ABSTRACT

Modern safety standards for hydrogen storage infrastructure must be assured before widespread public use of hydrogen can become possible. Fundamental insight into the physics of buoyant gas dispersion into ambient air from realistic flow geometries is necessary to properly predict flow structures associated with hydrogen outflow from accidental leaks and the associated flammability envelope. In the present study, a horizontal hydrogen jet was emulated experimentally using helium as a substitute working fluid issuing from a round orifice on the side wall of a vertically oriented circular tube. Particle image velocimetry (PIV) and planar laser-induced fluorescence (PLIF) techniques were employed simultaneously to provide instantaneous and time-averaged patterns of flow velocity and concentration. Effects of buoyancy on the resulting flow structure were studied over a range of Mach numbers and gas densities from 0.4 to 1.2 and 1.17 to 0.165 [Kg/m$^3$] for air and helium, respectively. Significant differences were found between the centreline trajectory, spreading rate and velocity decay of a round axisymmetric horizontal jet and that of leak-representative jets considered in the present study. It was found that the realistic leak geometry along pipeline orientation considered causes buoyancy effects to dominate much sooner than expected in a round jet. Therefore, caution is required when using round axisymmetric jet assumptions to describe the correct gas concentration, entrainment rates and, consequently, the extent of the flammability envelope of a jet emitted from realistic leak geometries.

INTRODUCTION

Hydrogen, a carbon-free energy carrier, is currently viewed as a clean alternative to traditional hydrocarbon-based fuels for transportation and energy storage applications. Despite this benefit, however, hydrogen jets resulting from an accidental leak are easily ignitable owing to a wide range of possible ignition limits (between 4%-75% by volume) [1]. Also, owing to the low molecular weight of hydrogen, buoyancy can significantly influence the development of the jet dispersion during a release scenario. In the current investigation, we attempt to quantify the dispersion of horizontal buoyant jets experimentally, as they emerge from a realistic pipeline geometry, using state-of-the-art experimental imaging techniques.

To date, there has been extensive work done to de-
scribe the evolution of axisymmetric round jets in terms of self-similarity correlations, obtained from statistical analysis from both experiments [2] and simulations [3]. In addition to this, some investigations have found that buoyant vertical plumes evolve into self-similarly much sooner owing to buoyancy driven turbulence in the near field [4]. Horizontal buoyant jets, however, have been much less studied. In general, increasing effects of buoyancy were seen to be proportional to the reduction of the Froude number [5]. It is noteworthy that all aforementioned studies on jets and plumes have been limited to leaks through flat surfaces. In reality, however, flow patterns and dispersion of accidental gas leaks would originate from cracks in the side walls of circular pipes. To address this, a recent study was investigated for buoyant vertical jet evolutions through round holes from curved surfaces, numerically and experimentally [6–8]. Through this recent work, significant discrepancies were found between the evolution of axisymmetric round jets through flat surfaces and those originating from curved surfaces. Most notably, jet deflection from the vertical axis, and asymmetric dispersion patterns are always observed in realistic situations. To our knowledge, however, the effects of buoyancy on horizontal jet evolutions from curved surfaces has not yet been investigated.

To investigate the effect of buoyancy on the evolution of horizontal jets issuing from realistic pipeline geometries, jet release experiments were conducted with air and helium, where flow patterns and dispersion of gas through a curved surface originating from a source whose original velocity components were nearly perpendicular to the direction of the ensuing jets. From now on, this jet configuration is referred as a 3D jet. A round hole as one of possible crack geometries, was considered in this study, although another possibility might include thin cracks around faulty or loose tube fittings [9], which is not considered here. The horizontal 3D jets were released through a 2mm diameter round hole in the side of a round tube (closed at one end), with an outer diameter of 6.36mm and 0.82mm wall thickness. The outer-scale flow Reynolds numbers ($Re_\delta$), based on the orifice diameter, and Mach numbers ($Ma$) of the jets ranged from 19,000 to 51,500 and 0.4 to 1.2, respectively. However, it is noted that for hydrogen jets of equivalent momentum flux, the expected Mach number and Reynolds number would be 1.5 and 55,915. At these conditions, hydrogen is expected to behave very similar to the helium jets considered here [6]. These realistic jets were also compared to axisymmetric leaks through flat surfaces accordingly. Particle imaging velocimetry (PIV) and planar laser-induced fluorescence (PLIF) were used to measure high-resolution instantaneous velocity and concentration fields, respectively. The purpose of this investigation was to identify and characterize departures from standard axisymmetric jet conditions, and to highlight the buoyancy effect and asymmetric nature of the 3D jets, which ensued from a practical geometry arrangement. It should be noted that, the effect of pipe wall thickness of the crack geometry has not yet been investigated.

**EXPERIMENTAL FACILITY AND MEASUREMENT TECHNIQUES**

Figure 1 illustrates the jet flow evolution from the tube orifice considered. To capture the three-dimensionality of the jet, measurements were obtained on two different two-dimensional planes (denoted $x$-$z$ and $x$-$y$), as indicated, for both air and helium. Also shown in the figure is the jet centreline, which acts as a reference from which measurements are later obtained in the $x$-$z$ plane. Owing to potential deviation of the jet from the orifice axis ($x$-axis), the jet centreline tangent and normal lines are shown as $s$ and $n$ coordinates in the figure, respectively.

The experiments were conducted within a controlled stagnant environment, at room temperature and pressure ($T_0 \sim 22^\circ\text{C}, p_0 \sim 100\text{kPa}$). The flow facility used for the present study is described in detail in [6]. The orifice, through which the gas dispersed, had a diameter of $D = 2\text{mm}$ and was located sufficiently downstream along the pipe length to ensure fully developed flow within the tube at the orifice location. Within the tube, flow controllers were used to ensure fully developed subsonic and turbulent flow inside the tube.

Particle imaging velocimetry (PIV) was used to cap-
A dual-head Nd: YAG pulsed laser (New Wave’s SOLO III 15 HZ) was used to illuminate a two-dimensional cross-section of the flow, which was seeded with Di-Ethyl-Hexyl-Sebacate (DEHS), with a typical diameter of less than 1 µm, to act as a tracer particle. The light sheet had an approximate height of 5 cm and thickness of 1 mm. The field of view of the camera (PIV CCD) was a 40×30 mm² window with an approximate pixel size of 6.5 µm in physical space. Each pair of images were then processed using LaVision DaVis 8.4 software to calculate the global instantaneous flow velocity field.

To measure the gas concentration, we applied planar laser-induced fluorescence (PLIF). To simultaneously apply PLIF, the flow was also seeded with acetone. A Pulsed Nd: YAG laser (Spectra-Physics INDI-40-10-HG) was used in order to excite the acetone molecules in a light sheet with an approximate height of 5 cm and a thickness of 350 µm, which was then recorded with a PLIF CCD camera. The camera field of view for all cases corresponded to a 38×28 mm² window with an approximate pixel size of 6.5 µm. The images were taken at a frequency of 5 Hz and then processed using LaVision DaVis 8.4 software. For each experiment, a total of $N = 500$ velocity and scalar field images were acquired for statistical averaging. Further details of the experimental procedure can be found in [6].

In order to compare the behaviour of both test gases, for each experimental setup, the averaged momentum flux ($\overline{M}$) at the jet exit was estimated and matched for all test cases. This matching was achieved, iteratively, by varying the volumetric flow rate ($Q$) in the system. Here, $\overline{M}$ was calculated by first obtaining the time-averaged jet exit velocity from two-dimensional PIV measurements. The two-dimensional momentum flux, in units of [N/m], was then calculated from

$$\overline{M} = \int_{-D/2}^{D/2} \rho_j u_j^2(r) \, dr$$  \hspace{1cm} (1)

where the subscript ‘$j$’ refers to the conditions at the nozzle, and the over-line $(\overline{\cdot})$ refers to a time-averaged quantity. Here $D = 2$ mm was the diameter of the orifice. $\rho$ and $r$ refer to density and radius, respectively. Table I shows the flow properties used in this study. Distances reported here have been normalized such that

$$x = \frac{X}{D}, \quad y = \frac{Y}{D}, \quad z = \frac{Z}{D}$$  \hspace{1cm} (2)

where $D$, the diameter of the orifice, is taken as a reference length scale.

## RESULTS AND DISCUSSION

### Time-Averaged Flow Fields

The time-averaged velocity and concentration contours, obtained in both the $x$-$z$ and $x$-$y$ planes for all of the 3D jet experiments conducted here, are shown in Fig. 2. For both experiments, significantly larger jet spreading was observed in the $x$-$z$ planes compared to the $x$-$y$ plane, suggesting an asymmetric flow structure. Also, the jets were found to deviate from the horizontal $x$-axis, in the direction of the initial flow inside the pipe, for both gases. There was also a shorter potential-core length observed for helium ($\approx 3D$), compared to air ($\approx 5D$). Also,

### Table I: Flow properties

<table>
<thead>
<tr>
<th>Jet</th>
<th>$Q$ [L/min]</th>
<th>$u_j$ [m/s]</th>
<th>$\rho_j$ [Kg/m³]</th>
<th>$v_j$ [m²/s]</th>
<th>$\overline{M}$ [N/m]</th>
<th>$Ma$</th>
<th>$Fr$</th>
<th>$Re_\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>15</td>
<td>147.5</td>
<td>1.17</td>
<td>$1.54 \times 10^{-5}$</td>
<td>50.9</td>
<td>0.43</td>
<td>-</td>
<td>19,000</td>
</tr>
<tr>
<td>He</td>
<td>35</td>
<td>399.5</td>
<td>0.165</td>
<td>$1.21 \times 10^{-4}$</td>
<td>51.3</td>
<td>1.2</td>
<td>1144</td>
<td>51,500</td>
</tr>
</tbody>
</table>
in the \( x-z \) plane, near the potential-core region, there was more jet spreading on the lower side of the jet compared to the top side. In the \( x-y \) planes of both gases, there were two high-velocity peaks (saddle-back behaviour), at \( y \pm 0.5D \), on each side of the \( x \)-axis, with a much shorter potential-core length (\( \approx 2D \)) compared to the \( x-z \) plane. This saddle-back behaviour was found to originate from a velocity deficit region which forms inside the orifice due to flow separation as the gas inside the pipe encountered the edge of the orifice [6].

In general, the concentration profiles were qualitatively similar to the velocity profiles presented in Fig. 2, with two exceptions. First, the potential core lengths in the \( x-z \) plane, for both gases, were approximately \( \approx 4D \); while the potential core lengths in the \( x-y \) plane, were approximately \( \approx 2D \) and \( \approx 1D \), for air and helium, respectively. Also, much higher concentration levels, with higher spreading rates, were observed for helium in the far field compared to air. This observation can be attributed to a low Schmidt number (\( Sc < 1 \)), in which case mass diffusion rates are higher than momentum diffusion rates.

The Jet Centreline Trajectory, Velocity Decay and Spreading Rates

In Fig. 3a, the jet centreline trajectories, determined in the \( x-z \) plane, are presented for all cases. Here, the trajectories were determined by the maximum velocity magnitude locations. Also shown for comparison are the jet centreline trajectories obtained from our previous vertical 3D jet experiments [6], and from horizontal sharp-edged orifice flat-plate (OP) helium jet measurements [5]. In order to determine the effect of buoyancy on the horizontal jets, lines of best fit, using linear regression to power law expressions, were obtained for the far field (beyond \( x \geq 10D \)), and are also shown in Fig. 3a. In general, the jet trajectory for the vertical jets, and the horizontal air jet, were found to be described by a relatively linear relation (i.e. power law exponent \( \sim 1 \)). The horizontal helium jet, however, was found to have a power law exponent \( \sim 1.3 \). Upon extrapolating these relations to the far field, beyond the experimental data collected, it became clear that buoyancy of the helium jet caused significant deflection from the horizontal axis, despite the high Froude number (\( Fr = 1144 \)). It should be noted that for horizontal flat-plate OP helium jets, with \( Fr = 1000 \), such buoyancy effects were not observed [5].

Fig. 3b shows the velocity decay along the jet cen-

FIGURE 3: a) Jet centreline trajectory b) jet velocity decay and c) jet widths (\( 2L_{1/2} \)) obtained along the [\( \bar{u} \)] \(_{max}\) centrelines, in \( x-z \) plane from measurements. Also shown, for comparison are axisymmetric round jet correlations [10], and vertical 3D & OP jets, horizontal round OP jets and round pipe jet experiments [5, 6, 11, 12].
The jets for all experiments. Also shown, for comparison, are velocity decay correlations [10] for compressible subsonic and supersonic axisymmetric round jets, along with velocity decay obtained from vertical 3D and OP jet experiments [6], and horizontal OP helium jet measurements [5]. Upon comparison to the Witze correlations [10], the air and helium OP jet experiments were found to reproduce well the expected velocity decay rate, with helium jet decaying faster than the air jet. On the other hand, the decay rates observed in the experimental 3D jets were much faster compared to the axisymmetric jets. In general, upon comparison between horizontal and vertical 3D jets, buoyancy was not found to significantly affect the velocity decay rates.

In the x-z plane, Figure 3c presents the jet widths ($2L_{1/2}$), that have been obtained by determining the locations where $\overline{n} = 0.5\overline{n}_{\text{max}}(x)$ along lines which were orthogonal to the jet-centrelines. These orthogonal lines have been indicated previously as coordinate $n$ in Fig. 1. For the 3D jets, in all cases, a slight contraction in the jet widths has been observed from $1D < x < 4D$. Beyond this point, the jet spreading rates, along $n$, were observed to be much greater compared to the axisymmetric jets for all cases. Moreover, the air and helium jet spreading, from the 3D experiments, was found to be comparable for both gases. However, In the far field (beyond $x \geq 13D$), helium 3D jets exhibited higher spreading rates, compared to air. This trend was slightly more clear, with comparing the horizontal 3D cases between helium and air. In general, the OP jets were found to have nearly constant jet widths in the potential core region, up until $x \approx 5D$. From this point on, the jet width was found to be much smaller compared to 3D jets, and increase linearly, consistent with the jet spreading rates of previous axisymmetric round jet experiments for a wide range of Reynolds numbers [11,12].

**Jet Centreline Statistics**

In the x-z plane, the time-averaged velocity profiles for all experimental investigations are shown in Fig. 4a) along the $n$-direction for several downstream locations along the jet centreline ($s$-curve Fig. 1). Also shown, for comparison, are the velocity statistics obtained for the vertical and horizontal OP jet experiments [5,6]. It should be noted that, the $s$-component velocities are presented here, were normalized by the local centreline velocity magnitudes ($\overline{n} = \overline{n}_{c}(x)$). Also, the $n$-coordinates, which was normal to the centreline $s$-curve, was normalized by the jet half widths ($L_{1/2}$) determined from Fig.3c. In all cases, the 3D jets emerged from the orifice with a semi top-hat profile, not shown here. In contrast, the OP jet had an initial semi saddle-back profile (not shown here). In general, all 3D jet cases developed into a self-similar Gaussian-like distribution of velocity within the range $|n/L_{1/2}| < 1$ for $x \leq 5D$. However, notable deviations from the self-similar solution were observed near the tail ends of the curves in the x-z plane, beyond this range . For vertical 3D jets, this was previously found to be due to the flow separation at the entrance to the orifice, which gave rise to a velocity deficit near the edge of the orifice [6–8]. Both air and helium experiments were found to exhibit more velocity spreading to the bottom of the jet centre (in the $+n$-direction), with more velocity spreading were observed for helium compared to air. Beyond $x > 5D$, in
the far field, the experimental 3D jets developed into, and matched, the self-similar Gaussian distribution obtained from the OP jets for the full range of \( n \). Finally, the curves obtained for all gases were found to be in agreement with each other.

The time-averaged concentration profiles for all 3D jet experiments are shown in Fig. 4b). Here, molar concentrations \((C)\), have been normalized by the local centreline concentrations \((C_c(x))\). The \( n \)-coordinates were normalized by the jet half widths \((L_{c,1/2})\) determined from the locations where \( C/C_c = 0.5 \). In general, they were found to be qualitatively similar to the velocity profiles in all cases. In the near field \((x \leq 5D)\), the range \( |n/L_{c,1/2}| < 1 \) for \( x \leq 5D \) was found to develop quickly into the self-similar solution as observed in the OP jet experiments [5,6]. Notable deviations from the self-similar flow structure were once again observed near the tail ends of the curves in the \( x-z \) plane, beyond this range. The 3D jet experiments were found to exhibit more concentration spreading to the lower side of the jet centre (in the \(+n\)-direction), as observed in the velocity profiles, with more concentration spreading found for helium compared to air. In the far field, beyond \( x > 5D \), the self-similar Gaussian distribution, as observed in the OP jet experiments, was recovered for both the 3D jet experiments.

**CONCLUSION**

In this study, experiments were conducted in order to investigate the effect of buoyancy on the evolution of horizontal jets, of varying gas densities and Reynolds numbers, issuing from a round orifice in a round pipe. The fluids considered were air and helium. The results were compared to previous studies of the vertical jet, issuing from the same pipeline geometry and axisymmetric round OP jets [6]. Comparison was also made to horizontal axisymmetric round jets, issuing through flat plates [5].

By considering flow emerging through a hole, located on the side of a pipe wall, it was found that the flow arrangement caused a significant deflection from the axis normal to the orifice as was observed in vertical jets with the same arrangement [6]. In the current investigation, the helium jet deflection was found to be initially governed by the density of the gas in the near field, and it experienced further deflection due to buoyancy in the far field. Such deviation due to buoyancy in the far field was found to be well reproduced by a power law expression with the exponent \( \sim 1.3 \). Also, it was found that such buoyancy effects were not present in axisymmetric round jet helium experiments, where the jet issued through flat-plates, with the same Froude number. This observation suggests that the realistic leak geometry along pipeline orientation considered in this study, causes buoyancy effects to dominate much sooner than expected in axisymmetric round jet. Finally, it was found that buoyancy effects did not have a significant impact on the jet velocity decay and spreading rates.

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