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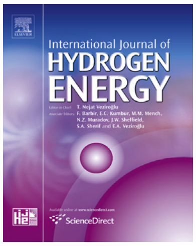

Experimental investigation on helium distribution and stratification in unventilated vertical cylindrical enclosure – Effect of jet release rates and total release volume

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ABSTRACT

Hydrogen leakages into enclosed spaces may occur in hydrogen storage and usage facilities and in nuclear power plants (NPP) following a severe accident. In the absence of either mitigation or combustion processes, hydrogen leaked into the enclosed space may accumulate and form large cloud of explosive mixture with air. This, when gets ignited, can lead to a strong deflagration or even detonation and cause huge threat to both life and property. In NPP, such events can cause over-pressurization of the containment, causing problems in the structural integrity of the containment and consequently result in the leakage of radioactivity into the environment. The present study reports the experimental investigation of the phenomenology of hydrogen distribution inside a cylindrical test enclosure (AIHMS). Different hydrogen leak scenarios are experimentally simulated using helium gas, which is its inert surrogate. The effect of helium release velocities on mixing and distribution of helium within the enclosure, for different quantities of helium released has been experimentally investigated. The experimental studies are conducted in a test enclosure having a volume of around 2 cubic-meters, specifically designed for the purpose and the results have been presented systematically.

Introduction

Hydrogen is expected to be introduced on a wide scale as a clean energy carrier and as a promising replacement for the traditional carbonized fuels in the drive towards future low carbon society [1–3]. Hydrogen in air has a flammability range between 4 and 75 vol % and detonability range between 18 and 59 vol % and very low ignition energy of 0.02 mJ [4]. As a result,

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the main concern against the wide spread acceptability of hydrogen lies in the problems associated with safe production, storage, handling and transportation. Systematic examination of the safety aspects of hydrogen in determining its safe use as a future energy carrier has been reported in the past [4–7].

Unintended release of hydrogen may take place in confined and unconfined enclosures such as storage rooms, laboratory, garages, hydrogen fuelling stations and hydrogen-fuelled vehicles. Schefer et al. [8] has characterised leaks due to pressure driven convection and permeation through metals from hydrogen storage and dispensing systems and related components. Hydrogen disperses rapidly in air and any leakage in confined space can lead to potential fire hazard. In water cooled nuclear reactors, hydrogen can be generated due to core over-heating and zircaloy oxidation during certain postulated accident conditions [9,10]. An important difference between the scenarios found in nuclear reactor containments and in industry handling hydrogen is that in the former, hydrogen release is accompanied by steam. Further, the thermal hydraulic processes and phenomena are more complex in the nuclear reactor containment than in other industries due to the presence of steam and other aerosols [11]. Safety study on the dispersion mechanism of hydrogen in air has to be done carefully before its widespread use as safety systems need continuous improvement in all technologies.

The concern of hydrogen release in confined space has been appreciated and numerous experimental and numerical studies on hydrogen release and distribution have been carried out. Experiment on subsonic jet release of hydrogen in a hermetically sealed cylindrical vessel, Russian-2 was carried out by Shebeko et al. [12]. Swain et al. [13] conducted experimental and numerical investigations to understand the ventilation requirements of a residential garage for hydrogen fuelled vehicles. The experimental studies were carried out using helium and the numerical calculations were performed using FLUENT. Subsequently, Swain et al. [14] showed the appropriateness of using helium gas leak experiments to verify CFD models which can then be used to predict the distribution and concentration of hydrogen gas in a real leakage scenario. Although, the geometry of the enclosure and position of the leak determines the helium and hydrogen concentration distributions, the maximum deviation in concentration observed at steady states was around 15%.

Helium dispersion experiments were carried out in a single vehicle private garage in the GARAGE facility [15]. The same facility was used later to study helium distribution from low velocity helium releases [16], varying helium release rates and location of vents [17,18], helium release in unventilated enclosures [19] and release from a vehicle parked in a realistic garage [20]. INERIS had set up a large scale rock gallery facility to study hydrogen release in an isothermal confined area where effects of flow rates and duration on spatio-temporal distribution of hydrogen were investigated [21]. Large scale experimental studies on the effect of buoyancy driven ventilation on flammable gas mixture accumulation in domestic enclosure were also reported [22]. Experimental investigations on hydrogen release and the potential effects of hydrogen deflagration from a fuel cell vehicle inside a garage [23] and the effect of vehicles parked inside the garage [24] has been carried out. Under project DRIVE, the leak rates occurring in the hydrogen circuit were quantified and the formation of explosive cloud in an out of a vehicle alongside the probable effects of ignition of this flammable atmosphere were investigated [25]. For hydrogen safety and risk assessment in NPP containment scenarios, various large scale experimental facilities like TOSQAN [26], MISTRA [27], ThAI [28] and PANDA [29] have been used to generate experimental data for code validation exercises and CFD benchmarking studies [28,30–32].

With the development of CFD tools and computational power, simulation studies using CFD have been considered as a very important alternative to avoid safety risk of a hydrogen experiment and to get detailed information of the relevant phenomena associated with spatial dispersion of hydrogen, evolution of flammable clouds etc [33,34]. Although the CFD codes have proven to be a powerful tool, adequate validation and clear guidelines are necessary before these codes can be reliably used for real plant analysis. Swain et al. [35] carried out CFD investigations on helium dispersion experiments to predict hydrogen distribution in enclosures and concluded that except in regions near the origin of a leak or near a vent, the concentrations of hydrogen and helium were nearly the same. Swain et al. [35] garage experiments were later simulated by Papanikolaou et al. [36] using standard $k-\varepsilon$ model and results were in good agreement with experiments. Gallego et al. [12] selected Russian-2 experiment as Standard Benchmark Exercise Problem (SBEP) V1, and carried out an intercomparison exercise to compare the different numerical codes and models and their approaches and assumptions in reproducing the experimental data. The study emphasized the importance of turbulence models, type of grid, size of grid and the importance of hydrogen mass balance in numerical calculations. Transient behaviour of hydrogen leakage, mixing and evolution of flammable zones in simple confined and partially confined geometries to demonstrate the complex flow patterns have been investigated [37–40]. Agrawal et al. [41] introduced four numerical indices which form an useful tool for characterising the mixing process and hazards of flammable cloud formation in an enclosure following unintended hydrogen releases. Different studies have been carried out to compare the capability of CFD models to predict the outcome of hydrogen/helium dispersion in confined and unconfined spaces under various release scenarios in pipelines [42], automotive scenarios like leakage from storage tanks [43,44] and refuelling stations [45], tunnels [46], laboratories [47], garages and confined compartmented spaces [48–50] open atmospheres [51] etc.

Agrawal et al. [52] have presented a detailed review on the problem of hydrogen leak and its distribution, which includes details of the experimental facilities, numerical models and issues with heat and mass transfer sub-models. Avenues for further studies were also identified in the review. In order to address the issues identified in the above review, an experimental facility named AIHMS (AERB-IIT Madras Hydrogen Mixing Studies) has been installed and commissioned at the