Hydrogen Wide Area Monitoring of LH2 Releases at HSE for the PRESHLY Project

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Key Words: HyWAM, LH2, Safety, Dispersion, PRESLHY

ABSTRACT

The characterization of liquid hydrogen (LH2) releases has been identified as an international research priority to facilitate the safe use of hydrogen as an energy carrier. Empirical field measurements such as those afforded by Hydrogen Wide Area Monitoring can elucidate the behavior of LH2 releases, which can then be used to support and validate dispersion models. Hydrogen Wide Area Monitoring can be defined as the quantitative three-dimensional spatial and temporal profiling of planned or unintentional hydrogen releases. The NREL Sensor Laboratory developed a Hydrogen Wide Area Monitor (HyWAM) based upon a distributed array of hydrogen sensors. The NREL Sensor Laboratory and the Health and Safety Executive (HSE) formally committed to collaborate on profiling GH2 and LH2 releases, which allowed for the integration of the NREL HyWAM into the HSE LH2 release behavior investigation supported by the FCH JU *Prenormative Research for the Safe Use of Liquid Hydrogen* (PRESLHY) program. A HyWAM system was deployed consisting of 32 hydrogen measurement points and co-located temperature sensors distributed downstream of the LH2 release apparatus developed by HSE. In addition, the HyWAM deployment was supported by proximal wind and weather monitors. In a separate presentation at this conference, "*HSE Experimental Summary for the Characterisation, Dispersion and Electrostatic Hazards of LH2 for the PRESLHY Project*", HSE researchers summarize the experimental apparatus and protocols utilized in the HSE LH2 releases that were performed under the auspices of PRESLHY. As a supplement to the HSE presentation, this presentation will focus on the spatial and temporal behavior LH2 releases as measured by the NREL HyWAM. Correlations to ambient conditions, such as wind speed and direction, plume temperature and hydrogen concentrations will be discussed in addition to the design and performance of the NREL HyWAM, and its potential for improving hydrogen facility safety.

1.0 INTRODUCTION

Hydrogen wide area monitoring is defined as the quantitative spatial and temporal 3-dimensional profiling of planned and unintentional hydrogen releases. The NREL Sensor Laboratory developed a prototype hydrogen wide area monitor (HyWAM) in response to a need for empirical data on the dispersion behavior of cold hydrogen plumes. This data can then be used to develop and validate cold plume behavior models. The NREL HyWAM is based upon an array of sensors and sampling points distributed around a hydrogen facility to continuously profile hydrogen dispersions following releases and was originally developed to characterize outdoor cold hydrogen plume behavior following venting of liquid hydrogen (LH2) [1]. The characterization of cold hydrogen releases with the NREL HyWAM is on-going and some of the most recent deployments was the collaboration with the Health and Safety Executive (HSE) in the United Kingdom in support of the PRESLHY program [2] and other HSE

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hydrogen safety research and development efforts (e.g., HyDeploy [3]). HSE was active in numerous PRESLHY work packages, including WP3 (Release and Mixing) [4], WP4 (Ignition) [5], and WP5 (Combustion) [6], and most recently WP6 (Implementation) [7]. One function of WP6 is to assure proper dissemination of test results and data to the hydrogen energy community to allow modelers and other stakeholders in the hydrogen energy community access to data to validate behavior and dispersion models [8]. WP3, WP4, and WP5 each involved a series actual LH_2 releases and their characterization. The HSE PRESLHY release studies provided an opportunity to obtain empirical field measurements of real-world cold hydrogen plume dispersions. It also provided an opportunity to demonstrate the capability of the NREL HyWAM. HSE has a history of investigating the behavior of cold hydrogen releases (e.g., [9] [10] [11]) and the NREL Sensor Laboratory has extensive experience in gas measurements and has developed a HyWAM to support profiling hydrogen releases [12], including the profiling of cold hydrogen plumes [13] as well as indoor gaseous hydrogen release behavior [14]. The NREL-HSE collaboration to profile hydrogen releases was formalized in 2019 [15]. A goal of this effort was to improve the understanding of cold plume behavior to ultimately improve the design of hydrogen facilities and to better inform setback distances, especially those required for LH2 facilities as prescribed in NFPA 2 [16].

Details on the HSE LH2 release apparatus and their participation in the PRESLHY project has been published in a report [17] and presented at a PRESLHY Dissemination Conference [8]. The HSE PRESLHY work will also be a topic of a 2021 International Conference on Hydrogen Safety (ICHS) paper (ICHS #024: "*HSE Experimental Summary for the Characterisation, Dispersion and Electrostatic Hazards of LH2 for the PRESLHY Project*") [18]. The work described in this paper supplements the HSE 2021 ICHS paper and will focus on the design and use of the NREL HyWAM at HSE for their PRESLHY LH2 release work and to provide an overview of critical outcomes of the HyWAM deployment. A preliminary assessment on the use of the NREL HyWAM in the HSE PRESLHY study was presented at the 2019 ICHS conference [19], but the discussion was limited because the LH2 releases were just initiating at the time of the conference. Some results and analyses were included in the special issue for the International Journal of Hydrogen Energy for the 2019 ICHS conference [20]. This paper will provide more details of the cold hydrogen behavior as measured by HyWAM that were not available for inclusion in the 2019 ICHS presentation.

2.0 APPROACH

HSE had developed a test facility and specialized hardware to carry out the PRESLHY LH2 releases as described by Lyons et al. [17]. The HSE LH2 release apparatus was designed to monitor and control critical experimental LH2 release parameters, and included sensors for monitoring hydrogen mass flow rate, internal pressure and temperature sensors, and orifice position and direction. The test apparatus also included external ambient weather sensors and video recording of tests [17]. In 2019, personnel from the NREL Sensor Laboratory worked on-site with HSE personnel to deploy a 32-point HyWAM system at the HSE LH2 Release facility. The NREL HyWAM is based upon an array of hydrogen measurement points distributed around a hydrogen facility. The NREL HyWAM uses an array of hydrogen thermo-conductivity sensors. A thermo-conductivity sensor was selected because of its metrological properties as confirmed by laboratory evaluations using test methods and apparatus developed by the NREL Sensor Laboratory [21]:

- Broad, nearly linear measurement range (from 0 to 100 vol% H_2)
- Good detection limits (ca. 0.1 vol% H_2)
- Fast response and recovery times (t_{90} < 250 ms)
- No hysteresis (even when exposed to 100% vol% H_2
- Good selectivity

Other sensor types may be included in HyWAM, including different hydrogen sensor types, physical sensors (e.g., T, P, RH, heat flux) and weather sensors (e.g., wind speed and direction). During the HSE LH2 releases, most hydrogen measurement points were co-located with thermocouples for local temperature measurements. Wind speed and direction was monitored during the releases with anemometers. Although sensors can be mounted directly within the plume for in-situ measurements, the NREL HyWAM was configured to continuously collect and transport gas samples to remote hydrogen sensors using pneumatic lines and gas pumps. This approach provides real-time spatial and temporal profiling of the cold hydrogen plume, while accommodating site safety requirements pertaining to the use of electrical equipment, including the hydrogen sensors that are not listed for hazardous locations while at the same time allowing flexibility in positioning of the gas measurement points. In this operation mode a *sampling point* is defined by the location of the inlet of the pneumatic tube within the plume. Conversely, sensors for physical parameters, such as thermocouples for ambient temperature measurements were mounted directly in the plume for in-situ measurements. For the HSE PRESLHY LH_2 releases a custom-designed support structure was assembled to accommodate a 3-dimensional distribution of precisely positioned sampling points. An illustration of the support structure and the location of the sampling points is shown in Figure 1. The support structure was mounted directly in front of the LH2 release point, and the sampling points were distributed directly in the expected cold hydrogen plume. Figure 1 illustrates the sampling point distribution relative to the LH2 Release Point (RP) for the horizontal LH2 release configuration. The position of the sampling points ranged from 0.35 m to 6.0 m from the release point, and 8 sampling points were positioned directly in line with the release direction, as well as 4 sampling points each for above, below, left and right of the release direction. The specific coordinates of the release point and sampling points are summarized in Table 1 (extracted from Table D3.6 in [16]). Each sample point consists of a pneumatic line connected to a remote hydrogen sensor. Most sampling points were co-located with thermocouples for simultaneous hydrogen and temperature profiling of the cold hydrogen plume. Complete details on the design of the NREL HyWAM, including the selection and performance assessment of the hydrogen sensors and its deployment at HSE was previously described [20], [22].

Table 1: Distribution of the 32 HyWAM sampling points. All distances are in meters and given relative to the release point or the centerline from the release point.

Centreline (Module I)			Below 1 (Module II)			Below 2 (Module II)			Left (Module III)			Right (Module III)			Above 1 (Module IV)			Above 2 (Module IV)		
X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
6.00	0	0	6.00	0	-0.25	6.00	0	-0.5							6.00	0	0.5	6.00	0	0.25
4.00	0	0	4.00	0	-0.25	4.00	0	-0.5	4.00	-1	0	4.00	1	0	4.00	0	0.5	4.00	0	0.25
2.67	0	0							2.67	-1	0	2.67	1	0		0	0.5			
1.78	0	0	1.78	0	-0.25	1.78	0	-0.5	1.78	-1	0	1.78	1	0	1.78	0	0.5	1.78	0	0.25
1.19	0	0																		
0.79	0	0	0.79	0	-0.25	0.79	0	-0.5	0.79	-1	0	0.79	1	0	0.79	0	0.5	0.79	0	0.25
0.53	0	0																		
0.35	0	0																		
8			4			4			4			4			4			4		

A summary on the performance of NREL HyWAM at the HSE LH2 release study was presented at the 2019 ICHS [19], but the discussion was brief because the release study only initiated just a few days prior to the conference. In part, this was due to delays in the acquisition of the LH2, which postponed execution of the releases from spring until early fall of 2019 . As a result, most testing was completed after the conference. Further preliminary assessments on the NREL HyWAM measurements and an analysis of hydrogen behavior have since been performed. Details on the HSE experimental setup and the HyWAM data were delivered to the PRESHLY program office by the HSE Project Team [18]. Representative release behavior as measured by the NREL HyWAM is presented in Section 3. At the conclusion of the PRESLHY project, all test data was to be made openly available on the Karlsruhe Institute of Technology (KIT) open research data repository [23] to allow for dissemination. The data are available to all stakeholders. Data availability in the KIT repository fulfill Horizon 2020 [24] requirements of being findable, accessible, interoperable and reusable (FAIR) [25].

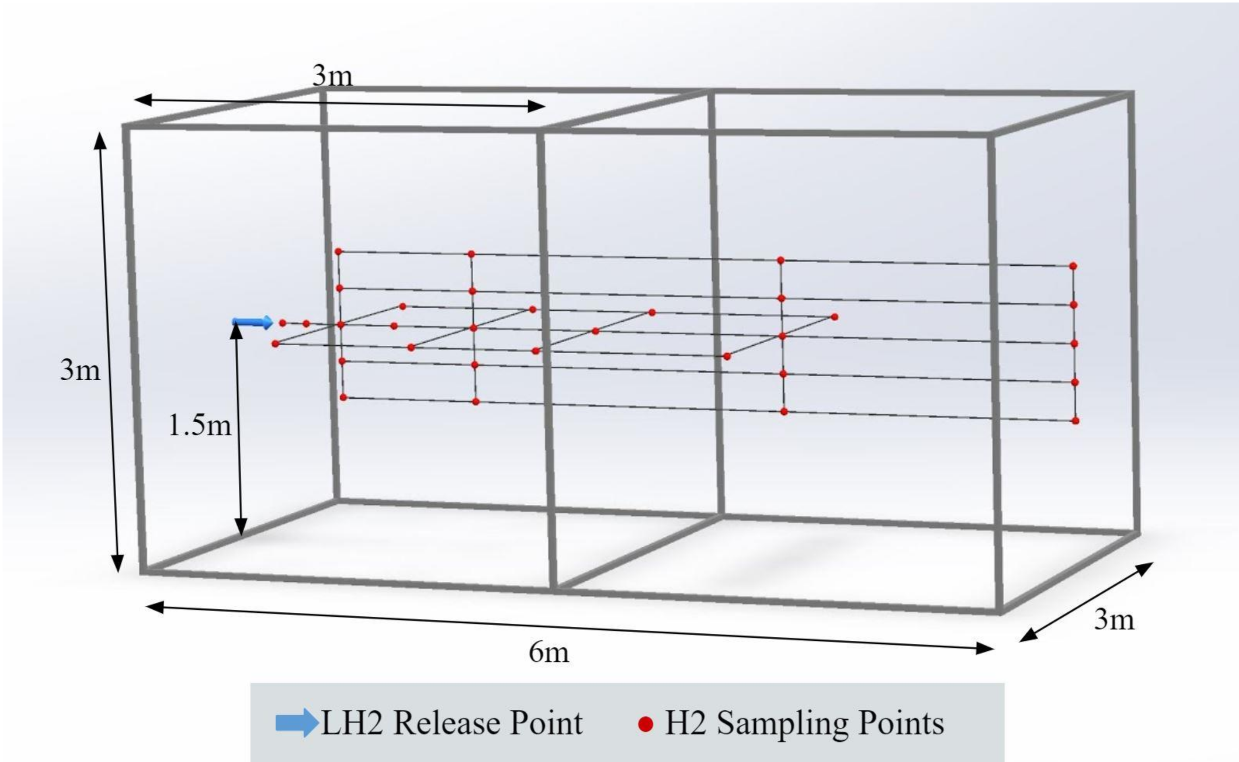

Figure 1: The fully assembled support structure (3 m by 3 m by 6 m) mounted directly downstream from a horizontal LH2 Release Point (RP). The red dots represent sampling points used for the LH2 releases.

3.0 RESULTS

3.1 Cold Plume Profiling by the NREL HyWAM

During the HSE PRESLHY LH2 release study, nearly 20 LH2 release scenarios were planned for WP3, as summarized in Table 2 of [26]. The releases were developed for different geometric parameters (height of release and horizontal vs. vertical release direction), orifice diameter and head pressure controls. However, testing was performed on different days and thus under variable weather conditions, including ambient temperature and wind conditions.

It was found that wind direction relative to the release direction had significant impact on the cold plume dispersion. This is clearly indicated in Figure 2 and subsequent figures, which plots the hydrogen temporal profiles for the 8 sampling points just downstream from the release point for two different releases:

- Run 2 was on a day with near steady wind speed with an average wind speed of 4.80 m/s with gusts up to 9.8 m/s (Figure 2, Right). The wind direction was nearly orthogonal relative to the release point.
- Run 4 was on a calm day, with a wind direction that were nearly in-line with the LH2 release direction with an average wind speed of 1.80 m/s and short gusts up to 7.2 m/s but with a period of near zero wind speed (Figure 2, Left)
- Run 12 was on performed on a day with near constant wind with an average wind speed of 3.40 m/s and in a direction that is nearly in-line with the release direction (Figure 5).

The wind speed and direction measurements corresponding to the hydrogen data plotted in Figure 2 for Runs 2 and 4 are plotted in Figure 3. With a low-velocity wind essentially in line with the release direction (Run 4, Figure 2 Left), the hydrogen profiles tend to move along with the wind and remain at significant concentrations out to 6 m (up to 20 vol%). At the nearest sampling point (0.35 m from the release point), hydrogen levels of up to nearly 90 vol% were measured with an average level of 50 vol%. Conversely, an orthogonal wind direction facilitated dispersion. At 6 m from the release point, the hydrogen is nearly totally dissipated, while at 0.35 m, the maximum level is less than 70 vol% (and an average level of approximately 20 vol%).

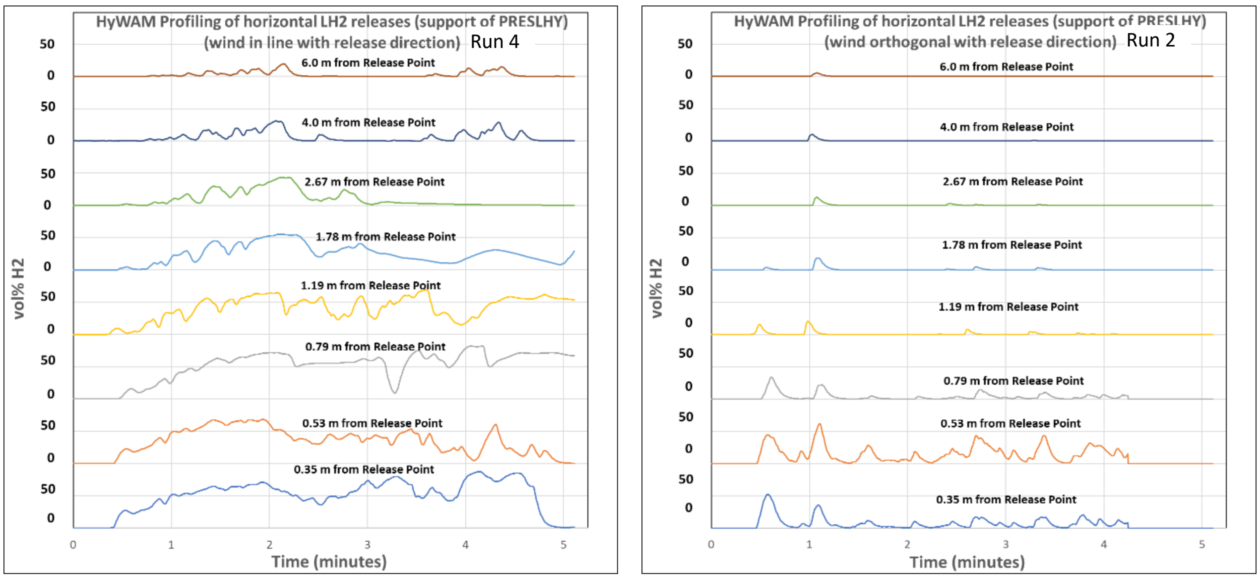

Figure 2: Hydrogen profiles for two LH2 releases performed (LEFT) on a day with the wind direction in line with the release direction (Run 4) and (RIGHT) on a day with a wind direction nearly orthogonal to the release direction (Run 2).

The impact of wind on hydrogen dispersion is further illustrated in Figure 4 which shows hydrogen profiles 0.79 m from the release point and to the left (downwind) and right (upwind) for the release point. The hydrogen is transported in the direction of the wind as evidenced by the higher concentration for the downwind profile with the orthogonal wind direction.

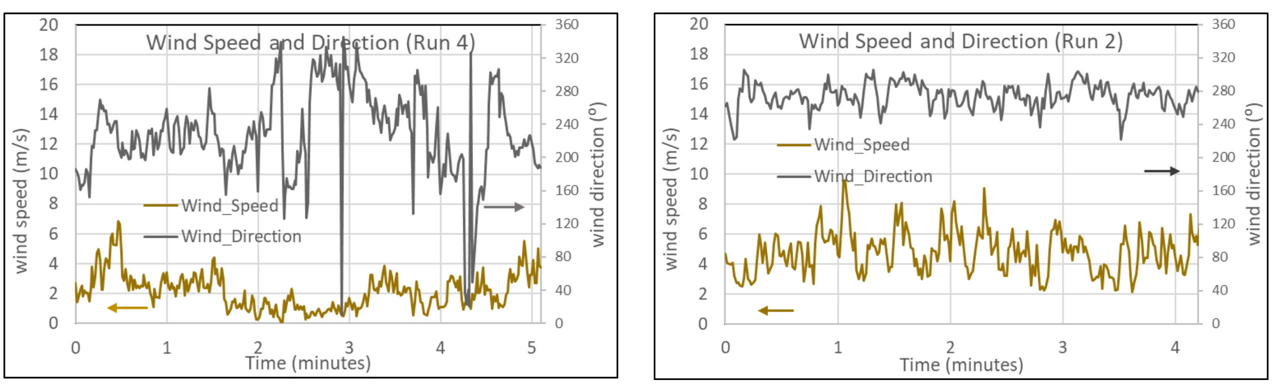

Figure 3: Wind speed and direction for the runs shown in Figure 2. A variable wind direction was observed for Run 4, but the wind on average was more in line with the release direction. However, when the wind dropped to near zero at about 3 minutes the hydrogen dispersion rate increased as evidenced by the hydrogen profiles for Run 4. (Right), hydrogen dispersion increased with a more orthogonal wind direction.

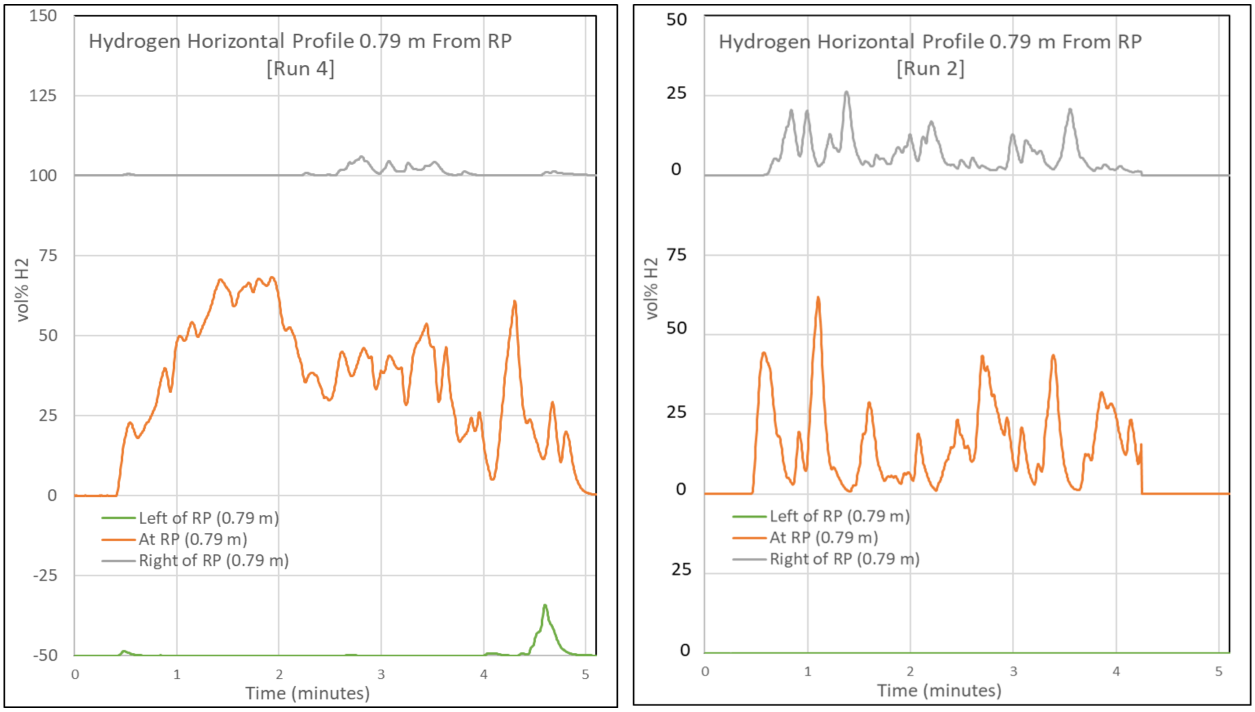

Figure 4: Impact of wind direction on horizontal hydrogen dispersion. (Right) For an in-line wind speed the hydrogen profiles to the left (downwind) and right (upwind) of the release point are near zero. (Left) For an orthogonal wind direction, a significant hydrogen concentration appears left (downwind) of the RP.

Multiple horizontal and vertical LH2 releases were performed over the course of several weeks. Run 12 was a horizontal release that also had a steady wind of moderate velocity that was almost directly in line with the release direction. Figure 5 shows the average wind speed and direction for this run, along with an annotated photograph of the release direction relative to the wind direction. The wind direction is essentially in line with the release direction. The wind direction was similar to Run 4 (Figure 3), but unlike Run 4 the wind maintained a near constant direction and speed for Run 12.

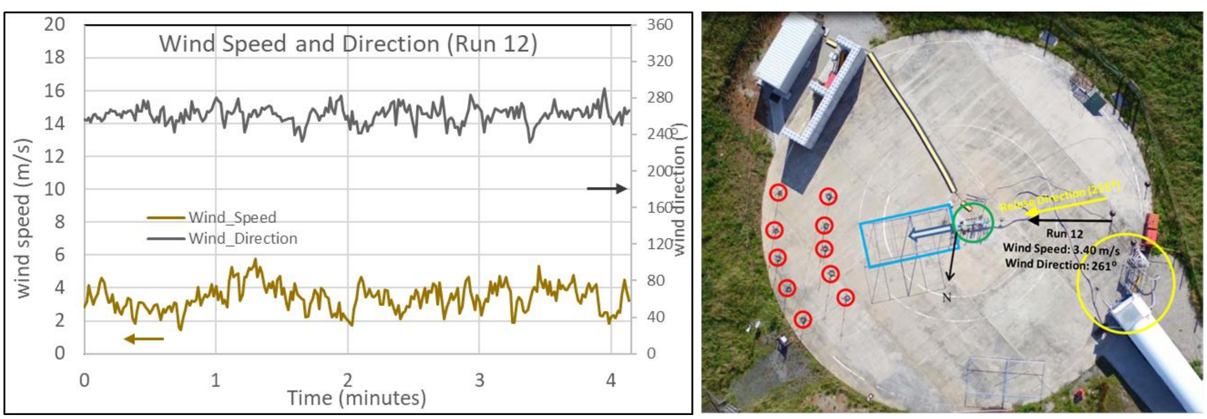

Figure 5: (Left): Wind speed and direction for Run 12. A moderate wind speed (3.4 m/s) prevailed during the test but was notable for being steady and nearly in line with the release direction. (Right): Illustration of the LH2 release direction relative to the wind direction.

Concentration profiles directly downstream from the release point for Run 12 are shown in Figure 6. In some runs, the sensor inlets near the release point suffered from icing and subsequent blockage which affected the measured hydrogen concentration. This is evident in the concentration profiles, where lower than expected values were recorded during the test for the nearest sampling point (0.35 m). This behavior affected primarily the closest sampling point, especially after the test had been running for several minutes (note the drop in hydrogen level at 0.35 m prior to the end of the release). Figure 6 also presents a 3-dimensional contour of the average concentration, over the duration of the run, again the lower-than-expected value at 0.35 is evident.

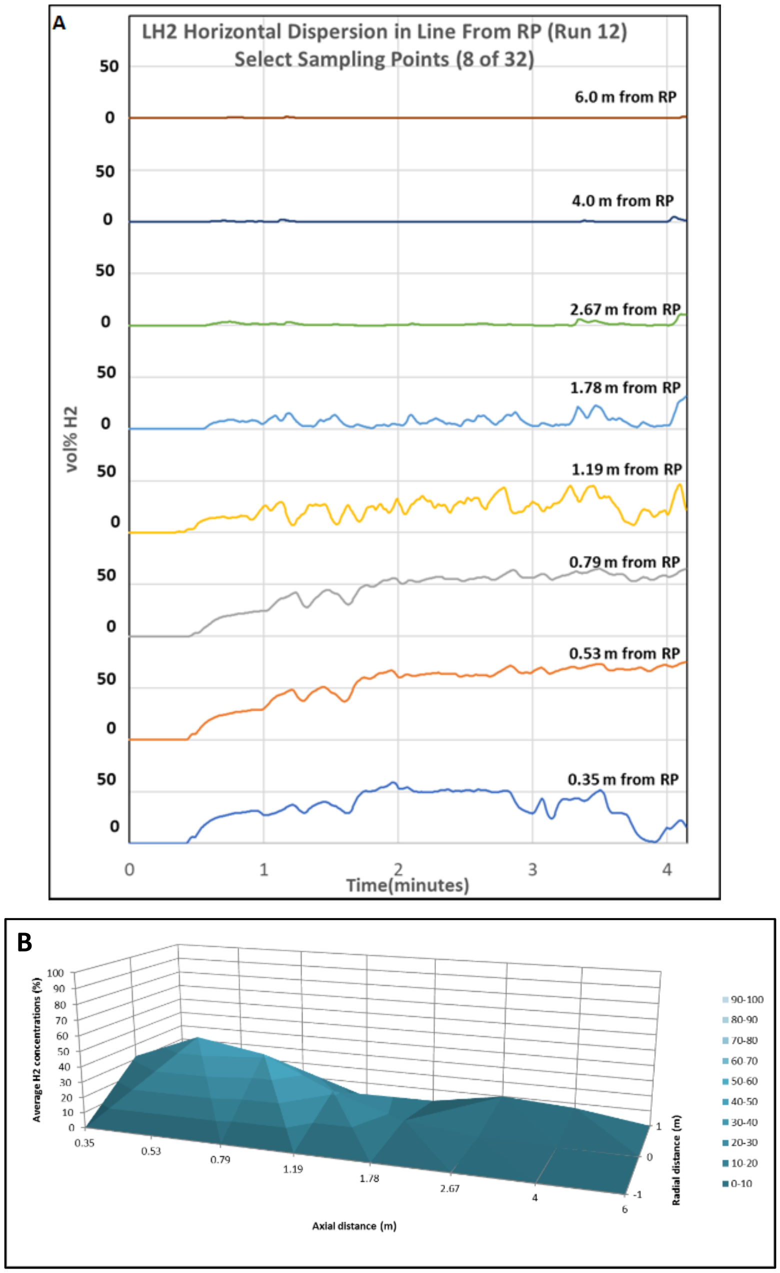

Figure 6: (A): Concentration profiles for 8 of 32 HyWAM measurement points. These measurement points were directly downstream from the RP. The drop in vol% H_2 for the 0.35 m profile is believed to be due to icing of the sample inlet tube which occurred in some test. (B) 3-dimensional profile of the average concentration at each HyWAM measurement point on the centerline, showing concentration drop at 0.35 m.

3.2 Correlation of Hydrogen Concentration to Temperature

Thermocouples were co-located with most of the hydrogen sampling points, which provided an opportunity to perform simultaneous temperature and hydrogen concentration measurements. In an earlier study only a small correlation between temperature and the cold hydrogen plume was observed [13]. This was a preliminary study, and the earlier observation can be ascribed to the experimental setup and the nature of the measurements. While high levels of hydrogen were observed, they were transitory in nature (typically less than a few seconds). Also, the thermocouples were not rigorously co-located with the corresponding sampling point, and it is possible that the HyWAM hydrogen sensors were monitoring a proximal but different gas environment than the thermocouples. However, in the work described in this paper, a much stronger correlation between the near-field hydrogen measurements and temperature was observed, as shown in Figure 7. Figure 7 shows temporal plots of the gas temperature and vol% H_2 (with a time correction to compensate for transit time through the pneumatic line). An excellent correlation is observed, even with low hydrogen concentrations. This is significant for it adds credibility to the adiabatic mixing assumption for estimating hydrogen concentrations in cold plumes from temperature measurements. Simultaneous temperature measurements with the co-located thermocouple indicate that the temperature near the hydrogen concentration maximum is nearly -40 °C (Figure 7). For low, near-zero hydrogen levels, the temperature is +15 °C.

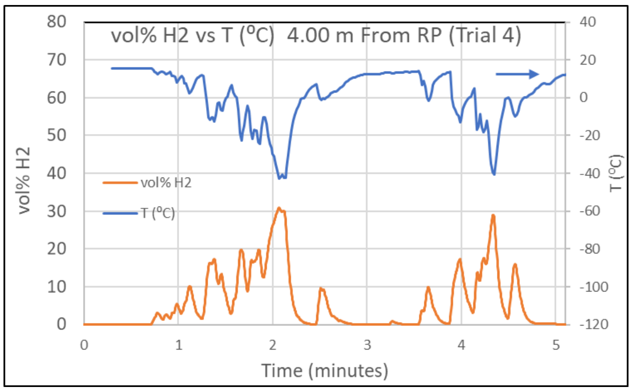

Figure 7: A representative plot of the hydrogen concentration as measured by HyWAM vs. the corresponding temperature profiles as measured by a co-located thermocouple.

The correlation between cold plume temperature and hydrogen concentration is further illustrated in Figure 8. Figure 8 is a plot of minimum temperature versus maximum concentration for all measurement locations over all the runs, again a good correlation is observed. Although this does not validate the adiabatic mixing assumption for the determinization of hydrogen levels in cold hydrogen plumes, it does demonstrate that there is a strong temperature-hydrogen concentration correlation, at least in the near-field range from the LH2 release. Validation of the adiabatic mixing assumption with the HyWAM measurements is ongoing at HSE.

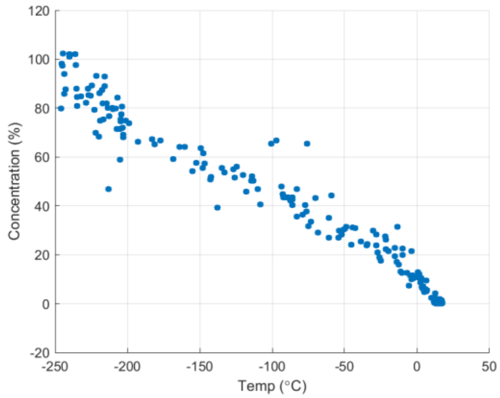

Figure 8: Overall correlation of minimum temperature and maximum concentration for all measurement locations for all runs.

4.0 SUMMARY

In September 2019 HSE initiated a series of LH2 releases in support of PRESLHY [2]. The NREL HyWAM was used during to profile the cold hydrogen plumes. The analysis of the results is on-going, of which some was presented here and in [20]. HyWAM data is also available in the KIT data repository. To support the HSE PRESLHY project, NREL deployed the HyWAM system to profile the cold hydrogen plumes formed during the LH2 release events. This work described herein focused on some of the hydrogen measurements made with the NREL HyWAM. Several key observations on cold hydrogen plume behavior were made. First, environmental condition, especially wind can control the release behavior. Secondly, the temperature of the plume is strongly correlated to the concentration of the hydrogen, at least for near field measurements. The data collected during this testing program will be made publicly available under the framework of the PRESLHY project, where it will be used to support modelling activities and feed into the development of hydrogen safety regulations, codes, and standards (RCS).

The deployment also verified the viability of the NREL HyWAM and its potential as an active monitoring system. Operationally, several key findings can be made for the NREL HyWAM:

- The NREL HyWAM performed well throughout the release program and showed no signs of drift or temperature effects caused by the LH2. The use of pneumatic lines to collect samples from within the plume minimized the impact of the harsh conditions within the plume and simplified the deployment requirements associated with use of equipment in classified areas.

- The open frame support structure performed well and supported both the HyWAM sampling points and co-located thermocouples, at least for horizontal releases. The open frame support structure did not appear to interfere with the hydrogen dispersion.

- The closest sample points did suffer from ‘icing’ for some of the tests. This sometimes even led to physical oscillation of the sample tube due to the momentum of the jet. An attenuation of the hydrogen concentration was also observed after icing (due to a physical blockage on the sample line).

- The NREL HyWAM sensors and mode of operation seem to be a very viable method of measuring point concentrations of H2 clouds from an LH2 release.

In is envisioned that the NREL HyWAM will be the basis for a commercial instrument to support active monitoring at hydrogen facilities [27].

5.0 ACKNOWLEDGEMENTS

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Hydrogen and Fuel Cell Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes. The development and deployment of the NREL HyWAM was supported through the DOE Hydrogen and Fuel Cells Technology Office, Hydrogen Safety Codes and Standards Program (Laura Hill, Program Manager).

The HSE PRESLHY project received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 779613. The contents of this paper, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

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