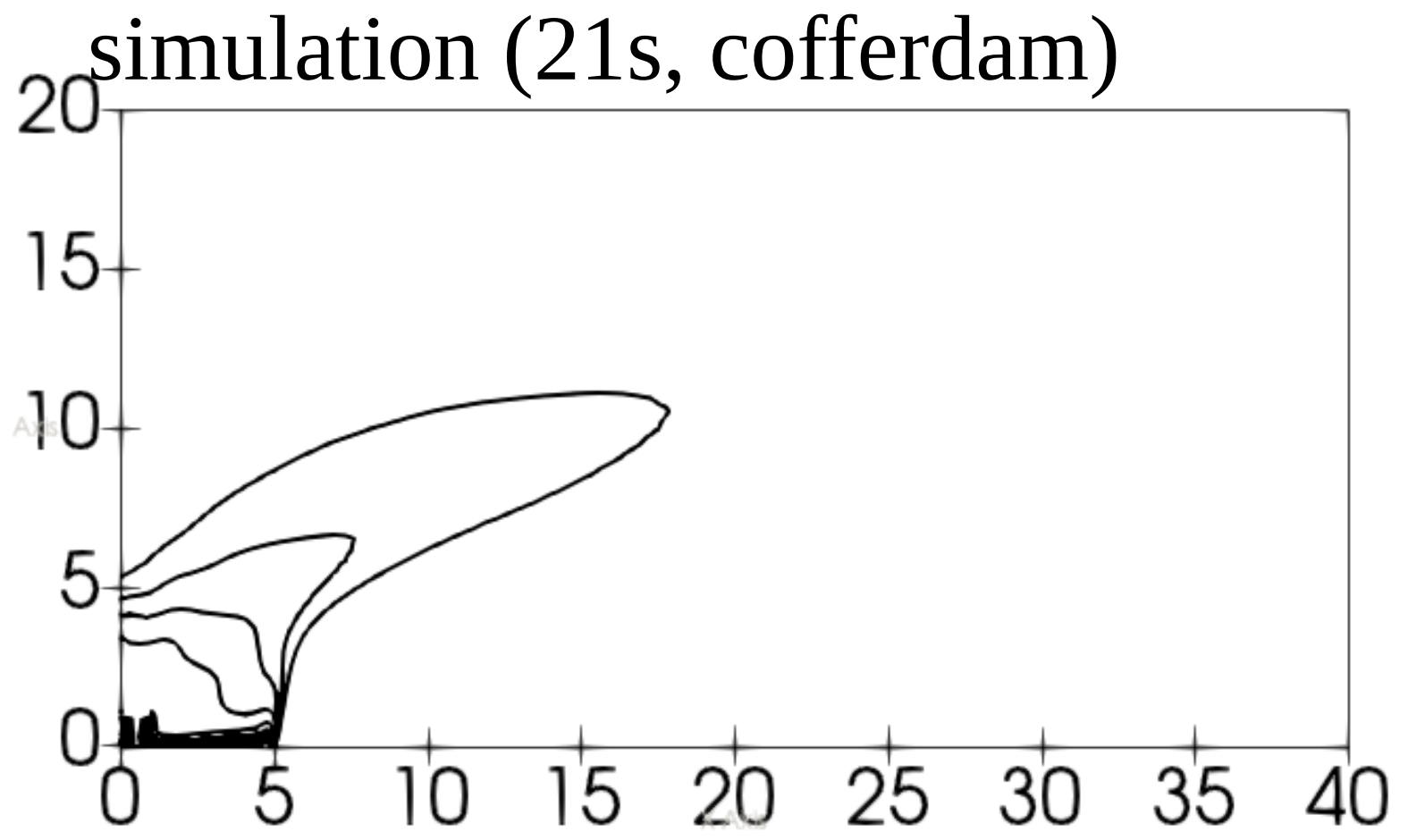
(c) Hydrogen concentration predicted by simulation (21s, cofferdam)



(d) Hydrogen contours predicted by simulation (21s, cofferdam)

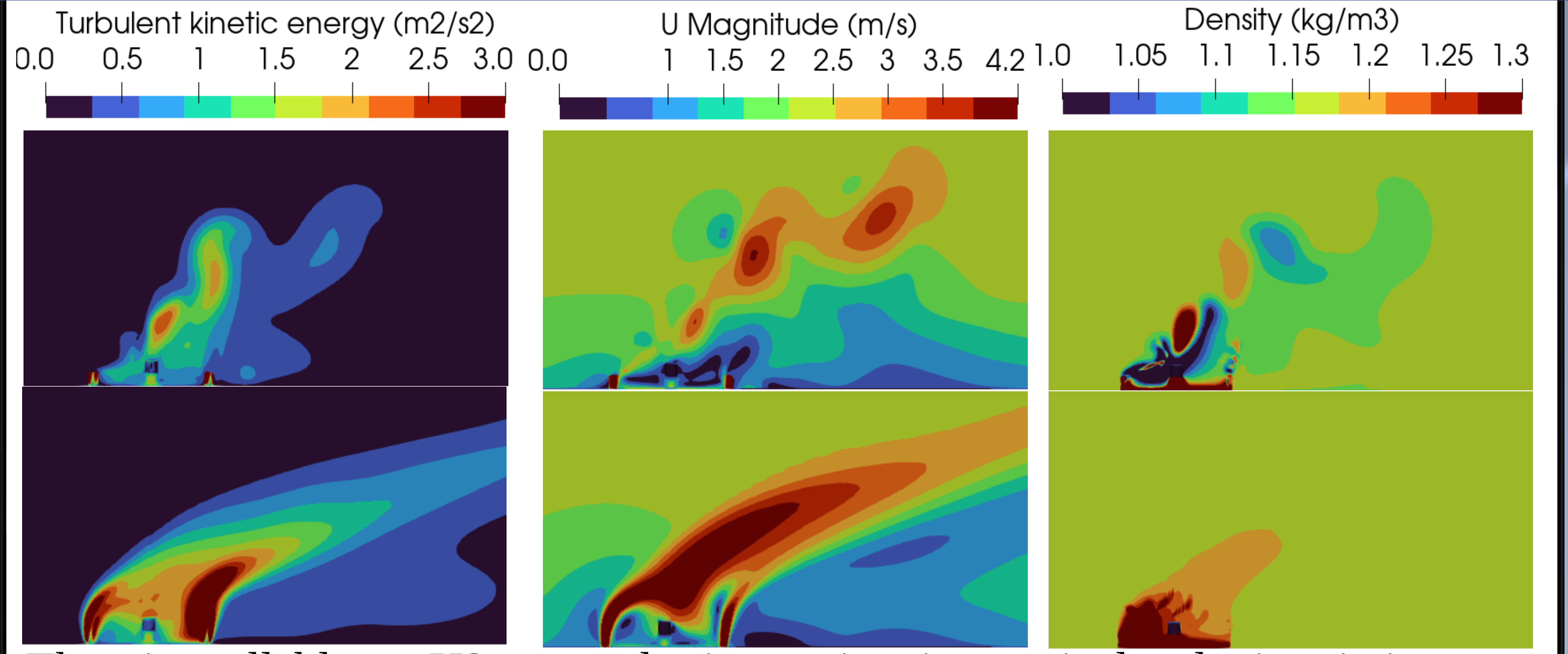


(e) Hydrogen concentration predicted by simulation (21s, air wall)



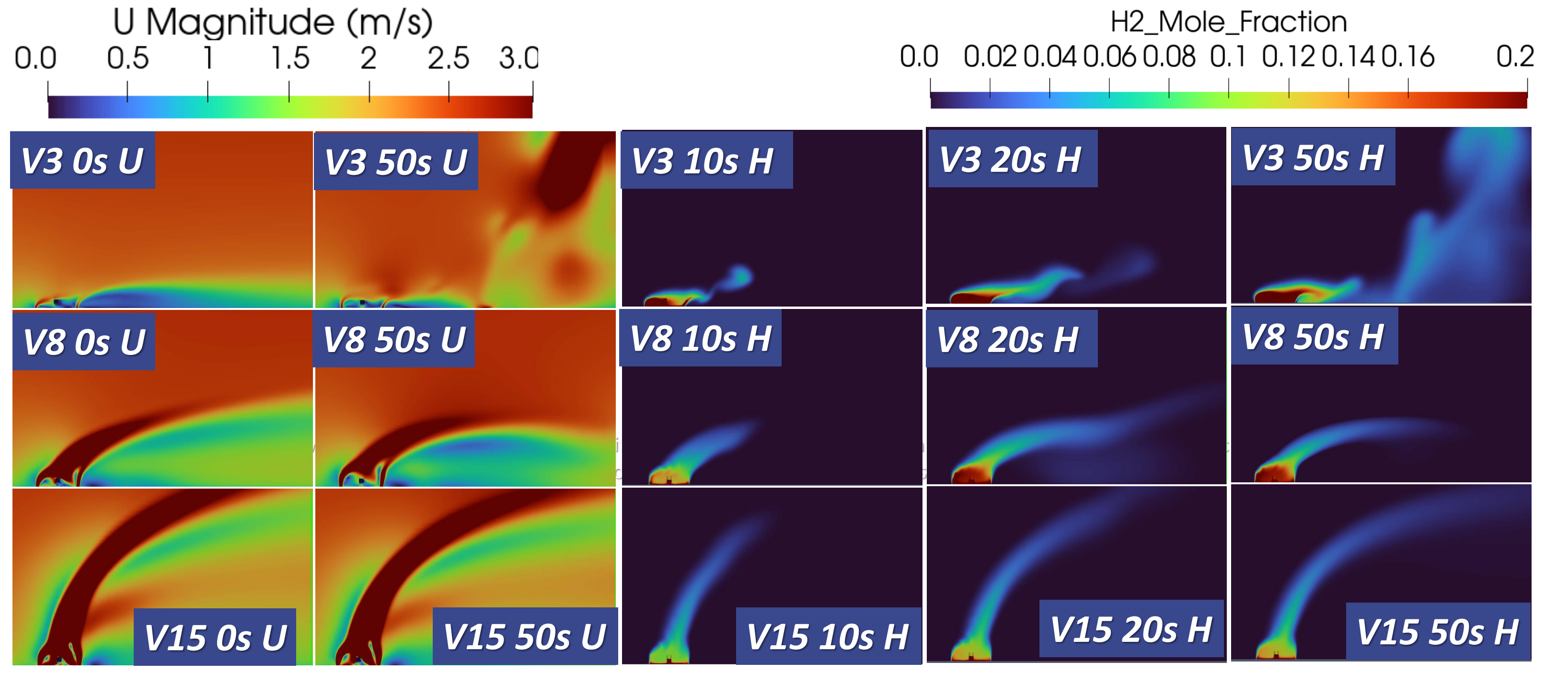
(f) Hydrogen contours predicted by simulation (21s, air wall)

Analysis of protective effect



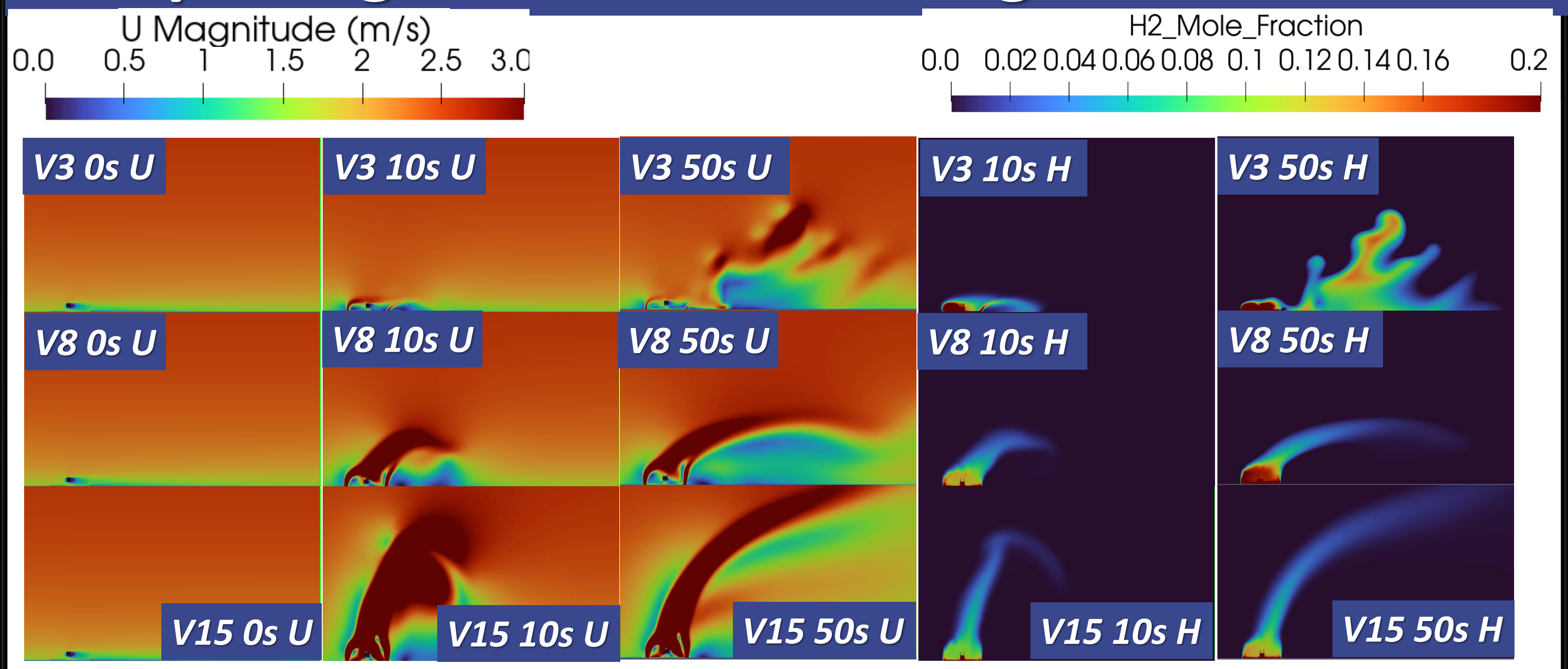
The air wall blows H2 upwards, increasing its vertical velocity; it increases turbulent kinetic energy, accelerating dissipation.

Impact of different air velocities



Here, V3 represents the velocity of the air wall 3m/s, 0s represents that the LH2 has been released for 0s, U represents the velocity distribution (U Magnitude), and H represents the hydrogen concentration distribution (H2_Mole_Fraction). The letters and numbers in subsequent pictures have the same meaning as here

Impact of different air velocities when opening the air wall during LH2 release



Conclusion

- Compared to cofferdam, air walls are significantly safer.
- The protective effect: it increases the upward velocity and enhances convection, thereby increasing the dissipation rate.
- The greater the air velocity, the more effective the protection.
- The air wall does not need to be turned on continuously. It can be turned on at the moment of leakage, and the protection effect is equally good.