Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

CFD modeling of hydrogen dispersion under cryogenic release conditions

S.G. Giannissi [a,b,*], A.G. Venetsanos [a], N. Markatos [b], J.G. Bartzis [c]

[a] Environmental Research Laboratory, National Center for Scientific Research Demokritos, Aghia Paraskevi, Athens, 15310, Greece

[b] National Technical University of Athens, School of Chemical Engineering, Department of Process Analysis and Plant Design, Heroon Polytechniou 9, 15780, Athens, Greece

[c] Department of Mechanical Engineering, University of Western Macedonia, Parko Agiou Dimitriou, West Macedonia, 50100 Kozani, Greece

ARTICLE INFO

Article history:
Received 24 January 2014
Received in revised form
7 July 2014
Accepted 10 July 2014
Available online 15 August 2014

Keywords:
LH2 dispersion
Two phase jet
Humidity
Slip velocity
Wind direction
ADREA-HF

ABSTRACT

The use of hydrogen as a fuel should always be accompanied by a safety assessment concerning the case of an accidental release. To evaluate the potential hazards in a spill accident both experiments and simulations are performed. In the present work, the CFD code, ADREA-HF, is used to simulate the liquefied hydrogen (LH2) spill experiments (test 5, 6, 7) conducted by the Health Safety Laboratory (HSL). Two horizontal releases, the one along the ground and the other one at a distance above the ground, and one vertical release are examined with spill rate 60 lt/min. The main focus of this study is on the presence of humidity in the atmosphere and its effect on the vapor dispersion. When humidity is present is cooled, condenses and freezes due to the low prevailing temperature (~20 K near the release), and releases heat. In addition, during the release hydrogen droplets are formed due to mechanical and flashing break up, and water droplets and ice crystals due to humidity phase change. Therefore, two models are tested: the hydrodynamic equilibrium model, which assumes that the phases are in thermodynamic and kinematic equilibrium and the non hydrodynamic equilibrium model (slip model), which assumed that the phases are in thermodynamic equilibrium but they can obtain different velocities. The fluctuating wind direction was also taken into account, since it greatly affects the hydrogen dispersion. The computational results are compared with the experimental measurements, and it is concluded that humidity along with the slip effect influences the buoyancy of the cloud to a great extent. The best simulation case (humidity and slip effect) is consistent with the experiment for all three tests for the majority of the sensors.

* Corresponding author. Tel.: +30 210 6503416.
E-mail addresses: sgiannissi@ipta.demokritos.gr (S.G. Giannissi), venets@ipta.demokritos.gr (A.G. Venetsanos), n.markatos@ntua.gr (N. Markatos), bartzis@uowm.gr (J.G. Bartzis).

http://dx.doi.org/10.1016/j.ijhydene.2014.07.042

Nomenclature

X_i	Cartesian j co-ordinate (m)
u_i	i component of velocity (m s^{-1})
p	pressure (Pa)
g_i	gravity acceleration in the i-direction (m s^{-2})
q_k	mass fraction of k component (dimensionless)
t	time (s)
H	Enthalpy (J kg^{-1})
Sc_t,Pr_t	turbulent Schmidt and Prandtl number (dimensionless)
N	particles' number (dimensionless)
$D, \overline{D}$	particle's diameter , mean diameter (m)
N_0	Marshal Palmer constant (m^{-4})
f_{drag}	drag function (dimensionless)
Greek	
δ_{ij}	Kronecker delta
ε	turbulent energy dissipation rate (m^2 s^{-3})
μ,μ_t	laminar and turbulent viscosity (kg m^{-1} s^{-1})
ρ	mixture density
δ	depth (m)
α	thermal diffusivity (m^2 s^{-1})
Subscripts	
nv	non vapor
l	liquid
sl	slip

Introduction

Hydrogen is a competitive fuel in the energy market due to its high energy carrier and low emissions. However, its wide flammability range brings up safety issues. A practice for hydrogen storage and handling is its liquefaction under pressure and low temperature. In case of a fracture in the cryogenic tank, LH2 is spilled forming a cryogenic pool and a dense vapor cloud. The jet release is two phase and prediction of both vapor dispersion and liquid pool evaporation and spreading is required. Computational Fluid Dynamics (CFD) codes are usually used to simulate such complicated cases.

In the past, several experiments have been performed related to hydrogen dispersion under cryogenic release conditions in open environment [1–7]. The most recent related experiments are the HSL experiments [7] that were conducted by the Health and Safety Laboratory in 2010. In the present work, these experiments (HSL experiments) have been simulated with the help of ADREA-HF code.

ADREA-HF is a CFD code that has been validated against hydrogen dispersion and other liquefied fuels such as natural gas, or denser than air gases [8–18], and it is considered to be a useful and reliable tool for such applications.

During HSL experiments LH2 was released above a concrete pad at a fixed rate of 60 lt/min. Four tests were performed with different release directions and duration. Wind speed and direction were measured at the edge of the pad 2.5 m from the ground. Sensors that measured the temperature were deployed in line with the release at several distances and heights. The hydrogen concentration was derived by the temperature data assuming adiabatic mixing. This approach is considered valid, since once the cloud is lifted off the ground the air and hydrogen mixing is adiabatic within 1% [1]. Thermocouples inside the ground measured also the underground temperature.

The parameters that influence the hydrogen dispersion are various, especially when the release takes place in an open environment. Apart from the release conditions significant role play the weather conditions (wind speed and direction, ambient humidity), the atmospheric conditions (neutral, stable, unstable), the ground terrain, etc.

Previous work has simulated tests 6 and 7 of the HSL experiments using the CFD software FLACS [19]. In that work, the condensation or solidification of the air (nitrogen and oxygen) was examined. In their computations of the two phase jet the dispersed and continuous phases were assumed to be in thermodynamic and hydrodynamic equilibrium. At the source they tested four different flashed hydrogen volume fractions and the case with pure gas flow, and it was concluded that for both tests the more coherent results were obtained with flashed volume fraction equal to 99%. The condensation and solidification of air affected the flow field in test 6, by releasing heat close to the ground, generated an upward velocity and made the cloud more buoyant. In test 7 the effect was not significant, because the area where condensation/solidification is occurred is located close to the release and seems not to influence the flow away from it.

When humidity is present in the atmosphere, apart from the air phase change, the water is also condensed and solidified due to the very low prevailing temperature. Moreover, the area where humidity phase change is occurred is much more extended than the area where air phase change is occurred. Therefore, the present work focuses on the effect of ambient humidity on vapor dispersion and on the computational results. Test 5, 6 and 7 of the HSL experiments are chosen to be simulated.

Moreover, during the release hydrogen droplets are formed due to mechanical and flashing break up. The humidity condensation and solidification produces also water droplets and ice crystals. These "particles" can be assumed either to have the same velocity as the vapor mixture or to obtain different velocities, because of the gravitational acceleration. The difference between the phases' velocity is called slip velocity.

In the simulation process two cases were examined: one case that solves assuming both thermodynamic and hydrodynamic equilibrium and one case that solves assuming thermodynamic equilibrium but non hydrodynamic equilibrium. With the non hydrodynamic equilibrium model the vapor and non vapor phase of both hydrogen and humidity are allowed to develop different velocities. The effect of the slip velocity on the flow field is studied.

In all simulation cases the fluctuating wind direction was taken into account, since it was observed that it results in many hydrogen concentration oscillations.

Description of the experiments

The HSL experiments were conducted by the Health and Safety Laboratory in 2010. During these experiments LH2 was spilled above a concrete pad in open environment. A number