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Experimental investigation of nozzle aspect ratio effects on underexpanded hydrogen jet release characteristics

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ABSTRACT

Most experimental investigations of underexpanded hydrogen jets have been limited to circular nozzles in an attempt to better understand the fundamental jet-exit flow physics and model this behaviour with pseudo source models. However, realistic compressed storage leak exit geometries are not always expected to be circular. In the present study, jet dispersion characteristics from rectangular slot nozzles with aspect ratios from 2 to 8 were investigated and compared with an equivalent circular nozzle. Schlieren imaging was used to observe the jet-exit shock structure while quantitative Planar Laser Rayleigh Scattering was used to measure downstream dispersion characteristics. These results provide physical insight and much needed model validation data for model development.

Introduction

A prerequisite for large-scale hydrogen storage and delivery infrastructure development is the implementation of science based safety codes and standards that are guided by validated engineering models within quantitative risk analysis tools [1]. A key input required for the efficacy of these tools is the release morphology and dominant flow phenomena from unintended hydrogen leaks [2]. Releases are typically assumed to be from circular sources since for fixed mass flow rates that are thought to produce the most conservative (i.e., longest) hazard boundaries used to specify separation distances [3,4]. Furthermore, a substantial amount of work has been performed to characterise relevant parameters due to axis symmetry, which is amenable to simplified one-dimensional modelling [5–11]. Releases from more realistic cracks and slits, are expected to have shorter flammable extents due to larger ratios of mixing surface area to leak volume. However, for applications where suitable separation distances from hydrogen bulk storage are prohibitive (e.g., releases from on-board storage) there remains a danger that highly flammable mixture could develop close to the release point, which could increase the localised harm potential [12].

Beck et al. [13], has developed analytic methods to model mass flow rates from cracks with varying tortuosity as a function of pressure dissipation from viscous, inertial, and expansion effects. Large pressure losses from thin cracks are likely to result in incompressible planar or slot jets, which Krothapalli et al. [14] noted contain 3 prominent decay regions: the potential core, a two-dimensional region with an inverse half-power centerline decay rate, and the canonical axisymmetric region observed for circular jets with an inverse centerline decay rate. Mi et al. [15] further noted the existence

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of a transition region between the two-dimension and axisymmetric regions that shrinks as nozzle aspect ratio (AR) increases. For lower AR releases where exit backpressures relative to the ambient are expected to be above the critical ratio (~1.9 for hydrogen), exit flows choke and an under-expanded jet with complex near-field shock structure forms. A Mach disk serves as the boundary between the supersonic and subsonic jet portions, and can be several factors larger than the original release diameter. Notional nozzle models have been developed to predict circular nozzle effective diameters and thermodynamic state variables; the effectiveness of different model formulations for choked hydrogen flows was evaluated experimentally by Ruggles and Ekoto [11] and numerically by Papanikolaou et al. [10]. Beyond the compressible flow region, subsonic integral dispersion models have been used to reconstruct mean scalar and velocity fields [7,8,16]. No analogous choked slot source model exists due to a lack of downstream scalar and/or velocity validation data.

Despite the lack of downstream dispersion measurements, there has been limited experimental and numerical research into choked slot nozzle near-field flow features for various gases. Rajakuperan and Ramaswamy [17] observed that the shock structure along the major axis of underexpanded elliptical air jets resembled that of circular jets, while the classic barrel shock disappeared along the minor axis. Furthermore, “axis switching” occurred for moderate AR (AR > 1.4) where the major axis jet spreading rate reached an asymptote, while the minor axis continued to grow beyond the Prandtl-Meyer expansion; the magnitude of the asymmetry increased with higher backpressures. Similar observations were made from slot air jet simulation and experimental results by Menon and Skews [18] along with simulation results of slot hydrogen jets by Makarov and Molkov [19]. Makarov and Molkov further noted that far-field velocity and scalar fields in the incompressible regime returned to axis-symmetry. For the present study, jet-exit shock structures were imaged via schlieren photography while quantitative Planar Laser Rayleigh Scattering imaging was used to measure downstream dispersion characteristics. These data will serve as validation benchmarks for numerical simulations and for follow-on slot nozzle source and dispersion modelling.

Experimental description

To create the desired circular and slot underexpanded hydrogen jets, a high-pressure stagnation chamber with a 1.24 l internal volume and capable of pressures up to 60 bar was used; a schematic is provided in Fig. 1. A uniform stagnation flow field was achieved through the use of a multi-hole injector at the chamber base. Interchangeable nozzles were machined from flanged blanks that attached to a Swagelok one inch VCO fitting at the chamber outlet. For the circular aperture, a standard ASME long radius nozzle profile with a 1.5 mm outlet diameter was selected due to its relatively top-hat exit profile and large discharge coefficients (CD = 0.979) [20]. Three knife edged rectangular slot nozzles with aspect ratios of 2, 4, and 8 were machined into the flanged VCO blanks. Note that the flow rates for jets with AR of 2 and 8 were found to be identical, while the jet with an AR of 4 was approximately 8% lower. The length and width of each slot nozzle was set such that the exit area was equivalent to that of the 1.5 mm diameter circular nozzle. Schematics of a representative slot and circular nozzle are included in Fig. 1. Chamber temperature and pressure were respectively monitored via a type K thermocouple and TESCOM series 100 pressure transducer, with dynamic feedback used to maintain a steady 10:1 pressure ratio. The Abel-Noble equation of state was used to account for compressibility effects in the mass flow rate calculations [6]. Atmospheric laboratory pressure and temperature were 99.67 kPa (±0.17 kPa) and 292 K (±1 K) respectively. The entire assembly was mounted to a computer controlled traverse, with data acquisition and system control handled via custom written LabView program.

The underexpanded jet shock structure was imaged by an in-line lens Schlieren system using a 5 μs pulsed single wavelength light-emitting diode (LED). After passing through the experiment the collimated light was focused and clipped

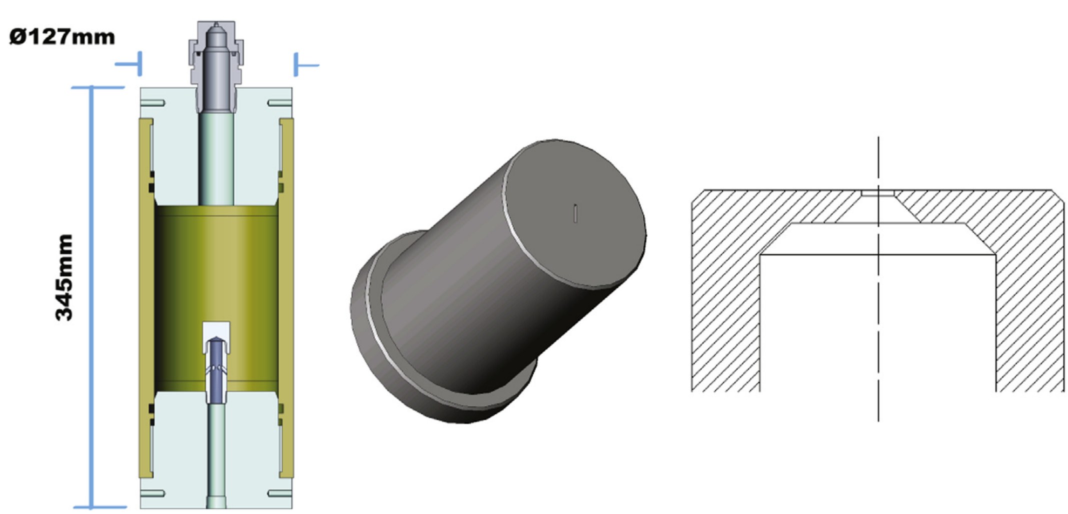

Fig. 1 – Sectional view of the stagnation chamber and nozzle assembly (left) along with a picture of the nozzle with the AR 8 exit (centre) and a corresponding sectional view (right).

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