EXPERIMENTAL STUDY OF LIGHT GAS DISPERSIION IN A CHANNEL

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ABSTRACT
Usage of hydrogen as fuel gives rise to possible accidental risks due to leakage and dispersion. A risk from hydrogen leak is the formation of a large volume of the hydrogen-air mixture, which could be ignited and leading up to a severe explosion. Prevention and control of formation and ignition of combustible hydrogen cloud necessitate sufficient knowledge of mechanisms of the hydrogen leak, dispersion, ignition, and over-pressures generated during combustion. This paper aims to investigate the momentum-controlled jet, the buoyancy-controlled wave and the parameters influencing hydrogen concentration distribution in an elongated space. It demonstrates experimental results and analysis from helium and hydrogen dispersion in a channel. A set of experiments were carried out for the release of helium and hydrogen jets in a 3 m long channel to record their concentrations in the cloud by concentration sensors at different horizontal and vertical positions. Flow visualization technique was applied using shadowgraph to image the mixing process next to the release point and the helium-, hydrogen-air cloud shape at the middle of the channel. Moreover, results were used for comparison of helium and hydrogen concentration gradients. The results of the experiments show that swift mixing occurs at higher flow rates, smaller nozzle sizes, and downward release direction. Higher concentration recorded in the channel with negative inclination. Results also confirmed that hydrogen/helium behavior pattern in the channel accords with mutual intrusion theory about gravity currents.

1.0 INTRODUCTION
In recent years, there has been an increasing interest in hydrogen as a sustainable energy carrier because of growing concerns about fossil fuel dependence. Risks of fire and explosions are central safety considerations connected to the hydrogen application in the processes industry and the transport sector. The hazard of hydrogen explosion is a concern when it leaks in confined spaces such as garages and tunnels. Hydrogen leak and dispersion in confined spaces may result in the formation and development of a combustible hydrogen-air mixture. For better development of risk mitigation requirements, it is essential to understand the processes involved during the hydrogen dispersion and hydrogen-air mixture explosion. Determination of the positions where the cloud could be ignited and the extent to which flame can accelerate depends on the concentration of hydrogen in the combustible cloud [1]. This study was designed to examine the hydrogen concentration distribution in a laboratory scale channel. Data for this study were collected using concentration sensors at six horizontal positions along the channel and five vertical locations on the channel side.

There is a potential risk for an unintended ignition when using hydrogen in dispersion tests. Therefore, helium was selected for a major part of this study. Helium is considered to resemble hydrogen since it has similar low density and high buoyancy (helium is twice dense as hydrogen, and they have about 8% difference in buoyancies). Helium and hydrogen volumetric flow rates were assumed to be equal in the prediction of hydrogen dispersion and explosion using helium. However, several studies were mentioned the difference between helium and hydrogen flow rates between helium and hydrogen flow rates [2-5]. To use helium as a substitute for hydrogen, He et al. [2] suggested that differences in air-helium and air-hydrogen densities should be considered.
1.1 Momentum- and buoyancy-controlled jets

The hydrogen gas released in a channel will disperse by diffusive and buoyant forces. The influence of buoyancy on the gas dispersion is more significant than diffusivity at low-momentum hydrogen releases\[6\]. Therefore, highly concentrated with hydrogen and less dense gas cloud arises close to release point, and the variation in densities promotes buoyancy forces which cause the cloud to upsurge vertically and to proceed to the upper part of the channel. The hydrogen-rich cloud loses its inertia gradually and becomes buoyancy-driven. The mixing process with air either in the formation of the cloud or when the cloud propagates downstream occurs in nonhomogeneous mode. Thus, concentration decays along the jet axis and horizontally away from the release site \[7\].

1.2 Gravity currents and Froude scaling

Gravity currents generated in the horizontal flows due to density differences in the fluid under a gravitational field. An important kind of gravity current is the flow of less dense gas caused by the accidental release in tunnels or other semi-confined spaces. Density variations in a gravitational field generate buoyancy forces which cause the flow into horizontal motion and produce horizontal pressure gradients. The front zone formed by a gravity current is characterized by the presence of a relatively sharp line dividing the two fluids. The front shape of the cloud formed by a gravity current is influenced by the reverse ambient flow \[8\]. Turbulent mixing typically occurs at gravity current front, and the mixing process continues at the interface between the two fluids as the cloud spreads. According to Simpson analysis \[8\], three regions are observed at the front of gravity current, the upper layer where the less dense cloud is moving, bottom layer with air and the mixing region between these two layers. Fig.1 represents the shape of the pre-mixed cloud as it propagates after the gas injection into the channel.

![Diagram of gravity current](image)

**Figure 1.** Schematic illustration of hydrogen/helium-air cloud formed by gravity current in the channel

Scaling techniques are extensively applied in researches of tunnel fire safety, and the major preserved dimensionless group in these researches is the Froude number. The dimensionless Froude number is the ratio between inertia and gravity forces exerting influence on the fluid flow in the gravity current, and it can be used to describe the dispersion of hydrogen/helium in a channel \[9\]. Froude number is related to the front velocity of a gravity current as

\[
Fr = \frac{u_f}{\sqrt{g l}},
\]

where \(u_f\) is the front velocity of the cloud in the channel, \(g\) is the acceleration due to gravity, and \(l\) is a characteristic length scale. The characteristic length scale, \(l\), can be represented as the theoretical layer of 100% hydrogen/helium, \(h_H\). The reasoning for this option is that the front velocity is not affected by the mutual intrusion in dispersion process since the increase in the height of the cloud depends on the hydrogen/helium flow rate and balanced by the decrease in cloud density \[10, 11\]. The gas flow rate into the channel, \(Q\) [\(m^3/s\)] can be connected to the unmixed layer, \(h_H\), as

\[
Q = u_f \cdot h_H \cdot w,
\]
where \( w \) is the width of the channel. Substitution of the unmixed layer, \( h_H \), in the Froude number expression, gives

\[
Fr = \sqrt{u_f^3 \cdot \frac{w}{gQ}},
\]

(3)

The average cloud front velocity, \( u_f \), can be expressed in terms of the distance covered by the cloud from the release point to reach the sensor’s position (or ignition point), \( L [m] \), and the time required to reach this point, \( \Delta t [s] \). Thus, Froude number can be rewritten as

\[
Fr = \sqrt{\frac{(L}{\Delta t})^3 \cdot \frac{w}{gQ}},
\]

(4)

### 2.0 EXPERIMENTAL SETUP

#### 2.1 Channel description

Experiments were executed in a horizontal rectangular cuboid channel with dimensions: 3 m length, 0.1 m width, and height. The channel was made of coated steel with transparent polycarbonate sidewalls. It was open on one side and closed in the other. Fig.2 represents a schematic design of the channel, indicating the positions of concentration measurement sensors, and Fig.3 shows an oblique image of its laboratory setup.

**Figure 2. Schematic design of the channel with sensors positions**

**Figure 3. An oblique image of the channel setup**

#### 2.2 Helium injection

Helium was provided from helium standard 180 bar cylinder. The gas flow was adjusted by Purgemaster volume flow meter with releasing flow rate in the range of 5 to 90 Ndm\(^3\)/min. The flow meter was calibrated before measurements start by Ritter drum-type TG 10/1. Then the gas was injected into the channel upwards or downwards through a 4 mm pipe, which located at centerline 100 mm from the closed end and had 50 mm height in the channel. At the exit of the 4 mm pipe, different circular nozzles with diameters 2.5, 1.0, and 0.5 mm were used for injection of helium into the channel.
2.3 Measurement devices

Measurement of helium concentration as volume percentage was recorded by XEN-5320 gas sensor for determining gas composition as illustrated in Fig.4 (on the left-hand side). The XEN-5320 is an integrated sensor based on the measurement of the thermal conductivity of the gas. It automatically corrects for the temperature and humidity. The sensor was WI-FI read out, connected to a laboratory WI-FI network and it sent the measurements to a specific computer program (Xen-5320 LabView Standard v3.20 WI-FI). Sensors were located at six different positions along the center line on the top of the channel. The first one was located 0.4 m from the release point, and the others were positioned 0.5 m from each other (Fig.2).

Helium volume fractions were similarly recorded at five vertical positions, at 10, 30, 50, 70 and 90 mm from the ceiling, at the horizontal location, 2.5 and 3 m from the closed channel end. Figure 4, on the right-hand side, shows the vertical sensor’s positions at two horizontal sites.

2.4 Flow visualization technique

Flow imaging systems provide a technique to visualize changes in refractive index depending on the density variation of transparent media [12]. The shadowgraph lens system (SLS) was used in this study in which a shadow projected from refractive deflection of a light ray creates a bright position on the recording plane while undeflected rays remain dark. Consequently, a visible pattern of lighting variations is generated on the recorded plane. Fig. 5 shows an image of the shadowgraph system fixed in the middle of the channel, 1.5 m from the channel closed end.

Shadowgraph system was utilized to visualize the air-helium cloud formation next to the release point and the shape of the cloud while it propagated passing the lenses location at 1.5 m from the channel closed end. The system includes lenses from OPTO ENGINEERING, Telecentric TC lenses, and LTCLHP high-performance illuminator to illuminate objects imaged by Telecentric lenses. The lenses were fixed to a slab with clamps. High-speed digital video camera, FastCam APX RS, was linked to the lenses for image recording.
2.5 Experimental variations

Various sets of experiments were performed to investigate the influence of different parameters on the helium concentration distribution in the channel. Parameters included flow rate, nozzle size, vertical concentration distribution, injection direction, and channel inclination. All parameters in the process are interrelated. Therefore, concentration measurements were divided into four series, helium horizontal, helium vertical, helium dispersal in inclined channel and helium/hydrogen horizontal concentration distribution. Horizontal measurements involved recording the concentration by sensors at six locations along the channel, as it defines in Fig. 2, for different flow rates, nozzle sizes and release directions: upward, U, and downwards, D. Table 1 gives an overview of the horizontal measurement’s series.

Table 1. The first experimental series. U: Upward, D: Downward

<table>
<thead>
<tr>
<th>Flow rate, Ndm³/min</th>
<th>Nozzle size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5 mm</td>
</tr>
<tr>
<td>5</td>
<td>U</td>
</tr>
<tr>
<td>15</td>
<td>U</td>
</tr>
<tr>
<td>40</td>
<td>U</td>
</tr>
</tbody>
</table>

The second of experimental series is vertical concentration measurements at two horizontal locations on the channel side, 2.5 m from the channel closed end and at the exit. Sensor’s vertical positions were 0, 10, 30, 50, 70 and 90 mm from the ceiling as presented in Fig. 4 (right). Table 2 defines the parameters used during the measurements.

Table 2. Experimental set for vertical concentration distribution.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Nozzle size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate, Ndm³/min</td>
<td>1 mm</td>
</tr>
<tr>
<td>5, 15 and 40</td>
<td>D</td>
</tr>
<tr>
<td>Release direction</td>
<td>2.5 and 3</td>
</tr>
<tr>
<td>Position from the channel end, m</td>
<td></td>
</tr>
</tbody>
</table>

The third of experimental series is the determination of helium concentration along the inclined channel. Measurements were done for the channel with an inclination of 10 and -10 degrees. Fig.6 illustrates a drawing of the inclined channel towards the exit ($\varphi = -10^\circ$). Helium released downward at flow rates 15 and 40 Ndm³/min through a pipe diameter 4 mm.

Figure 6. Schematic representation of the channel with an inclination of -10°

The fourth set of experiments covered the measurements of helium and hydrogen concentrations as it explained in the horizontal helium model with the same parameters in Table 1. In this experimental series, pneumatic valve, Swagelok, connected to the inlet pipe for better control of gas flow rate. The pneumatic valve was triggered together with a pressure sensor to record the pressure at the valve during the gas release.
3.0 RESULT AND DISCUSSION

3.1 Flow rate effect

Results from the sensor’s measurements for helium concentration along the channel at flow rates 5, 15 and 40 Ndm$^3$/min and 3 minutes release time are shown in Fig. 7. The figure shows an apparent increase in helium concentration recorded by sensors at all measurements locations with an increase in flow rate. Simultaneously, the time between the sensor’s start signals decreases. This indicates a rise in the cloud’s velocity with an increase in flow rates.

Figure 7. Helium output concentration over time for upward release through 4 mm diameter pipe and at flow rates: (a) 5, (b) 15 and (c) 40 Ndm$^3$/min

Concentration decay lengthways the channel signifies that helium-air cloud loses its inertia while it propagates through the channel and turns to be buoyancy-driven. This process decreases in the case (c) compared to the case (a) in Fig.7.

The concentration distribution of helium vertically in the channel was determined by recording the concentration in two horizontal positions, at 2.5 m from the channel closed end and the channel exit. Vertical positions were 0, 10, 30, 50, 70, 90 mm from the ceiling. Fig.8 shows helium output concentration as the function of time at cited vertical locations for downward release through 2.5 mm nozzle and at 2.5 m from the closed end.

Figure 8. Distribution of helium concentration vertically over time for downward release through 2.5 mm nozzle size and at flow rates: (a) 5, (b) 15 and (c) 40 Ndm$^3$/min

Over-all constructed concentration profiles with different flow rates were observed unchanged. Helium concentration moved upward close to the ceiling from 13.8 % in (a) to 28.2 % in (c) while the flow rate was raised from 5 in (a) to 40 Ndm$^3$/min in (c) graphs in Fig. 8. This indicates that concentration decays horizontally and vertically while the cloud is propagating in the channel.

3.2 Nozzle size effect

Sensors measurements for helium dispersal in the channel were done using different nozzle sizes, 0.5, 1, 2.5 mm and pipe diameter 4mm. Fig.9 illustrates helium concentration over 5 minutes for downward release at 40 Ndm$^3$/min for four defined nozzle sizes. As evident from the graphs in Fig. 9, the upper lines are becoming more undulate, and the differences between two upper concentration lines decrease from 1.86% in the graph (d) to 1.15% in the graph (a), with a decrease in nozzle size, from 4 to 0.5 mm.
This specifies more rapid mixing of helium with air close to the release point as the nozzle size decreases due to the rise in flow velocity. It can also be observed from the time that lines are level out, 87 s in the graph (a) to 71 s, in (d).

Figure 9. Output concentration over time of downward helium release at 40 Ndm$^3$/min and through nozzle sizes: (a) 0.5, (b) 1, (c) 2.5 mm and (d) pipe diameter 4 mm.

Fig. 10 shows helium concentration vertical measurements for 3 minutes downward release at a flow rate of 40 Ndm$^3$/min through 2.5 mm nozzle size and 4 mm pipe. The trends presented in this figure are like those in Fig. 7. The concentration slightly increased with nozzle size has been changed from 2.5 mm to 4 mm. Simultaneously, the difference between the two upper lines increased. This may be explained by the concentration drop as the mixing process developed faster with a smaller nozzle size.

Figure 10. Vertical concentration distribution over time of downward helium release at 40 Ndm$^3$/min and through nozzle sizes, 2.5 mm (left) and pipe diameter 4 mm (right).

3.3 The influence of release direction

Changes in helium concentration distribution were identified by helium upward and downward injections at different flow rates and nozzle sizes. Fig. 11 presents helium concentration over time for releases through a 2.5 mm nozzle size at a flow rate of 15 Ndm$^3$/min. it is apparent from the graphs displayed in Fig. 11 that the concentration recorded by the first sensor is higher for upward release than for downward. This happened because of the mixing process is higher near the release point and mainly induced by momentum. Formed mixture by downward release changes direction upwards due to density difference and mixes additionally with air while it proceeds downstream at the upper part of the channel. No differences in vertical distribution have been observed between upward and downward releases away from the release point.
Figure 11. Output helium concentration versus time for upward release, left and downward, right at flow rate 15 Ndm$^3$/min and 2.5 mm nozzle size.

3.4 Channel inclination

The channel was inclined by 10 and -10 degrees in order to analyze how inclination affects concentration distribution in the channel. Helium was released downward through 4 mm pipe at 15 and 40 Ndm$^3$/min. Descriptive data were generated for all sensor positions depicting dissimilarity of the two tilted channel structures. Fig. 12 displays helium concentration over time for downward releases in the inclined channel by 10 degrees, left and -10 degrees, right at 15 Ndm$^3$/min.

Figure 12. Helium concentration over time for downward release in the channel with an inclination of 10°, left and -10°, right at 15 Ndm$^3$/min and through 4 mm pipe.

From the data in the above graphs, it is apparent that helium concentration is swiftly rising and reach much higher levels in an inclined channel by -10° than by 10°. Furthermore, the concentration lines are situated closer to each other for the channel with positive inclination, left than with negative inclination, right. The observed differences in concentrations could be attributed to the rapid mixing process in the positive channel inclination. In the channel with negative inclination, the air inflows and mixes with helium is affected by gravity leading up to a reduction in the mixing intensity and growth of the cloud leading-front propagation rate. This outcome can be well observed comparing positive and negative channel inclination with horizontal channel position. Fig. 13 compare helium concentration distribution in an inclined channel by 10°, horizontal channel and inclined channel by -10°.

Figure 13. Helium concentration over time for downward release through 4 mm pipe at 40 Ndm$^3$/min and in the channel with an inclination of 10°, left, horizontal, middle and inclination of -10°, right.
3.5 Mixing process

As expected, the results of the experiments show that helium mixes with air more rapidly at higher flow rates, smaller nozzle sizes, and downward release direction. Dispersion of helium in the channel characterized by the formation of inhomogeneous and stratified cloud. The mixing phenomena primarily start rapidly near the injection pipe and can be described as jet momentum-induced mixing. The cloud is developed around the injection pipe with high helium concentration and less dense than air. Subsequently, the cloud starts to rise due to buoyancy induced by density difference. Buoyancy-induced mixing continues as the cloud propagates through the channel creating a mixing zone as a line dividing the two fluids. In an attempt to visualize described phenomena, shadowgraph lens system was performed as defined in section (2.4) and the result is shown in Fig.14. Fig. 14 shows images of concentration gradients at the upper part of the channel after helium release at a flow rate of 50 Ndm³/min for 5.4 seconds.

Figure 14. Helium concentration gradients next to the release point visualized by shadowgraph for downward release at 50 Ndm³/min through pipe diameter 4 mm, and at 1.5 m from the channel closed end.

Above images designate a complex mode of mixing flow pattern next to injection pipe and show how the mixing zone develops from breakage into multiple fragments with a narrow region on the interface between helium and air, to rapidly emerging of the thin layer which is further becoming wider. Images show evidently the formation of a layer dividing the two fluids as specified in the gravity currents theory in section (1.3). Furthermore, they also express the inhomogeneous and stratified nature of the cloud on the channel.

3.6 Comparison of hydrogen and helium results

Measurements of hydrogen and helium concentration along the channel were performed for 3 minutes release time through pipe diameter 4 mm and flow rates, 5, 15 and 40 Ndm³/min. The results of these measurements are shown in Fig. 15 and Fig. 16. Hydrogen concentration is higher from (a) to (c) graphs in Fig. 15 compared with corresponding graphs for helium in Fig. 16. These results are likely to be related to the differences in density hydrogen/air and helium/air which has been reported by He et al. [2].

Figure 15. Hydrogen concentration over time for downward releases at flow rates, 5 (a), 15 (b) and 40 Ndm³/min (c), through pipe diameter 4 mm.

Comparing hydrogen and helium releases at low flow rates is given in graphs (a) in Fig.15 and Fig.16. The hydrogen concentration is slightly higher than that for helium, but they behave differently at the channel exit. The lowest concentration line for hydrogen in Fig.15 is rippling, which denotes higher mixing of the hydrogen-air cloud with air at the channel exit than for helium-air cloud.
Figure 16. Helium concentration over time for downward releases through 4 mm pipe at flow rates, 5 (a), 15 (b) and 40 Ndm³/min (c).

A comparison of the hydrogen-air cloud shape and front velocity and the helium-air cloud was drawn by implementing shadowgraph technique as described in section (2.4) at the middle of the channel, 1.5 m from the closed end, and the results are shown in Fig.17. Hydrogen and helium were released downward through 4 mm pipe at a flow rate of 40 Ndm³/min.

Figure 17. Concentration gradients of helium, upper series, and hydrogen, lower series, visualized by shadowgraph while the cloud propagating through the channel for at 1.5 m from the channel closed end for downward releases through 4 mm pipe and flow rate 40 Ndm³/min, and 0.15 s time separation between frames.

The most interesting aspect of these images is the thickness of the mixing zone, which represents the higher gradient in the images, is thicker for helium-air cloud than that for hydrogen. This is likely related to the differences in viscosity and diffusivity.

3.7 Froude scaling

Froude number is used to describe the pattern of the flows driven by buoyancy. Several studies have explored the relation of inertia forces to buoyancy by Froude number, for instance, Houf et al. [13] and Sommersel et al. [11, 14]. To verify whether the experimental results accord with previous researches findings, the Froude number was calculated using formula (4) for different hydrogen and helium flow rates. Time in the formula defined as the start time recorded by each sensor relative to the first one. Results from calculations are shown in Fig.18.

Figure 18. Froude numbers for downward releases of helium, (left) and hydrogen, (right) through pipe diameter 4 mm at a flow rate 40 Ndm³/min.
Calculated average Froude number was found to be 0.55 which corresponds to dotted lines in Fig. 18. In order to assess how thoroughly the experimental time data accord with theoretical calculations of Froude number, the experimental data were compared with computed time values by using average Froude number as a function of volumetric flow rate. Fig. 19 compares the time calculated theoretically applying the average Froude number, the solid lines, with experimentally recorded data for helium releases, left, and hydrogen, right.

![Figure 19](image_url)

Figure 19. Sensor’s response time versus flow rate for helium releases (left) and hydrogen (right). Solid lines represent calculated time values for Fr = 0.55.

There is a difference between obtained Froude number for hydrogen experiments and the previous results reported by Sommersel et al. [11, 14] in which the time was determined as the time of ignition from fast camera recording videos and the Froude number has been quantified to be 0.68. A possible explanation for this difference in results might be the time taken by the sensors to measure and record the reading and that for electrode spark and video recording.

4 CONCLUSION

The present study is designed to investigate the concentration distribution of dispersed hydrogen in partly confined spaces and the parameters influencing the concentration in the hydrogen-air cloud.

A sequence of experiments was carried out on laboratory scale 3 m long steel framed channel with transparent polycarbonate sidewalls. A quantitative approach was employed for assessment of helium and hydrogen concentration distribution along the channel by using WI-FI read out concentration sensors. Concentrations were measured at various horizontal and vertical positions for releases at different flow rates, through different nozzle sizes and different injection directions. Flow visualization technique was applied with the assistance of shadowgraph in this study to record an image of the concentration gradients of the mixing process next to the release point and the cloud propagation at the middle of the channel.

The results of this study indicate that the mixing of helium and hydrogen with air occur rapidly at higher flow rates, smaller nozzle sizes, and downward release direction. Moreover, these experiments confirmed that jet momentum-induced mixing happen close to release point and wave buoyancy-induced, away from it. Dispersion of helium in the channel characterized by the formation of inhomogeneous and stratified cloud. The relevance of mutual intrusion theory for gravity currents is clearly supported by flow imaging results.

The average Froude number obtained from concentration measurements is not in complete accord with the results from previous studies obtained from video recording data and further investigations by different methods should be done to re-evaluate the findings.

Overall, this study contributes to the existing knowledge of hydrogen dispersion in confined spaces by providing practical data for further analyses and validation of CFD codes.
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