Characterising the Acoustic Properties of Hydrogen Leaks

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Abstract— **The transition toward a global hydrogen economy has spurred major investments in transport and energy, yet the safe management of inevitable leaks remains a critical challenge. Large-scale hydrogen farms require cost-effective, instantaneous monitoring solutions. This project investigates the feasibility of detecting high-pressure hydrogen leaks acoustically before they register on standard particle detectors. Because hydrogen leaks typically act as choked free jets, they are anticipated to produce distinct jet screech tones with spectral classifications entirely different from air. To characterise these acoustics, a dedicated, remotely operated hydrogen jet facility will be designed and commissioned within the Monash University Shock Lab. This paper details the strict safety methodologies, thermodynamic considerations, and fluid system design required to safely conduct these experiments, laying the groundwork for initial high-speed schlieren and acoustic testing.**

I. INTRODUCTION

THE rising global investment towards a transport and energy industry powered from hydrogen has exposed existing issues with safe storage management of inevitable hydrogen leaks. The global hydrogen market is expected to reach US$1.4 trillion in 2050 [1], to meet this demand, large scale hydrogen farms will be needed, demanding a safe, cost-effective way to monitor leaks produced.

Traditional particle leak detectors suffer from several issues that will affect scaling the hydrogen industry. They have delayed response times from requiring a dispersion of the leaking hydrogen before it is detected. Furthermore, they only provide an extremely local measurement, and thus massive quantities will be needed to adequately cover the area required. Additionally, they are costly. Using basic acoustic measurements has the potential to bring the cost down while being able to instantaneously detect hydrogen leaks with the only delay being the sound speed, with the range only being restricted by the microphone sensitivity.

This is possible because when hydrogen leaks it typically acts as a free jet due to having a choked critical pressure ratio of ~1.9, the overwhelming majority of hydrogen is stored at much higher pressures than this due to it being either stored as a compressed gas (typically 100-300 bar) or as a sub-cooled liquid (typically 10-16 bar). It is expected that when these supersonic leaks occur, jet screech tones will be produced. The acoustic spectra of the hydrogen should differ greatly to that of air, so these new spectra will need to be characterised. Jet screech is seen as distinct peaks at specific frequencies caused by an aeroacoustic feedback loop in the exhausts of jets (see figure 1) [2].

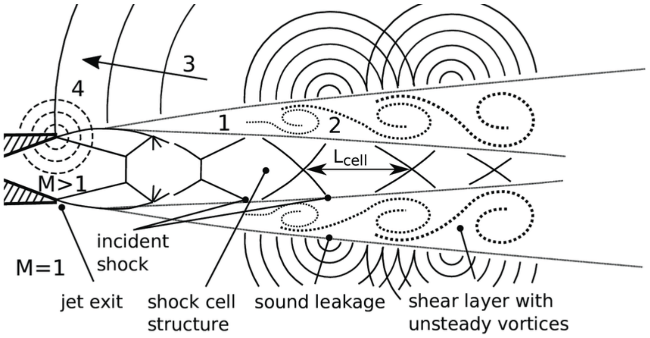

Fig 1. Schematic of jet screech noise mechanism.

To characterise the hydrogen leaks, a safe hydrogen jet facility will need to be made. The primary aim of this project is to build and commission this facility and take first measurements of a hydrogen jet with high speed schlieren and acoustic measurements and determine if hydrogen screech tones are detectable and what they are.

II. SAFETY AND REGULATORY COMPLIANCE

The primary constraint concerning any experiment with hydrogen is safety. In Australia, WorkSafe and AS/NZS IEC 60079.10.1 Explosive atmospheres both dictate the safety practices that must be followed for this hydrogen jet facility.

A. Hazard Classification and Ignition Mitigation

Hydrogen is extremely flammable, a Lower Explosive Limit (LEL) determines the safe quantity of hydrogen in any given volume of air, which is 4% by volume. The Occupational Health and Safety Regulations 2017 – Reg 60 states a person can only be in a confined space when the flammable gas is below 5% of its LEL [3], but if it is above 10% of its LEL the person must be removed from the space. For this experiment it is impracticable to maintain a 5% LEL, so all persons will be removed from the space. A self-imposed factor of safety of 4 will be put on the LEL to account for any uneven mixing and concentrations.

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B. Ventilation and Dilution Standards

The jet sizing was based directly on the extraction capable in the lab and ensuring it remained within the bounds given by AS/NZS IEC 60079.10.1. The experimental jet was classified as a "primary" grade of release with a Type B opening classification. The lab's dedicated local ventilation system provides an extraction velocity of 19 m/s. According to the standard, this velocity constitutes a "high" degree of dilution for release rates under 1500 L/s (see figure 2). Due to the high dilution and primary release grade during operations, the testing area is classified as Zone 1 NE (negligible extent), effectively rendering the operational zone non-hazardous.

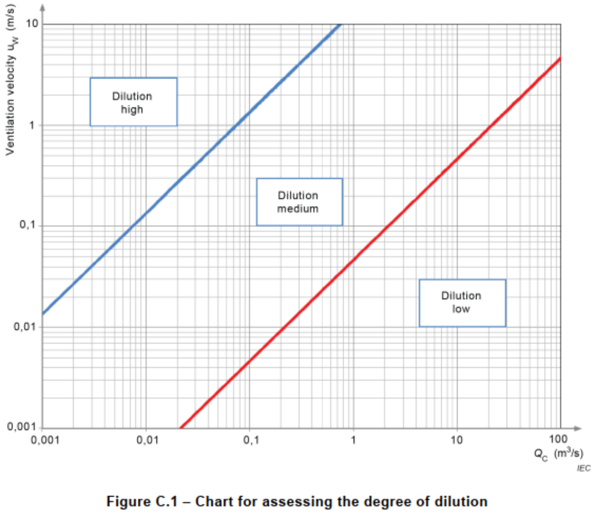

Fig. 2. Chart for assessing the degree of dilution [4].

C. Background Concentration

While general room extraction without local mitigation would theoretically result in a background concentration (Xb) of 63% of the LEL, which doesn't meet the critical threshold of 25%, this assumes a steady-state, continuous release and a general room extraction as opposed to a local extraction hood. Because the blowdown experiments are transient and utilise active local extraction, the background concentration can be safely considered zero during normal operations. As a redundant safety measure, atmospheric hydrogen detectors will be placed throughout the facility.

III. EXPERIMENTAL FACILITY DESIGN

This facility will utilise the existing Shock Lab room at Monash University, existing infrastructure will be leveraged where possible.

A. Fluid Systems Control

The gas feed system requires a strict order of operations, controlled remotely to ensure personnel are isolated from the test cell during active hydrogen flow. To address off-nominal conditions, an emergency stop (e-stop) system will be routed directly to the operator's control station. Engaging the e-stop initiates an automated abort sequence that immediately isolates the hydrogen supply and cuts power to the normally open (NO) pneumatic valves to dump residual line pressure into the safe extraction path (as shown in figure 3). A dedicated nitrogen purge sequence is integrated into the control architecture, running both before the hydrogen supply is opened, during e-stop and immediately following the conclusion of a test run to ensure no combustible mixtures remain in the feed lines. Additionally, the components used will be from Swagelok, to ensure minimal leaks, maximum compatibility and high reliability.

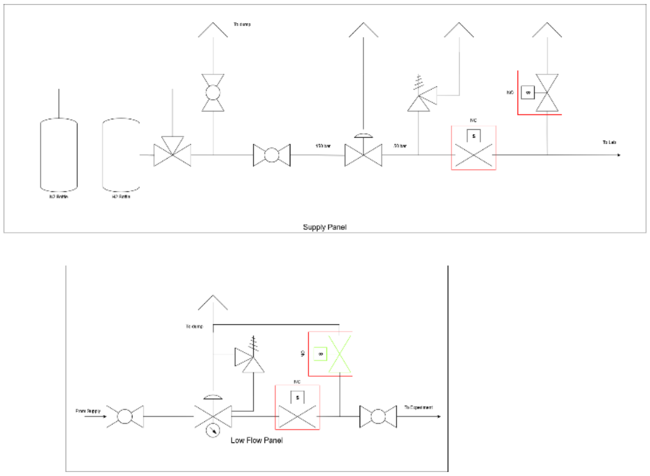

Fig. 3. Piping and Instrumentation Diagram for Lab Feed System.

B. Jet Sizing and Thermodynamics

To induce the required choked flow while remaining within the safe dilution limits of the 19 m/s extraction system, the jet nozzle was sized using isentropic flow equations.

$$\frac{T}{T_0} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{-\gamma}{\gamma-1}} \tag{1}$$

$$U = M\sqrt{\gamma R T} \tag{2}$$

$$\dot{m} = \frac{A_t p_0}{\sqrt{T_0}} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \tag{3}$$

Applying a 1.25 factor of safety to the calculated mass flow rates gives a maximum nozzle diameter of 3.5 mm. At a nozzle pressure ratio (NPR) of 6, this diameter yields a predicted hydrogen volumetric flow rate of 43.8 L/s

$$\dot{V} = \frac{\dot{m}}{\rho}. \tag{4}$$

using isentropic relations, which with LEL applied sits below the extraction system's 1500 L/s ceiling. It is critical to note that thermodynamic modelling must account for the substantial cooling of the hydrogen gas as it expands through the nozzle, this rapid temperature drop significantly increases the local gas density, which will directly alter the real mass flow rate and the resulting acoustic signature compared to assuming room temperature.

IV. METHODOLOGY AND METHODS

The jet must be sized such that the equipment used for measurement, both a high speed schlieren set up and an acoustic microphone can detect the expected frequency range of the screech tones.

Because hydrogen is typically stored as a high-pressure compressed gas or sub-cooled cryogenic liquid well above atmospheric pressure, it can be assumed that all leaks will result in choked flow.

To ensure safety, the nozzle diameter is restricted to 3.5 mm or less to maintain safe extraction across pressure ratios up to 6. The selected equipment allows for theoretical measurements up to a Strouhal number of 1.46 (figure 4). The acoustic phenomena of interest are expected to occur at Strouhal numbers between 0 and 0.2 for hydrogen [5] based on Large Eddy Simulations performed. These values are currently theoretical and thus a minimum Strouhal number of 1 will be required to ensure any potential screech tones are captured as this is a known expected maximum for air based on extensive research.

$$St = \frac{fL}{U} \qquad (5)$$

Due to this being a converging nozzle, choked flow will ensure the exhaust velocity is constant regardless of pressure ratio and the only variables that affect the Strouhal number is the frequency and nozzle diameter. The high-speed camera in the lab can measure up to 500 kHz, using this and the goal to resolve a minimum Strouhal number of 1, figure 4 shows the nozzle size is not constrained by the measurement requirements and instead will be flow rate constrained.

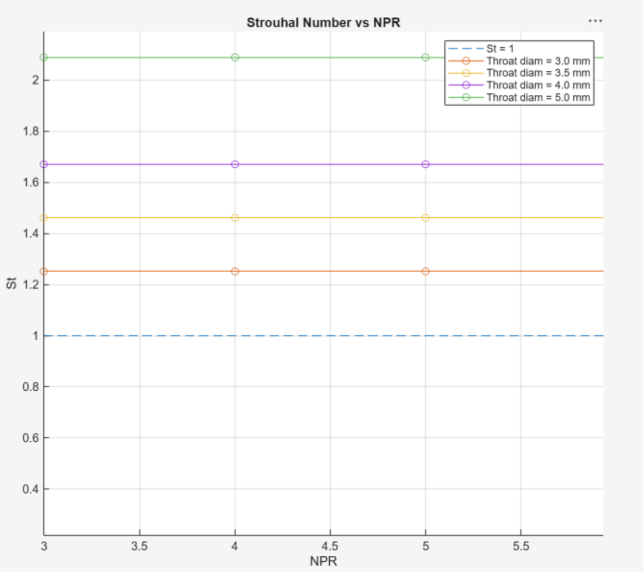

Fig. 4. Strouhal number vs Nozzle Pressure Ratio for various jet diameters.

Following the critical design and feasibility review, the immediate methodology involves the assembly, leak-checking, and commissioning of the physical rig to initiate testing and subsequent data analysis. The first tests will likely be performed with nitrogen gas, which is inert and removes the flammability risk if there are issues that arise.

V. PROJECT TIMELINE AND FUTURE WORK

Currently this project is at the late stage of the feed system design and purchasing is scheduled to begin end of Week 12 (see figure 5). Following this, the jet itself will need critical design and manufacturing.

Commissioning of the facility will require assembly of all the fluid panels, leak testing of individual sections, then a complete assembly leak test using inert nitrogen. Full actuation tests will be needed to confirm the controller is working as intended, with all the e-stop and purge functions working. Finally, a complete gas test will be done with nitrogen gas before doing the first hydrogen test.

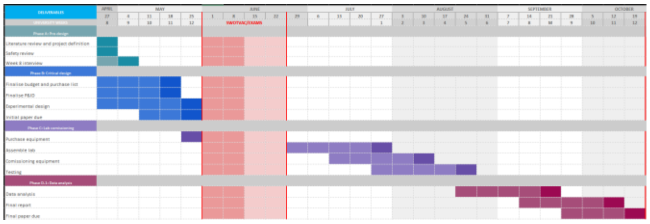

Fig. 5. Project Timeline.

The project will be concluded with data analysis, using techniques such as Spectral Proper Orthogonal Decomposition (SPOD) and determining the Power Spectrum Density (PSD) to locate potential screech tones and other phenomena that might arise.

VI. CONCLUSION

The development of a safe, reliable hydrogen jet facility is a critical first in characterising the acoustic properties of hydrogen leaks. By adhering to hazardous atmosphere regulations, employing high-dilution local extraction, and integrating an automated emergency stop system, the severe flammability risks of hydrogen are mitigated. With the physical infrastructure and safety parameters established, the project will move into its purchasing and commissioning phase, beginning with inert nitrogen tests before progressing to hydrogen. With the eventual goal of characterising the acoustic spectra of hydrogen jets to determine the viability of acoustic leak detection in a growing hydrogen industry.

ACKNOWLEDGMENT

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