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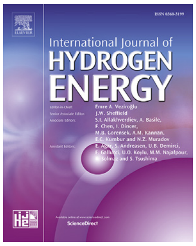

# Numerical investigation of flammable cloud on liquid hydrogen spill under various weather conditions

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ABSTRACT

The investigations of hydrogen leakage during the latest decades, have developed our knowledge level. However, few studies concerned the whole dispersion history of the flammable cloud (from generating to disappearing in the atmosphere). A Non-Homogeneous Equilibrium Model (NHEM) was used, and validated by a large scale $LH_2$ spill experiment. The predicted data displayed good agreement with the experiment. Moreover, the experiment was further investigated on the colourless flammable cloud. Three primary questions of the hydrogen dispersion process were concerned: the maximum spreading range, the minimum distance above the ground, and the duration time of the flammable cloud in the atmosphere. Three major influence factors were selected to simulate various weather conditions, including ambient temperature (coupled with ground temperature), wind speed and atmospheric pressure. The hydrogen dispersion can be excited with the increased wind speed, and be impeded with the increased atmospheric pressure. The hydrogen dispersion process in four seasons of a year appears a different trend.

## Introduction

It is commonly considered that the origin of global warming is the sharply increasing use of fossil fuels in industrial and civil applications, from the beginning of the last century [1]. Facing this challenge, it is urgent to develop new energy technologies that do not emit greenhouse gas. At this aspect, hydrogen energy has its special merit, since the only by-product of its combustion is water. Moreover, the hydrogen molecule is the most energetic:120 MJ/kg [2], about 4–5 times of coal and 2.2 times of LNG. As an energy carrier, hydrogen can be converted to energy through combustion or electrochemical reactions, in the form of heat or electricity. Now it has been used in the engines of the space shuttle and rocket, and the hydrogen internal combustion engines and fuel cells technologies have been greatly developed in recent years as well [3–6]. In China, the government has realized the urgency of changing the proportion of fossil energy in the energy structure, to reduce its impact on the environment. In the energy science and technology roadmap to 2050, the utilization of hydrogen has been planned as one of the ten major technological directions of the future energy [7]. However, there are many factors may cause the structure failure of $LH_2$ storage vessels or

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**Nomenclatures**

| | |
|---|---|
| **a** | secondary phase partical's accelaration vector, $m/s^2$ |
| coeff | coefficent, 1/s |
| $d_p$ | particle diameter of secondary phase $p$, m |
| $D_{eff}$ ,$D_t$ | effective diffusivity, turbulent diffusivity, $m^2/s$ |
| $D_{i,m}$ | molecular diffusivity for species $i$ in the mixture, $m^2/s$ |
| $E_k$ | total energy of phase $k$, J |
| $f_{drag}$ | drag function, dimensionless |
| **F** | body force vector, N |
| **g** | gravitational accelaration, $m/s^2$ |
| $h_k$ | enthalpy of phase $k$, J/kg |
| **J** | diffusion flux vector, $kg/(m^2 \cdot s)$ |
| $k_{eff}$, $k_k$,$k_t$ | effective conductivity, thermal conductivity of phase $k$, turbulent thermal conductivity, $W/(m \cdot K)$ |
| $\dot{m}_{l \rightarrow v}$, $\dot{m}_{v \rightarrow l}$ | mass flow rate: liquid phase to vapor phase, vapor phase to liquid phase, $kg/(m^3 \cdot s)$ |
| $\dot{m}_{pq}$ ,$\dot{m}_{qp}$ | mass flow rate: secondary phase $p$ to primary phase $q$, primary phase $q$ to secondary phase $p$, $kg/(m^3 \cdot s)$ |
| M | molecular weight of the gas |
| $p$ | pressure, Pa |
| R | the universal gas constant, $J/(mol \cdot K)$ |
| $Re$ | Reynolds number, dimensionless |
| s | dispersion distance of the flammable cloud, m |
| $Sc_t$ | turbulence Schmidt number, dimensionless |
| $S_E$ | volumetric heat source, J |
| t | time, s |
| $T_a$, $T_s$ | air temperature, soil temperature, K |
| $T_{sat}$, $T_l$,$T_v$ | saturation temperature, liquid phase temperature, vapor phase temperature, K |
| $\mathbf{v}_{dr,p}$, $\mathbf{v}_{pq}$, $\mathbf{v}_{qk}$ | drift velocity vector, secondary phase $p$ slip velocity vector, the $k$ species of $q$ phase velocity vector, m/s |
| $\mathbf{v}_m$ | mixture velocity vector, m/s |
| $V_L$, $V_{max}$ | $LH_2$ release volume, maximum flammable cloud volume, $m^3$ |
| $Y_i$ | mass fraction of species $i$, dimensionless |

*Greek symbols*

| | |
|---|---|
| $\alpha_k$, $\alpha_p$, $\alpha_v$, $\alpha_l$ | volume fraction: phase $k$, secondary phase $p$, liquid phase, vapor phase, dimensionless |
| $\rho_k$, $\rho_p$, $\rho_m$, $\rho_l$, $\rho_v$ | density: phase $k$, secondary phase $p$, mixture, liquid phase, vapor phase, $kg/m^3$ |
| $\mu_k$, $\mu_q$, $\mu_m$, $\mu_t$ | viscosity: phase $k$, secondary phase $p$, mixture, turbulent, $kg/(m \cdot s)$ |
| $\tau_p$ | secondary phase $p$ partical relaxation time, s |

*Subscripts*

| | |
|---|---|
| a | air |
| drag | drag |
| dur | duration |
| eff | effective |
| H | horizontal |
| i,k | index of species or phase |
| l | liquid |
| m | mixture |
| max | maximum |
| min | minimum |
| op | operating |
| $p$ | secondary phase |
| $q$ | primary phase |
| s | soil |
| sat | saturation |
| t | turbulent |
| v | vapor |
| V | vertical |

*Other symbols*

| | |
|---|---|
| $i^{th}$ | the $i$ species |
| $p1$, $p2$, $p3$ | pressure for 78,630Pa, 91,920Pa, 102,800Pa |
| Q1, Q2, Q3 | season for transition season, winter,summer |
| $v1$, $v2$, $v3$ | wind speed for 2.2 m/s,5.0 m/s,10.0 m/s |

transportation pipes, for instance: external strike, manufacturing defect, fatigue or corrosion of the material, loss vacuum of the high vacuum multilayer insulation, etc. Furthermore, hydrogen is easier to be burning, because it has a wide flammable range of 4–75% (in air, v/v), and very small ignition energy of 0.019 mJ, which is less than 10% of classic hydrocarbons [2,8].

An effective practice for hydrogen storage and transportation is liquefaction. Hazardous characterizes mentioned above may result in potential hazardous issues, during the production, storage and transportation of $LH_2$. Therefore, it is necessary to investigate the accidental $LH_2$ leakage associated hazardous issues, resulting from structure failures or transport accidents. Several organizations have studied the consequence of $LH_2$ leakage by experiment and simulation investigation.

As a major user of $LH_2$, NASA (National Aeronautics and Space Administration, US) had conducted seven large-scale (1350gal) $LH_2$ spill tests in 1980, at WSTF (White Sands Test Facility). The vaporization time of $LH_2$, the concentration history of hydrogen and the maximum downwind distance of visible cloud were collected. Meanwhile, the visible cloud was recorded by static and motion camera [9,10]. Although $LH_2$ spill experiment was started in the late 1950s [11], NASA's program was the first meaningful and valuable $LH_2$ spill experiment. Fourteen years later, BAM (Federal Institute for Materials Research and Testing, Germany) conducted several small-scale (5~6 l/s) $LH_2$ spill tests [12,13]. In these tests, the pool spreading was investigated in detailed. The $LH_2$ was released both on a water surface and a solid surface (a square aluminum sheet). The pulsation-like behavior of the pool front was observed, and massive ice layer was identified on the water surface. Almost at the same time, BAM conducted six $LH_2$ experiments between buildings near the village of Drachhausen (Brandenburg), in 1994 [14]. In these tests, a release rate of about 0.4 kg/s was implemented and the lasting

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