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A Multi-source Data Fusion Method for Visualizing Image Reconstruction of Hydrogen Leakage Concentration Distribution

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ABSTRACT

Hydrogen safety is intrinsic to the popularization and application of hydrogen energy. Leakage is a major source of hydrogen-related safety accidents, so the research on leakage is crucial. The visual calibration method can quickly visualize the concentration distribution in the area of hydrogen leakage, but the accuracy of the visualized images needs to be improved. To solve the problem, this paper proposes a multi-source data fusion method based on a deep learning framework, which reconstructs the concentration distribution of the hydrogen leakage and obtains a reconstructed concentration distribution image. Firstly, the leakage images are obtained from the schlieren visualization experiment and using the calibration equations for concentration identification. The visualization experiment is simulated by using ANSYS Fluent, and the simulation result was analyzed and studied with the visualization experiment result. Then, the concentration data obtained from the simulation is used for the training, optimization and validation of the multilayer perceptron neural network, and the axial concentration data obtained from the visualization experiments was used as input to the net to obtain the radial concentration data of the reconstructed visualization image, and the attenuation law of radial concentration at three sections were analyzed. From the result, the reconstructed visualization image by this data fusion method can well reflect the concentration distribution of hydrogen leakage.

Keywords: hydrogen safety, data fusion, hydrogen leakage distribution

NONMENCLATURE

Abbreviations	
EP	Energy Proceedings

Symbols	
n	Year

1. INTRODUCTION

With economic development and increasing industrialization, the problems of environmental pollution and the greenhouse effect problems are becoming increasingly serious worldwide. Energy transition is a necessary change to overcome the environmental problems caused by the large-scale use of fossil energy sources. Hydrogen energy, with its high energy density and reaction with air to produce only water, is considered a clean and non-polluting new energy source and an ideal alternative to fossil fuels, which is an essential developing direction for energy transformation worldwide. The acceleration of the development of the hydrogen energy industry is a key strategic choice for the management of global climate change and the realization of sustainable development. The U.S. National Clean Hydrogen Energy Strategy and Roadmap, published by the U.S. Department of Energy in May 2023, provides a strategic framework for achieving the large-scale production and use of clean hydrogen energy, with the goal of accelerating the process of producing, processing, delivering, storing, and using hydrogen energy. Japan formulated the “Green Growth Strategy Through Achieving Carbon Neutrality in 2050” which emphasizes the use of hydrogen energy to decarbonize key fields such as power generation, industry and transportation. China maps 2021-2035 plan on hydrogen energy development, which outlines important measures to promote high-quality development of the hydrogen energy industry and various stages of industrial development goals. By 2030, the plan aims to decarbonize existing hydrogen-intensive industrial clusters and scale up green hydrogen production.

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While hydrogen energy boasts numerous advantages, its high energy density and distinctive physicochemical properties often present a series of safety challenges during its preparation, storage, transportation, and utilization. Hydrogen has a wider flammability range in air than conventional fuels and requires very low ignition energy to burn in air. Furthermore, its high diffusivity causes rapid dispersion in the event of a leak, posing significant safety management challenges.

Currently, numerical simulations and experiments are the primary methods used to study hydrogen leakage. A numerical simulation method was applied to understand potential hazards, reduce safety risks. Ba et al. used Fluent software to study the hydrogen jets and dispersion characteristics, and found that the radial concentration spreading rate of cryogenic hydrogen jets is similar to that of room temperature jets[1].Moen et al. studied the profile morphology of hydrogen jets at high and low momentum using FLACS software, and found that the jet profiles was in close agreement with experimental schlieren images[2].Huang et al. numerically simulated hydrogen leaks and diffusion in an actual size underground parking garage, and showed that the fully developed hydrogen jets could be divided into three distinct layers: the bottom layer without hydrogen, the top layer with a rather uniform hydrogen concentration, and the transition layer[3].Compared with numerical simulations, experiments to quantify the hydrogen concentration field provide more accurate data. Visualization experiments, as an intuitive and non-invasive measurement method, are ideally suited to accurately reflect the concentration distribution of hydrogen jets in real time. Gong et al. used sensors to study the concentration distribution of hydrogen release at different barrier wall distances and hydrogen temperatures, and the results showed that the concentration distribution in the axial direction followed an exponential distribution, and the distribution in the horizontal direction followed a Gaussian distribution[4]. Wang et al. used the schlieren method to observe the flow of hydrogen after leaks in a double ferrule joint, combined with CFD simulation results indicated that forced convection in the hydrogen system reduces the combustible volume generated by hydrogen jet[5].Sun et.al. used Background Oriented Schlieren to detect hydrogen leakage in the low and high power consumption peaks, and corrected the formed displacement function of the hydrogen jet by laser beam profile deformation technique, and the results showed that the proposed BOS displacement function correction method can realize the high-precision detection of hydrogen concentration distribution[6].

Existing studies of hydrogen leak jet distributions are based on a single data source, neglecting the integration and comparison of different data sources such as visualization experiments, numerical simulations, mathematical models, etc. Multi-source data fusion solves this problem very well. Multidimensional data obtained through multiple methods can be fused and integrated for accurate identification of concentration distributions. In this paper, a novel multi-source data fusion method based on deep learning is proposed, which can employ simulation results to correct hydrogen leakage jet concentration data obtained from schlieren visualization images, enabling visual image reconstruction to accurately describe the distribution of hydrogen leakage concentration. The main contributions of this paper are as follows:

1. A new data fusion method is proposed to reconstruct visual images, hence improving the accuracy of concentration distribution in visualization images.

2. Based on gray-scale concentration equation, quantify concentration distribution of visualized images, and compared with the radial concentration data obtained from simulation, and the radial concentration distribution law was studied.

The paper is organized as follows. Section 2 introduces some relevant details on schlieren experiment and numerical simulation. Section 3 shows and discusses the experimental and simulation results. In Section 4, the multi-source data fusion method is proposed. Section 5 shows the reconstructed image, and Section 6 provides the conclusion.

2. SCHLIEREN EXPERIMENT AND NUMERICAL SIMULATION

2.1 Visualization experiment of hydrogen leakage

2.1.1 Experimental set up

As shown in Fig. 1, a hydrogen leakage simulation test device was built.

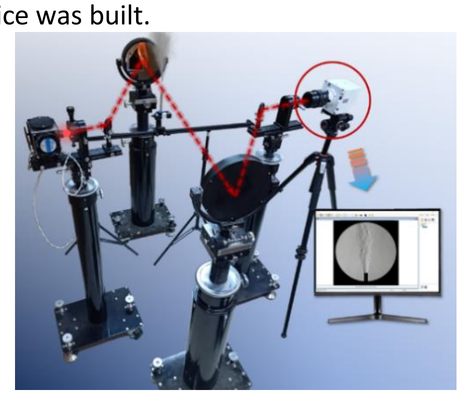

Fig. 1. Visual imaging system for hydrogen leakage.

The concentration visualization experiment system includes a gas injection system including nozzle guides, nozzles, connecting lines, and gas sample bags; and a visualization imaging system including a rippling system, a light source and brightness regulator, and a high-speed camera.

In this experiment, different concentrations of standard gas are used to ensure the stability of the concentration and the gas pressure is one atmosphere. Different concentrations of gases were injected from the circular nozzle through the injection system with a low initial jet velocity, where the leak can be considered as a subsonic jet. A circular nozzle with a vertically upward opening was used to ensure the axial symmetry of the jet. The concentration gradient of helium is converted into a textured image with different gray values by means of a visualization imaging system. The effective range of the visualization system is a circular area with a diameter of 20 cm. In addition, a high-speed camera was used to capture the texture image and upload the image to the host computer for further image processing.

The visual experimental apparatus was adjusted to keep the nozzle position fixed at the lower center, and the image at this point was recorded as the background image. With the position and external conditions of the schlieren devices unchanged, the standard gas was connected to the gas injection system, the gas was ejected from the nozzle at a stable rate, and the visual image was recorded after the jet shape was stable. Repeat the above steps with different concentrations of standard gas. A group of visualized images for calibration is obtained, as shown in Fig. 2.

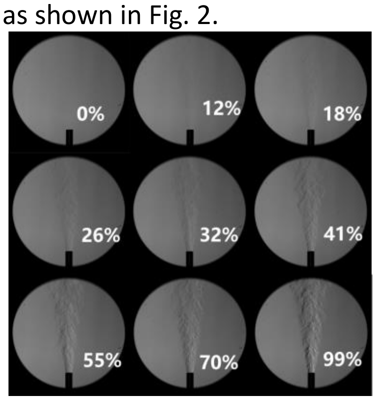

Fig. 2. A group of visual images for calibration.

2.1.2 Calibration method based on visual identification

The concentration of the visual image is quantified by the relationship between the leakage concentration and the gray value. In this paper, after the steps of mean filtering, calculating the characteristic gray level difference, and fitting the gray level concentration, a function between the gray level and the concentration of the textured image is obtained, and this function quantifies the helium concentration in the gray level image. And the function is

$$\triangle G(k) = 3.55\times10^{-5}k^3 - 3.29\times10^{-3}k^2 + 0.31k - 0.17$$

where $\triangle G$ is the gray difference, and k is the concentration of the hydrogen.

2.2 Model and numerical approach

2.2.1 Governing equations

The conservation equations for mass, momentum and energy of substances were used to characterize the flow of a compressible fluid following a hydrogen leakage process as calculated in ANSYS Fluent. The mass conservation equation of gas is

$$\frac{\partial\rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \quad (1)$$

where u, v, w are the velocity components in the x, y, z coordinate directions, and ρ is the density, that is the mass per unit volume. The momentum conservation equation is

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i \quad (2)$$

where u_i is the velocity component in the i-direction; u_j is the velocity component in the j direction; τ_{ij} is the stress tensor; g_i and F_i denote the gravity and external force in the i-direction. The energy conservation equation is

$$\frac{\partial(\rho T)}{\partial t} + \nabla(\rho u T) = \nabla\left(\frac{k}{c_p} gradT\right) + S_T \quad (3)$$

where T is the temperature; k is the fluid heat transfer coefficient; c_p is the specific heat capacity; S_T is the viscous dissipative term.

The component equation is required when simulating experiments with a hydrogen leak jet in order to accurately describe the diffusion process. The components equation is an expression of the conservation of mass. The component equation is

$$\frac{\partial(\rho Y_s)}{\partial t} + \nabla(\rho u c_s) = \nabla\left[D_s grad(\rho c_s)\right] + S_s \quad (4)$$

where Y_s is the mass fraction of s; D_s is the diffusion coefficient; S_s is the reaction rate of s.

2.2.2 Turbulence model

The hydrogen leakage process was simulated using transient modeling. Due to the large pressure difference between inside and outside during hydrogen leakage, the flow and diffusion process at the leakage outlet is turbulent. In this study, the turbulence was simulated by a standard k-ε model.

It contains two transport equations: the turbulent kinetic energy equation (k) and the momentum dissipation rate equation (ε).

The turbulent kinetic energy transport equation is

$$\frac{\partial(\rho k)}{\partial t}+\nabla(\rho u k)=\nabla\left[\left(\mu+\frac{\mu_l}{\sigma_k}\right)gradk\right]+G_k+\rho\varepsilon \qquad (5)$$

where k is the turbulent kinetic energy; ε is the dissipation of turbulent kinetic energy; σ_k is the Prandtl number of turbulence for k taken as 1; G_k is the turbulent kinetic energy. The momentum dissipation rate equation is

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\nabla(\rho u\varepsilon)=\nabla\left[\left(\mu+\frac{\mu_l}{\sigma_k}\right)grad\varepsilon\right]+\frac{\varepsilon}{k}(C_{1\varepsilon}C_k-C_{2\varepsilon}\rho\varepsilon) \qquad (6)$$

where σ_ε is the Prandtl number of turbulence for ε taken as 1.3; $C_{1\varepsilon}$ =1.44, $C_{2\varepsilon}$ =1.92 are constants.

The temperature of environment was set as 25 °C and the ambient pressure was set as standard atmospheric pressure to simulate the visual experiment of the hydrogen jet. The effect of gravity was set to 9.8 m/s^2, with a direction in the x-axis. The SIMPLE method was chosen for the simulation solutions, and the discretization format of the momentum and energy equations was set in the first-order windward format, and the other terms were in the second-order windward format. The solutions were considered to converge when the residual mass was less than 10^{-5} for the continuity, momentum, and energy equations.

3. THE DISCUSS OF THE RESULT

3.1 Concentration Comparison

To study the axial concentration distribution, the visual image of the 79% concentration with obvious gray scale variation was selected.

The image of visual experiment and 2D numerical simulation result, as shown in Fig. 3.

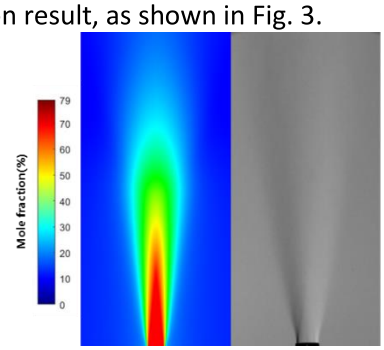

Fig. 3. Visual images of hydrogen leakage with an initial concentration of 79%.

3.2 Radial Concentration Comparison

Establish a coordinate system with the intersection point of the jet axis and the line intersecting the outlet as the origin, where the horizontal direction corresponds to the y-axis, and the vertical direction corresponds to the z-axis. The pixel values of the image were converted to distances by dimensional calibration(1mm=5px). In order to compare the radial concentration data, radial concentration data were extracted at selected distances of 20mm, 40mm, and 60mm from the nozzle.

As shown in Fig. 4, the left plot shows the radial concentration data quantified using calibration equations from visual imagery, and the right plot shows the concentration data obtained by numerical simulation.

In the section near the nozzle, the maximum concentration is higher, and the concentration decreases more rapidly along the radial direction, whereas the situation is exactly the opposite at sections farther away from the nozzle.

The concentration data extracted from the visualized images declines faster compared to the simulated data and is not similarly Gaussian distributed. It may be due to mixing and shearing of gas and air at jet edges, resulting in mismatch between boundary and interior gray levels, leading to large errors in quantified concentration in this area. There is also the possibility that using Grain Imaging, three-dimensional projection into a two-dimensional plane, resulting in radial gray scale changing law cannot be well represented. The simulation is limited by the physical model and computational accuracy, and it is difficult to accurately reproduce the complex flow details of the hydrogen jet, and the maximum concentration obtained by the simulation at the same interface is significantly higher than the experimental data and decays very slowly.

Therefore, the visualization experiment can reflect the real concentration attenuation change of the flow field, but limited by the quantitative calibration and data processing inevitably have some errors, and the numerical simulation has some limitations based on the concentration data obtained from the computational fluid dynamics theory, which cannot reproduce the real details of the flow field.

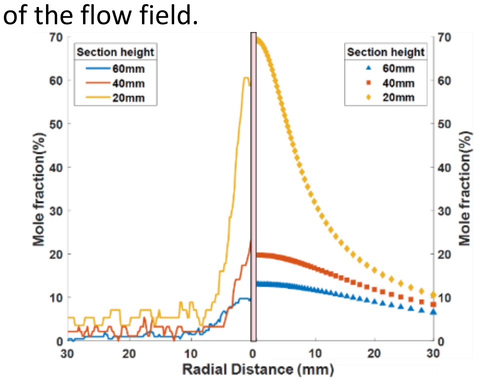

Fig. 4. Radial concentration distribution with experiment and simulation.

4. DATA FUSION METHOD

Based on the previous discussion, the axial concentration distribution obtained from the visual experiments shows good agreement with the simulation results. However, the radial concentration data cannot be directly extracted from the visual images. In order to obtain the accurate concentration of the hydrogen leakage, this paper adopts the data fusion method to reconstruct the radial concentration distribution.

Because the axial concentration distribution data obtained from the visualized images have credibility, the concentration on the axes is completely adopted from the experimental data. In order to solve the problem of inaccuracy of the radial experimental results, the radial concentration decay law will be obtained based on the simulation results when the image is reconstructed.

Along the z (axial distance) direction, the y-coordinate (radial distance) at this height and the concentration data at the axes were used as characteristic variables to fit the radial concentration data obtained from the simulation, so that a mathematical relationship was obtained for the variation of the radial concentration with the concentration at the axes and the y-coordinate (radial distance). Therefore, for each different concentration at the axis, the fitted concentration distribution in the radial direction can be obtained. The fitting relationship contains several feature variables, making it difficult to pre-determine the appropriate fitting expression, so a neural network fitting method was used.

The network is structured as two layers, and the input feature variables include the concentration data at the axis, z coordinate, and y coordinate in three dimensions, and the input data is the concentration at the point (y, z).

To extract concentration data from the Fluent solved leak area grid nodes (including 6900 data points), the concentration data at the y-coordinate, z-coordinate, and (0, z) should be used as the independent variables (features), while the concentration data at (y, z) would be used as the dependent variable (output).

The axial concentration data obtained from the quantization of the visualization image is used as input, and the trained neural network is used to obtain the concentration data in the radial direction to realize the data fusion of experiment and simulation.

5. RESULT

With the data fusion method, the experimentally obtained axis concentration data were used as inputs to the network in order to obtain the concentration data for the reconstructed visualization image. Some regions of the stripe image were reconstructed, and the reconstructed visualization image is shown in Fig. 5.

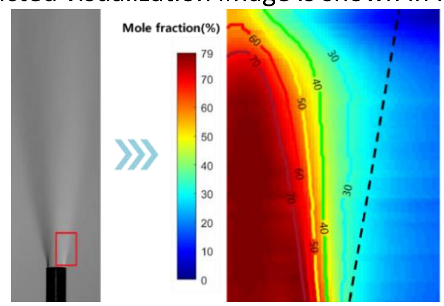

Fig. 5. Reconstructed radial concentration distribution

The radial concentration data were observed by selecting the cross section at 20mm, 40mm, and 60 mm from the nozzle as shown in Fig. 6.

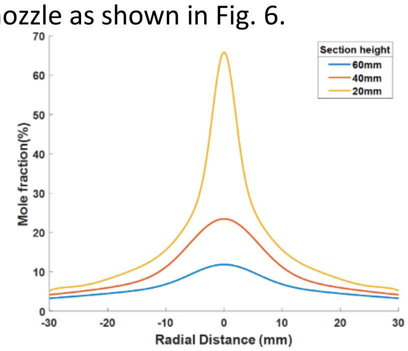

Fig. 6. Reconstructed radial concentration distribution

In the radial direction, the concentration decreases sharply with distance and then stabilizes, and this decay rate is related to the concentration at the axis, and the decay rate decreases rapidly with the initial concentration. It can be seen that the radial concentration decline law is consistent with the distribution law obtained from simulation.

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