Preliminary analysis of gas release and dispersion behaviour relevant to the use of hydrogen in the natural gas distribution network

Presented by
Simon Gant
Health and Safety Executive
Preliminary analysis of gas release and dispersion behaviour relevant to the use of hydrogen in the natural gas distribution network

Simon Gant¹, Ann Halford², Graham Atkinson¹, Adrian Kelsey¹, David Torrado¹, Phil Hooker¹, Dave Lander³, Thomas Isaac⁴, Russ Oxley⁵, Andrew Garrison¹, Richard Goff¹ and Catherine Spriggs¹

¹ HSE, ² DNV GL, ³ Dave Lander Consulting Ltd, ⁴ Progressive Energy, ⁵ NGN

Research - HSE funded to provide evidence which underpins its policy and regulatory activities
Guidance - freely available to help people comply with health and safety law
Outline

- Background
- Aims
- Gas properties
- Release rates
- Jet and plume dispersion
- Comparison to Quadvent
- Gas accumulation
- IGE/UP/1
- Conclusion
Background

- Climate change: UK to bring all greenhouse gas emissions to net zero by 2050 (Rt Hon Chris Skidmore, BEIS, 27 June 2019)

- Several ongoing projects investigating if it is technically feasible and safe to replace natural gas with hydrogen in the gas network, in commercial/residential buildings and gas appliances
  - HyDeploy: 20% hydrogen in natural gas
  - H21: 100% hydrogen
  - H100: 100% hydrogen in a new gas network
  - Hy4Heat: hydrogen appliances, gas quality criteria, meters
Aims

To address the following questions:

- Does hydrogen leak more than natural gas?
  - If so, by how much?
- What is its effect on the size of the flammable cloud?
- What are the implications for gas industry procedures, like IGE/UP/1?
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Gas Properties

Density

Viscosity

Viscosity graph:

- GasVLe model predictions using the Wilke-Brokaw formula with the Dean-Stiel density correction
  https://www.dnvgl.com/services/gasvle-8331


Gas Properties

Flammability limits

<table>
<thead>
<tr>
<th>Hydrogen volume fraction, $f_{H_2}$</th>
<th>Flammability Limit (% v/v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.2</td>
<td>10</td>
</tr>
<tr>
<td>0.4</td>
<td>20</td>
</tr>
<tr>
<td>0.6</td>
<td>30</td>
</tr>
<tr>
<td>0.8</td>
<td>40</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
</tr>
</tbody>
</table>

Assumed LFL$_{CH_4}$ = 5.0 % v/v; LFL$_{H_2}$ = 4.0 % v/v
UFL$_{CH_4}$ = 15 % v/v; UFL$_{H_2}$ = 75 % v/v

Ratio of Specific Heat Capacities, $\gamma$

<table>
<thead>
<tr>
<th>Hydrogen volume fraction, $f_{H_2}$</th>
<th>Ratio of specific heats, $\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.8</td>
</tr>
<tr>
<td>0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>0.4</td>
<td>1.0</td>
</tr>
<tr>
<td>0.6</td>
<td>1.1</td>
</tr>
<tr>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>1</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Sources:
https://encyclopedia.airliquide.com
https://webbook.nist.gov
Outline

▪ Background
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▪ Jet and plume dispersion
▪ Comparison to Quadvent
▪ Gas accumulation
▪ IGE/UP/1
▪ Conclusion
A COMPARISON OF H₂, CH₄ AND C₃H₈ FUEL LEAKAGE IN RESIDENTIAL SETTINGS

M. R. SWAIN and M. N. SWAIN
Department of Mechanical Engineering, University of Miami, Coral Gables, FL 33124, U.S.A.

(Received for publication 19 May 1992)

Abstract—One of the boundary conditions for modeling gas cloud motion from a residential gas leak is the leakage rate at the source of the cloud. The literature presents estimates of the leakage rate of hydrogen relative to methane or propane based on diffusion, laminar flow and turbulent flow. These three methods yield significantly different values for the relative leakage rate of hydrogen. An experimental study was therefore conducted to measure the relative leakage rate of hydrogen compared with methane or propane for various leaks. The results from the experimental study were used as input to a computer model to predict combustible gas cloud size and motion in residential kitchens.

INTRODUCTION

Present concern about possible changes in climate due to the greenhouse effect has renewed interest in the use of hydrogen as a fuel. The analysis presented here was made to compare hydrogen leakage, from premise fuel lines (residential gas distribution systems), with that of methane or propane. Gas leakage in premise fuel lines increases energy consumption and sets the stage for accidental combustion.

where $A$ is the cross-sectional area of the leak, $D$ is the diffusion constant of the gas, and $\frac{\partial c}{\partial x}$ is the concentration gradient. If we compare the leakage rate of hydrogen with that of methane, using diffusion, the area for leakage is the same for both gases (same leak) and $\frac{\partial c}{\partial x}$ is defined by the length of the leak pathway which remains the same for each gas. Therefore, the ratio of molar flow rates between hydrogen and methane would be:

https://doi.org/10.1016/0360-3199(92)90025-R
Laminar and Turbulent Flow

Reynolds number

\[ Re = \frac{\rho UD}{\mu} \]

- \( \rho \): Density
- \( U \): Velocity
- \( D \): Pipe diameter
- \( \mu \): Dynamic viscosity

- \( Re < 2000 \): Laminar
- \( 2000 < Re < 4000 \): Transitional
- \( Re > 4000 \): Turbulent

https://en.wikipedia.org/wiki/Osborne_Reynolds
Release Rate

Laminar

Volume flow rate

\[ \dot{V}_{\text{laminar}} = \frac{\Delta P \pi D^4}{128 L \mu} \]

\[ \Delta P \quad \text{Pressure drop} \]
\[ D \quad \text{Leak diameter} \]
\[ L \quad \text{Leak path length} \]
\[ \mu \quad \text{Dynamic viscosity} \]

For the same pressure, leak diameter and leak length:

\[ \frac{\dot{V}_{H_2}}{\dot{V}_{C_3H_8}} = \frac{\mu_{CH_4}}{\mu_{H_2}} = \frac{1.1 \times 10^{-5}}{8.7 \times 10^{-6}} = 1.23 \]

Source:

Release Rate

Turbulent

Volume flow rate

\[ \dot{V}_{turbulent} = 0.354\pi \frac{D^{2.5}\sqrt{\Delta P}}{\sqrt{fL\rho}} \]

For the same pressure, leak diameter and leak length:

\[ \frac{\dot{V}_{H_2}}{\dot{V}_{CH_4}} = \sqrt{\frac{\rho_{CH_4}}{\rho_{H_2}}} = \sqrt{\frac{M_{CH_4}}{M_{H_2}}} = \sqrt{\frac{16}{2}} = 2.8 \]

Source:

Release Rate

Subsonic, below approx. 0.9 barg

Mass flow rate\[\dot{m} = C_d A P \sqrt{\frac{M}{Z R T}} \frac{2\gamma}{(\gamma - 1)} \left[1 - \left(\frac{P_{\text{atm}}}{P}\right)^{(\gamma - 1)/\gamma}\right] \left(\frac{P_{\text{atm}}}{P}\right)^{1/\gamma}\]

For the same pressure, leak diameter and leak length:

\[\frac{\dot{m}_{H_2}}{\dot{m}_{C_\text{H}_4}} = C_{\text{subsonic}} \sqrt{\frac{M_{H_2}}{M_{C\text{H}_4}}} = \begin{cases} \sqrt{\frac{2}{16}} = 0.35 & \text{for } P = 21 \text{ mbarg} \\ 1.026 \sqrt{\frac{2}{16}} = 0.36 & \text{for } P = 0.9 \text{ barg} \end{cases}\]

\[\text{Gas distribution pressure}\]
\[\text{Choke pressure}\]

*Source:

Release Rate

Choked, above approx. 0.9 barg

Mass flow rate*

\[ \dot{m} = C_d A P \sqrt{\frac{M}{ZRT}} \left( \frac{\gamma}{\gamma + 1} \right)^{(\gamma + 1)/(\gamma - 1)} \]

For the same pressure, leak diameter and leak length:

\[ \frac{\dot{m}_{H_2}}{\dot{m}_{CH_4}} = C_{choked} \sqrt{\frac{M_{H_2}}{M_{CH_4}}} = 1.025 \sqrt{\frac{2}{16}} = 0.36 \]

*Source:

Release Rate

Converting between volume, mass and energy

Mass
\[
\frac{\dot{m}_{H_2}}{\dot{m}_{CH_4}} = \frac{M_{H_2}}{M_{CH_4}} \frac{\dot{V}_{H_2}}{\dot{V}_{CH_4}} = \frac{2}{16} \times 1.23 = 0.15
\]

Energy
\[
\frac{\dot{Q}_{H_2}}{\dot{Q}_{CH_4}} = \frac{Q_{H_2}}{Q_{CH_4}} \frac{\dot{V}_{H_2}}{\dot{V}_{CH_4}} = \frac{285.8}{890.8} \times 1.23 = 0.40
\]

- “Gross” heats of combustion used here, i.e. water produced in the combustion reaction is condensed into liquid, and the heat of combustion value accounts for the resulting release of latent heat.
- To calculate the heat released in a fire, it is more appropriate to use the “net” heat of combustion, which is 5 – 15% lower, since water remains as vapour in that case. Also need to consider combustion efficiency and radiative heat fraction. Such analysis is left for future work.
Volumetric Release Rate

No change in volumetric flow rate for laminar leaks up to around 70% hydrogen.
Mass Release Rate

Ratio of hydrogen blend to methane mass flow rate

Hydrogen volume fraction, $f_{H2}$
Energy Release Rate

Ratio of hydrogen blend to methane energy flow rate

Hydrogen volume fraction, $f_{H2}$

- Choked
- Subsonic
- Turbulent
- Laminar
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- Gas accumulation
- IGE/UP/1
- Conclusion
Dispersion

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VIRTUAL TURBULENT BUOYANT JETS
A Review of Experimental Data

By
CHING JEN CHEN
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And
WOLFGANG RODI
Sonderforschungsbereich 80
Universität Karlsruhe, Karlsruhe, Germany

Fig. 1. Buoyant jets in uniform surroundings
Dispersion

Jets

Gas concentration (mass fraction) \( y = k \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{2}} \frac{D}{x} \)

Distance to LFL for hydrogen

Distance to LFL for methane

\[
\frac{x_{H2}}{x_{CH4}} = \left( \frac{\rho_{H2}}{\rho_{CH4}} \right)^{\frac{1}{2}} \frac{y_{CH4}}{y_{H2}} = \left( \frac{M_{H2}}{M_{CH4}} \right)^{\frac{1}{2}} \frac{y_{CH4}}{y_{H2}} = \left( \frac{2}{16} \right)^{\frac{1}{2}} \frac{2.8}{0.29} = 3.5
\]

LFLs expressed as mass fractions (% w/w)
Dispersion

Intermediate Jet-Plume

Gas concentration (volume fraction) \( C^* = 4.4 Fr^8 \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{7}{16}} \left( \frac{x}{D} \right)^{-\frac{5}{4}} \)

Buoyant plumes

Gas concentration (volume fraction) \( C^* = 9.35 Fr^\frac{1}{3} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{1}{3}} \left( \frac{x}{D} \right)^{-\frac{5}{3}} \)

\( Fr = \frac{\rho_0 U_0^2}{gD(\rho_a - \rho_0)} \)

- \( Fr \) Froude number
- \( \rho_0 \) Gas density
- \( \rho_a \) Air density
- \( x \) Axial distance
- \( D \) Leak diameter
- \( U_0 \) Exit velocity
- \( g \) Gravitational accel.
Dispersion

For **choked** jet releases

Gas concentration (mass fraction)

\[ y = k \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{2}} \frac{D_{eff}}{x + a} \]

Effective source diameter, \( D_{eff} \)

Effective source offset distance, \( a \)

1.) Birch, A.D., Hughes, D.J., Swaffield, F., 1987. Velocity decay of high pressure jets, Combust. Sci. and Tech. 52, 161-171, [https://doi.org/10.1080/00102208708952575](https://doi.org/10.1080/00102208708952575)

\[
\frac{D_{eff}}{D} = C_D \sqrt{\left[ \frac{P}{P_{atm}} \left( \frac{2}{\gamma + 1} \right)^{\frac{1}{\gamma - 1}} \frac{\gamma}{(\gamma C_D^2 + 1)} \right]}
\]


\[
\frac{D_{eff}}{D} = \left( \frac{P_e}{P_a} \right)^{\frac{1}{2}} \quad ; \quad P_e = P \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}}
\]
The graph illustrates the dispersion of a hydrogen blend compared to methane. It shows the ratio of the distance to 50% LFL (Lower Flammability Limit) of the blend to that of pure methane, as a function of the hydrogen volume fraction, $f_{H2}$. The plot includes curves for different operating conditions:

- **Jet (subsonic)**: Solid blue line
- **Jet (choked, 7 barg)**: Dotted blue line
- **Jet (choked, 85 barg)**: Dotted green line
- **Intermediate Jet-Plume**: Dotted green line
- **Plume**: Red line

A factor of 3.5 increase in distance to 50% LFL for pure hydrogen relative to methane is indicated on the graph, highlighting the significant dispersion characteristics of hydrogen blends.
When is it a jet or a plume?

- **Hydrogen, 100% LFL**
  - JET
  - INTERMEDIATE
  - PLUME

- **Hydrogen, 50% LFL**
  - JET
  - INTERMEDIATE
  - PLUME

- **Methane, 100% LFL**
  - JET
  - INTERMEDIATE
  - PLUME

- **Methane, 50% LFL**
  - JET
  - INTERMEDIATE
  - PLUME
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Quadvent model

Comparison to Quadvent model

Point A
Pressure = 10 barg
Orifice diameter = 0.1 mm

<table>
<thead>
<tr>
<th></th>
<th>100% LFL</th>
<th>50% LFL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen distance ($x_{H2}$)</td>
<td>0.11 m</td>
<td>0.22 m</td>
</tr>
<tr>
<td>Methane distance ($x_{CH4}$)</td>
<td>0.030 m</td>
<td>0.062 m</td>
</tr>
<tr>
<td>Ratio of hydrogen to methane distances ($x_{H2}/x_{CH4}$)</td>
<td>3.6</td>
<td>3.6</td>
</tr>
</tbody>
</table>
Comparison to Quadvent model

**Point A**
Pressure = 10 barg
Orifice diameter = 0.1 mm

<table>
<thead>
<tr>
<th></th>
<th>100% LFL</th>
<th>50% LFL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen distance ($x_{H2}$)</td>
<td>0.11 m</td>
<td>0.22 m</td>
</tr>
<tr>
<td>Methane distance ($x_{CH4}$)</td>
<td>0.030 m</td>
<td>0.062 m</td>
</tr>
<tr>
<td>Ratio of hydrogen to methane distances ($x_{H2} / x_{CH4}$)</td>
<td>3.6</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Chen and Rodi (1980) for jets gives ($x_{H2} / x_{CH4}$) = 3.5 to 3.6
Comparison to Quadvent model

**Point B**
Pressure = 0.1 barg
Orifice diameter = 100 mm

<table>
<thead>
<tr>
<th></th>
<th>100% LFL</th>
<th>50% LFL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen distance ((x_{H2}))</td>
<td>34 m</td>
<td>57 m</td>
</tr>
<tr>
<td>Methane distance ((x_{CH4}))</td>
<td>12 m</td>
<td>23 m</td>
</tr>
<tr>
<td>Ratio of hydrogen to methane distances ((x_{H2}/x_{CH4}))</td>
<td>2.9</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Chen and Rodi (1980) for intermediate and plumes gives \((x_{H2}/x_{CH4}) = 2.3 \text{ to } 1.5\)
Comparison to Quadvent model

**Point C**
Pressure = 0.01 barg
Orifice diameter = 500 mm

<table>
<thead>
<tr>
<th></th>
<th>100% LFL</th>
<th>50% LFL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen distance ($x_{H2}$)</td>
<td>93 m</td>
<td>146 m</td>
</tr>
<tr>
<td>Methane distance ($x_{CH4}$)</td>
<td>49 m</td>
<td>84 m</td>
</tr>
<tr>
<td>Ratio of hydrogen to methane distances ($x_{H2}/x_{CH4}$)</td>
<td>1.9</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Chen and Rodi (1980) for plumes and intermediate gives ($x_{H2}/x_{CH4}$) = 1.5 to 2.3
Comparison to Quadvent model

Conclusion:

- Quadvent gives similar results to the Chen and Rodi (1980) correlations for the limiting conditions of momentum-dominated jets and buoyancy-dominated plumes.

- Independent check supports the earlier analysis using empirical correlations.

Chen and Rodi (1980) for plumes and intermediate gives $(x_{H2}/x_{CH4}) = 1.5$ to $2.3$. 

Pressure = 0.01 barg
Orifice diameter = 500 mm
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- IGE/UP/1
- Conclusion
Gas accumulation models

NaturalHy project

https://repository.lboro.ac.uk/articles/Gas_build-up_in_a_domestic_property_following_releases_of_methane_hydrogen_mixtures/9242582

HSE simplified model:
• Fully-mixed upper layer
• No jet model
• No wind: buoyancy drives flow
IGE/UP/1

Utilization Procedures
IGE/UP/1 Edition 2
Reprint with Amendments
August 2005
Communication 1716

Strength testing, tightness testing and direct purging of industrial and commercial gas installations

5.5 MAXIMUM PERMITTED LEAK RATE ( MPLR )

MPLR is the maximum permitted leak rate of the operating gas when the pipework is at OP. For a new installation, MPLR is a fixed value dependent only on the operating gas and is based on an energy release rate of 0.054 MJ h⁻¹. Hence, MPLR for other gases not included in the tables can be calculated (see A4.1). The tightness test may use a different test gas and/or be at a pressure other than OP. Both of these will affect the measured leakage. The tables included in this section account for this for the common range of fuel gases and specified test pressures. Separate calculations would be needed for other gases or different pressures (see Appendix 4 or 5).

5.5.1 New installations and extensions

MPLR as shown in Table 7 shall apply irrespective of the location of the pipework.

Note: The prescribed test procedures will be capable of detecting the leakage rates shown.

<table>
<thead>
<tr>
<th>GAS TYPE</th>
<th>MPLR (m³ h⁻¹) at OP</th>
</tr>
</thead>
<tbody>
<tr>
<td>NATURAL</td>
<td>0.0014</td>
</tr>
<tr>
<td>BUTANE</td>
<td>0.00044</td>
</tr>
<tr>
<td>PROPANE</td>
<td>0.00057</td>
</tr>
<tr>
<td>LPG/AIR (SNG)</td>
<td>0.0013</td>
</tr>
<tr>
<td>LPG/AIR (SMG)</td>
<td>0.0021</td>
</tr>
<tr>
<td>COAL GAS</td>
<td>0.0029</td>
</tr>
</tbody>
</table>

TABLE 7 - MPLR (NEW INSTALLATIONS AND EXTENSIONS)
Based on previous analysis, can we answer these questions?

1. Is a leak of gas at the MPLR laminar or turbulent?

2. For an installation with a natural gas leak equal to the MPLR, how would the leak rate change if the gas was switched to hydrogen? What would be the implications in terms of flammable cloud size?

3. The MPLR for different gases is based on equivalent energy content (in MJ/hr). What would be the MPLR for hydrogen using this approach? What would be the implications in terms of the flammable cloud size?
Is the MPLR Laminar or Turbulent?

<table>
<thead>
<tr>
<th>Methane MPLR volumetric flow rate</th>
<th>0.0014 m³/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Laminar flow calculation</strong></td>
<td></td>
</tr>
<tr>
<td>Methane MPLR hole diameter*</td>
<td>0.095 mm</td>
</tr>
<tr>
<td>Methane MPLR Reynolds number</td>
<td>330</td>
</tr>
<tr>
<td><strong>Subsonic flow calculation</strong></td>
<td></td>
</tr>
<tr>
<td>Methane MPLR hole diameter</td>
<td>0.080 mm</td>
</tr>
<tr>
<td>Methane MPLR Reynolds number</td>
<td>395</td>
</tr>
</tbody>
</table>

Assumed pressure = 21 mbarg

\[
\dot{V}_{laminar} = \frac{\Delta P \pi D^4}{128 L \mu} \\
\dot{m}_{subsonic} = C_d A P \sqrt{\frac{M}{Z R T}} \frac{2 \gamma}{\gamma - 1} \left[ 1 - \left( \frac{P_{atm}}{P} \right)^{(\gamma - 1)/\gamma} \right] \left( \frac{P_{atm}}{P} \right)^{1/\gamma}
\]

Conclusion: Flow through leak is laminar
Volumetric Release Rate

Volume flow rate unchanged with up to 70% hydrogen
IGE/UP/1: Scenario 1 calculations

Scenario 1

Flow rates calculated using 0.095 mm hole size that gives MPLR flow rate for methane at pressure of 21 mbarg

<table>
<thead>
<tr>
<th>Scenario 1 calculations</th>
<th>Methane</th>
<th>20% Hydrogen</th>
<th>50% Hydrogen</th>
<th>100% Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower flammability limit (% v/v)</td>
<td>5.0</td>
<td>4.8</td>
<td>4.4</td>
<td>4.0</td>
</tr>
<tr>
<td>Volumetric flow rate for the hole diameter calculated for the methane MPLR (0.095 mm) assuming laminar flow (m³/hr) and pressure of 21 mbarg</td>
<td>0.0014</td>
<td>0.0014</td>
<td>0.0014</td>
<td>0.0017</td>
</tr>
</tbody>
</table>
Gas Accumulation Results (Scenario 1)

Flow rates calculated using 0.095 mm hole size that gives MPLR flow rate for methane (pressure = 21 mbarg)

Conclusion: for gas installations tested to IGE/UP/1 with natural gas, the calculation shows there is no increased risk of forming a flammable cloud from adding 20% or 50% hydrogen into natural gas.
### IGE/UP/1: Scenario 2 calculations

**Scenario 2**

Calculate flow rates from 0.054 MJ/hr

#### Maximum Permitted Leak Rate (MPLR)

MPLR is the maximum permitted leak rate of the operating gas when the pipework is at OP. For a new installation, MPLR is a fixed value dependent only on the operating gas and is based on an energy release rate of 0.054 MJ/hr⁻¹. Hence, MPLR for other gases not included in the tables can be calculated (see A4.1). The tightness test may use a different test gas and/or be at a pressure.

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<tr>
<th></th>
<th>Methane</th>
<th>20% Hydrogen</th>
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<tr>
<td>Lower flammability limit (% v/v)</td>
<td>5.0</td>
<td>4.8</td>
<td>4.4</td>
<td>4.0</td>
</tr>
<tr>
<td>Gross heat of combustion (MJ/m³)</td>
<td>37.7</td>
<td>32.6</td>
<td>24.9</td>
<td>12.1</td>
</tr>
<tr>
<td>Volumetric flow rate that gives an energy flow rate of 0.054 MJ/hr (m³/hr) – Scenario 2</td>
<td>0.0014</td>
<td>0.0017</td>
<td>0.0022</td>
<td>0.0045</td>
</tr>
</tbody>
</table>

Increased flow rates with increased hydrogen content due to low heat of combustion per unit volume for hydrogen.
Gas Accumulation Results (Scenario 2)

Flow rates calculated using MPLR energy release rate of 0.054 MJ/hr

Conclusion: increased risk of forming a flammable cloud if hydrogen blend MPLR is calculated from 0.054 MJ/hr
IGE/UP/1: Scenario 3 calculations

Scenario 3

What would happen if we fixed the MPLR for hydrogen blends to be the same as that for natural gas (i.e. 0.0014 m³/hr)?

<table>
<thead>
<tr>
<th>GAS TYPE</th>
<th>MPLR (m³ h⁻¹) at OP</th>
<th>methane</th>
<th>20% Hydrogen</th>
<th>50% Hydrogen</th>
<th>100% Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>NATURAL</td>
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<td>0.00057</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LPG/AIR (SNG)</td>
<td>0.0013</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LPG/AIR (SMG)</td>
<td>0.0021</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COAL GAS</td>
<td>0.0029</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE 7 - MPLR (NEW INSTALLATIONS AND EXTENSIONS)

<table>
<thead>
<tr>
<th></th>
<th>Methane</th>
<th>20% Hydrogen</th>
<th>50% Hydrogen</th>
<th>100% Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower flammability limit (% v/v)</td>
<td>5.0</td>
<td>4.8</td>
<td>4.4</td>
<td>4.0</td>
</tr>
<tr>
<td>Volumetric flow rate that gives an energy flow rate of 0.054 MJ/hr (m³/hr) – Scenario 2</td>
<td>0.0014</td>
<td>0.0014</td>
<td>0.0014</td>
<td>0.0014</td>
</tr>
</tbody>
</table>
Gas Accumulation Results (Scenario 3)

Flow rates all set to 0.0014 m$^3$/hr (the current MPLR for natural gas)

No increased risk of producing flammable cloud

Hydrogen-rich clouds are more buoyant, producing higher ventilation flow rates and lower concentrations

Is the solution to make the MPLR for hydrogen blends equal to the MPLR for natural gas on a volumetric (not energy) basis, equal to 0.0014 m$^3$/hr?
Conclusions

The aim of this work was address the following questions:

- Does hydrogen leak more than natural gas?
  - If so, by how much?
- What is its effect on the size of the flammable cloud?
- What are the implications for procedures, like IGE/UP/1?
Conclusions

Does hydrogen leak more than natural gas?

- Laminar leaks:
  - Blends < 70% v/v hydrogen, no change in volume flow rate
  - Blends > 70% v/v hydrogen, increase up to factor of 1.23 for pure hydrogen

- Turbulent/choked/subsonic leaks:
  - Increase in volume flow rate up to factor of 2.8 for pure hydrogen

![Graph showing the ratio of hydrogen blend to methane volumetric flow rate against hydrogen volume fraction, fH2.](image)
Conclusions

What is its effect on the size of the flammable cloud?

• For free vertical releases, an increased size of flammable cloud relative to natural gas

Factor of 3.5 increase in distance to 50% LFL
Conclusions

What are the implications for procedures, like IGE/UP/1?

- For gas installations tested to IGE/UP/1 with natural gas, the gas accumulation model gave no increased risk of forming a flammable cloud from adding 20% or 50% hydrogen into natural gas.

- If the MPLR for hydrogen is defined using an energy flow rate of 0.054 MJ/hr there is an increased risk of producing flammable clouds.

- If the MPLR for hydrogen is defined as the same volume flow rate as natural gas (0.0014 m³/hr), there is no increased risk of producing a flammable cloud (including blends with up to 100% hydrogen).

<table>
<thead>
<tr>
<th>GAS TYPE</th>
<th>MPLR (m³ h⁻¹) at OP</th>
</tr>
</thead>
<tbody>
<tr>
<td>NATURAL</td>
<td>0.0014</td>
</tr>
<tr>
<td>BUTANE</td>
<td>0.00044</td>
</tr>
<tr>
<td>PROPANE</td>
<td>0.00057</td>
</tr>
<tr>
<td>LPG/AIR (SNG)</td>
<td>0.0013</td>
</tr>
<tr>
<td>LPG/AIR (SMG)</td>
<td>0.0021</td>
</tr>
<tr>
<td>COAL GAS</td>
<td>0.0029</td>
</tr>
</tbody>
</table>

Solution: Hydrogen 0.0014 m³/hr?
Acknowledgements

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Thank you

Any questions?

For a copy of HSE Research Report RR1169, please contact: simon.gant@hse.gov.uk
Ratio of specific heat capacities

Data at 15 °C from NIST webbook
https://webbook.nist.gov
When is the flow laminar or turbulent?

Maximum limiting hole diameters for laminar flow:
- hydrogen
- methane

Assuming leak flow path length of $L = 5$ mm
Assuming pressure of $P = 21$ mbarg

Conclusion: hydrogen more likely to produce laminar flow than methane
Ratio of distance to 100% LFL and 50% LFL, using Birch *et al.* (1987) and Ewan & Moodie (1986) models for choked releases

**Birch *et al.* (1987)**

**Ewan & Moodie (1986)**

**Conclusion:**
All four results practically identical
5.5.2.6  **Test criteria**

The test criteria given in Table 8 shall be applied.

<table>
<thead>
<tr>
<th>GAS TYPE</th>
<th>MPLR (m³ h⁻¹ (st))</th>
<th>LOCATION OF PIPEWORK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Inadequately ventilated areas (Area type A)</td>
</tr>
<tr>
<td>NATURAL</td>
<td>0.0014</td>
<td>Adequately ventilated internal area volume ≤ 60m³ rate per m³ of smallest space</td>
</tr>
<tr>
<td></td>
<td></td>
<td>volume (Area type B)</td>
</tr>
<tr>
<td>BUTANE</td>
<td>0.00044</td>
<td>Adequately ventilated internal area. Volume 60m³ or greater, external exposed, or</td>
</tr>
<tr>
<td></td>
<td></td>
<td>buried (Area type C and D)</td>
</tr>
<tr>
<td>PROPANE</td>
<td>0.00057</td>
<td></td>
</tr>
<tr>
<td>LPG/AIR(SNG)</td>
<td>0.0013</td>
<td></td>
</tr>
<tr>
<td>LPG/AIR(SMG)</td>
<td>0.0021</td>
<td></td>
</tr>
<tr>
<td>COAL GAS</td>
<td>0.0029</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 8 - MPLR (EXISTING INSTALLATIONS) ASSUMING TTP = OP**
Jet Correlation

Concentration (mass fraction)

\[ y = 5.4 \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{2}} \frac{D}{x} \]

Rearranged in terms of distance

\[ x = 5.4 \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{2}} \frac{D}{y} \]

Ratio of hydrogen to methane distance to LFL

\[ \frac{x_{H2}}{x_{CH4}} = \left( \frac{\rho_{H2}}{\rho_{CH4}} \right)^{\frac{1}{2}} \frac{y_{CH4}}{y_{H2}} = \left( \frac{M_{H2}}{M_{CH4}} \right)^{\frac{1}{2}} \frac{y_{CH4}}{y_{H2}} \]

Original as it appears in Chen and Rodi (1980)
Jet Correlation

Ratio of hydrogen to methane distance to LFL

\[
\frac{x_{H2}}{x_{CH4}} = \left( \frac{\rho_{H2}}{\rho_{CH4}} \right)^{\frac{1}{2}} \frac{y_{CH4}}{y_{H2}} = \left( \frac{M_{H2}}{M_{CH4}} \right)^{\frac{1}{2}} \frac{y_{CH4}}{y_{H2}}
\]

Mass fraction \( y \) as function of volume fraction \( f \)

\[
y = \frac{f M_{gas}}{f M_{gas} + (1 - f) M_{air}}
\]

Using LFL\(_{CH4} = 5.0 \% \) v/v

\[
y_{CH4} = \frac{(0.05)(16.043)}{(0.05)(16.043) + (1 - 0.05)28.97} = 0.028
\]

Using LFL\(_{CH4} = 4.4 \% \) v/v

\[
y_{CH4} = \frac{(0.044)(16.043)}{(0.044)(16.043) + (1 - 0.044)28.97} = 0.025
\]

Using LFL\(_{H2} = 4.0 \% \) v/v

\[
y_{H2} = \frac{(0.040)(2.016)}{(0.040)(2.016) + (1 - 0.040)28.97} = 0.0029
\]
Jet Correlation

Ratio of hydrogen to methane distance to LFL

\[ \frac{x_{H_2}}{x_{CH_4}} = \left( \frac{\rho_{H_2}}{\rho_{CH_4}} \right)^{\frac{1}{2}} \frac{y_{CH_4}}{y_{H_2}} = \left( \frac{M_{H_2}}{M_{CH_4}} \right)^{\frac{1}{2}} \frac{y_{CH_4}}{y_{H_2}} \]

Using LFL\(_{CH_4} = 5.0 \% \text{ v/v} \) (in mass terms 2.8 \% w/w)

\[ \frac{x_{H_2}}{x_{CH_4}} = \left( \frac{2}{16} \right)^{\frac{1}{2}} \frac{2.8}{0.29} = 3.5 \]

Using LFL\(_{CH_4} = 4.4 \% \text{ v/v} \) (in mass terms 2.5 \% w/w)

\[ \frac{x_{H_2}}{x_{CH_4}} = \left( \frac{2}{16} \right)^{\frac{1}{2}} \frac{2.5}{0.29} = 3.0 \]
Jet Correlation: Choked

Where did these formulae come from for the flammable cloud size for choked releases?

Birch *et al.* (1987)

\[
\frac{x_{H2}}{x_{CH4}} = \left( \frac{M_{H2}}{M_{CH4}} \right)^{\frac{1}{2}} \frac{y_{CH4}}{y_{H2}} \frac{f(y_{H2})}{f(y_{CH4})} = \left( \frac{2}{16} \right)^{\frac{1}{2}} \frac{2.8}{0.29} 1.02 = 3.5
\]

Ewan & Moodie (1986)

\[
\frac{x_{H2}}{x_{CH4}} = \left[ \frac{M_{H2}}{M_{CH4}} \frac{(y_{H2} + 1)}{(y_{CH4} + 1)} \right]^{\frac{1}{2}} \frac{y_{CH4}}{y_{H2}} \left( \frac{2}{y_{H2} + 1} \right) \frac{y_{H2}}{y_{H2} - 1} \left( \frac{2}{y_{CH4} + 1} \right) = 3.4
\]
Jet Correlation: Choked  
(Birch et al., 1987)

Concentration  
(mass fraction)

\[ y = k \left( \frac{\rho_0}{\rho_a} \right)^\frac{1}{2} \frac{D_{eff}}{x + a} \]

Concentration offset distance, \( a \), is small and is ignored

Velocity ratio

\[ \frac{V_3}{V_2} = C_d + \frac{1}{\gamma C_d} \left[ 1 - \frac{P_{atm}}{P_1} \left( \frac{2}{\gamma + 1} \right)^{-\gamma/(\gamma-1)} \right] \]

Critical pressure

\[ P_c = P_{atm} \left( \frac{2}{\gamma + 1} \right)^{-\gamma/(\gamma-1)} \]

Effective source diameter

\[ \frac{D_{eff}}{D} = \left[ C_d \frac{P}{P_a} \left( \frac{2}{\gamma + 1} \right)^{1/\gamma-1} \left\{ C_d + \frac{1}{\gamma C_d} \left[ 1 - \frac{P_c}{P} \right] \right\}^{-1} \right]^{1/2} \]
Jet Correlation: Choked  
(Birch et al., 1987)

Effective source diameter

\[
\frac{D_{\text{eff}}}{D} = \left[ C_d \frac{P}{P_a} \left( \frac{2}{\gamma + 1} \right)^{\frac{1}{\gamma - 1}} \left\{ C_d + \frac{1}{\gamma C_d} \left[ 1 - \frac{P_c}{P} \right] \right\}^{-1} \right]^{\frac{1}{2}}
\]

For pressures much higher than the critical pressure \((P \gg P_c)\)

\[
\frac{D_{\text{eff}}}{D} = \left[ C_d \frac{P}{P_a} \left( \frac{2}{\gamma + 1} \right)^{\frac{1}{\gamma - 1}} \left\{ C_d + \frac{1}{\gamma C_d} \left[ 1 - 0 \right] \right\}^{-1} \right]^{\frac{1}{2}}
\]

\[
\frac{D_{\text{eff}}}{D} = \left[ C_d \frac{P}{P_a} \left( \frac{2}{\gamma + 1} \right)^{\frac{1}{\gamma - 1}} \left\{ \gamma C_d^2 + 1 \right\}^{-1} \right]^{\frac{1}{2}}
\]

\[
\frac{D_{\text{eff}}}{D} = C_d \left[ \frac{P}{P_a} \left( \frac{2}{\gamma + 1} \right)^{\frac{1}{\gamma - 1}} \frac{\gamma}{\gamma C_d^2 + 1} \right]^{\frac{1}{2}}
\]

\[
d_t = C_D \sqrt{\left[ \frac{P_1}{P_a} \left( \frac{2}{\gamma + 1} \right)^{1/\gamma - 1} \frac{1}{(\gamma C_d^2 + 1)} \right]}.
\]

Missing \(\gamma\) in Birch et al. (1987) paper
Jet Correlation: Choked
(Birch et al., 1987)

Concentration (mass fraction)

\[ y = k \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{2}} \frac{D_{\text{eff}}}{x} \]

\[ x = k \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{2}} \frac{D_{\text{eff}}}{y} \]

Effective source diameter

\[ \frac{D_{\text{eff}}}{D} = C_d \left[ \frac{P}{P_a} \left( \frac{2}{\gamma + 1} \right) \left( \frac{\gamma}{(\gamma C_d^2 + 1)} \right)^{\frac{1}{2}} \right] \]

\[ \frac{D_{\text{eff}}}{D} = C_d \left( \frac{P}{P_a} \right)^{\frac{1}{2}} \left( \frac{2}{\gamma + 1} \right)^{\frac{1}{2}} \frac{\gamma}{(\gamma C_d^2 + 1)} \]

Ratio of hydrogen to methane distance to LFL

\[ \frac{x_{H_2}}{x_{CH_4}} = \left( \frac{M_{H_2}}{M_{CH_4}} \right)^{\frac{1}{2}} \frac{y_{CH_4}}{y_{H_2}} \frac{f(\gamma_{H_2})}{f(\gamma_{CH_4})} = \left( \frac{2}{16} \right)^{\frac{1}{2}} \frac{2.8}{0.29} 1.02 = 3.5 \]
Jet Correlation: Choked
(Ewan & Moodie, 1986)

Concentration (mass fraction)
\[ y = k \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{2}} \frac{D_{eff}}{x + a} \]

Concentration offset distance, \( a \), is small and is ignored

Effective source diameter
\[ D_{eff} = D \left( \frac{P_e}{P_a} \right)^{\frac{1}{2}} \]

Exit pressure
\[ P_e = P \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}} \]

Source density
\[ \rho_0 = \rho_g \left( \frac{2}{\gamma + 1} \right)^{\frac{1}{\gamma - 1}} \]

Source density
\[ \rho_{eq} = \rho_g \left( \frac{2}{\gamma + 1} \right)^{-1} \]

Combined:
\[ x = k \left[ \frac{\rho_g}{\rho_a} \left( \frac{\gamma + 1}{2} \right) \right]^{\frac{1}{2}} \frac{D}{P} \frac{P}{P_a} \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}} \]

Thus the equivalent jet diameter may be given by
\[ D_{eq} = D_j \left( \frac{P_e}{P_a} \right)^{0.5} \]

\[ P_{eq} = P_0 \left( \frac{2}{\gamma + 1} \right)^{^{\gamma}/\gamma - 1} \]

\[ \rho_{eq} = \rho_g \left( \frac{2}{\gamma + 1} \right)^{-1} \]
Jet Correlation: Choked
(Ewan & Moodie, 1986)

\[ x = k \left[ \frac{\rho_g}{\rho_a} \left( \frac{\gamma + 1}{2} \right) \right]^{1/2} \frac{D P}{y P_a} \left( \frac{2}{\gamma + 1} \right)^{\gamma \over \gamma - 1} \]

Ratio of hydrogen to methane distance to LFL

\[
\frac{x_{H2}}{x_{CH4}} = \left[ \frac{M_{H2}}{M_{CH4}} \left( \frac{\gamma_{H2} + 1}{\gamma_{CH4} + 1} \right) \right]^{1/2} \frac{\gamma_{CH4}}{\gamma_{H2}} \left( \frac{2}{\gamma_{H2} + 1} \right)^{\gamma_{H2} - 1} \left( \frac{2}{\gamma_{CH4} + 1} \right)^{-\gamma_{CH4} - 1}
\]
Where did this formula come from for the flammable cloud size for plumes?

\[
\frac{x_{H2}}{x_{CH4}} = \left( \frac{C_{CH4}^*}{C_{H2}^*} \right)^{\frac{3}{5}} \left( \frac{U_{H2}}{U_{CH4}} \right)^{\frac{2}{5}} \left( \frac{M_{air} - M_{CH4}}{M_{air} - M_{H2}} \right)^{\frac{1}{5}} = \left( \frac{5.0}{4.0} \right)^{\frac{3}{5}} \left( \frac{2.8}{29 - 2} \right)^{\frac{1}{5}} = 1.5
\]
Buoyant Plume Correlation

Concentration (volume fraction)

\[ C^* = 9.35 Fr^{\frac{1}{3}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{1}{3}} \left( \frac{x}{D} \right)^{-\frac{5}{3}} \]

Froude number

\[ Fr = \frac{U_0^2}{gD \left( \rho_a - \rho_0 \right) / \rho_0} \]

Combined:

\[ \left( \frac{x}{D} \right)^{\frac{5}{3}} = \frac{9.35}{C^*} \left( \frac{U_0^2}{gD \left( \rho_a - \rho_0 \right) / \rho_0} \right)^{\frac{1}{3}} \left( \frac{\rho_a}{\rho_0} \right)^{\frac{1}{3}} \]

\[ x = D \left( \frac{9.35}{C^*} \right)^{\frac{3}{5}} \left( \frac{\rho_a U_0^2}{gD \left( \rho_a - \rho_0 \right)} \right)^{\frac{1}{5}} \]

Original as it appears in Chen and Rodi (1980)
Buoyant Plume Correlation

\[ x = D \left( \frac{9.35}{C^*} \right)^{\frac{3}{5}} \left( \frac{\rho_a U_0^2}{gD(\rho_a - \rho_0)} \right)^{\frac{1}{5}} \]

Ratio of hydrogen to methane distance to LFL

\[ \frac{x_{H_2}}{x_{CH_4}} = \frac{D \left( \frac{9.35}{C_{H_2}^*} \right)^{\frac{3}{5}} \left( \frac{\rho_a U_{H_2}^2}{gD(\rho_a - \rho_{H_2})} \right)^{\frac{1}{5}}}{D \left( \frac{9.35}{C_{CH_4}^*} \right)^{\frac{3}{5}} \left( \frac{\rho_a U_{CH_4}^2}{gD(\rho_a - \rho_{CH_4})} \right)^{\frac{1}{5}}} \]

\[ \frac{x_{H_2}}{x_{CH_4}} = \left( \frac{C_{CH_4}^*}{C_{H_2}^*} \right)^{\frac{3}{5}} \left( \frac{\rho_a - \rho_{CH_4}}{\rho_a - \rho_{H_2}} \right)^{\frac{1}{5}} \left( \frac{U_{H_2}}{U_{CH_4}} \right)^{\frac{2}{5}} \]
Buoyant Plume Correlation

Ratio of hydrogen to methane distance to LFL

\[
\frac{x_{H2}}{x_{CH4}} = \left( \frac{C_{CH4}^*}{C_{H2}^*} \right)^{\frac{3}{5}} \left( \frac{\rho_a - \rho_{CH4}}{\rho_a - \rho_{H2}} \right)^{\frac{1}{5}} \left( \frac{U_{H2}}{U_{CH4}} \right)^{\frac{2}{5}}
\]

Inserting values
(LFL_{CH4} = 5.0 % v/v)

\[
\frac{x_{H2}}{x_{CH4}} = \left( \frac{0.05}{0.04} \right)^{\frac{3}{5}} \left( \frac{28.97 - 16.043}{28.97 - 2.016} \right)^{\frac{1}{5}} (2.82)^{\frac{2}{5}} = 1.5
\]

Inserting values
(LFL_{CH4} = 4.4 % v/v)

\[
\frac{x_{H2}}{x_{CH4}} = \left( \frac{0.044}{0.040} \right)^{\frac{3}{5}} \left( \frac{28.97 - 16.043}{28.97 - 2.016} \right)^{\frac{1}{5}} (2.82)^{\frac{2}{5}} = 1.4
\]
Intermediate Jet-Plume Correlation

Where did this formula come from for the flammable cloud size for intermediate jet-plumes?

\[
\frac{x_{H2}}{x_{CH4}} = \left( \frac{C_{CH4}^*}{C_{H2}^*} \right)^{\frac{4}{5}} \left( \frac{U_{H2}}{U_{CH4}} \right)^{\frac{1}{5}} \left( \frac{M_{air} - M_{CH4}}{M_{air} - M_{H2}} \right)^{\frac{1}{10}} \left( \frac{M_{CH4}}{M_{H2}} \right)^{\frac{1}{4}} = \left( \frac{0.05}{0.04} \right)^{\frac{4}{5}} \left( \frac{2.8}{29 - 16} \right)^{\frac{1}{10}} \left( \frac{16}{2} \right)^{\frac{1}{4}} = 2.3
\]
Intermediate Jet-Plume Correlation

Concentration (volume fraction)

\[ C^* = 4.4 Fr^{1/8} \left( \frac{\rho_0}{\rho_a} \right)^{7/16} \left( \frac{x}{D} \right)^{-5/4} \]

Froude number

\[ Fr = \frac{U_0^2}{gD (\rho_a - \rho_0)/\rho_0} \]

Combined:

\[ \left( \frac{x}{D} \right)^{5/4} = \frac{4.4}{C^*} \left( \frac{U_0^2}{gD (\rho_a - \rho_0)/\rho_0} \right)^{1/8} \left( \frac{\rho_a}{\rho_0} \right)^{7/16} \]

\[ x = D \left( \frac{4.4}{C^*} \right)^{4/5} \frac{U_0^{12}}{gD^{4/5}} \left( \frac{1}{\rho_a - \rho_0} \right)^{1/10} \left( \frac{\rho_a}{\rho_0} \right)^{7/20} \]

Original as it appears in Chen and Rodi (1980)
Intermediate Jet-Plume Correlation

\[ x = D \left( \frac{4.4}{C^*} \right)^{\frac{4}{5}} U_0^{\frac{1}{5}} \left( \frac{1}{gD} \right)^{\frac{1}{10}} \left( \frac{1}{\rho_a - \rho_0} \right)^{\frac{1}{10}} (\rho_a)^{\frac{7}{20}} \left( \frac{1}{\rho_0} \right)^{\frac{1}{4}} \]

Ratio of hydrogen to methane distance to LFL

\[ \frac{x_{H2}}{x_{CH4}} = \left( \frac{C_{CH4}^*}{C_{H2}^*} \right)^{\frac{4}{5}} \left( \frac{U_{H2}}{U_{CH4}} \right)^{\frac{1}{5}} \left( \frac{\rho_a - \rho_{CH4}}{\rho_a - \rho_{H2}} \right)^{\frac{1}{10}} \left( \frac{\rho_{CH4}}{\rho_{H2}} \right)^{\frac{1}{4}} \]

Inserting values (LFL\textsubscript{CH4} = 5.0 % v/v)

\[ \frac{x_{H2}}{x_{CH4}} = \left( \frac{0.05}{0.04} \right)^{\frac{4}{5}} (2.82)^{\frac{1}{5}} \left( \frac{28.97 - 16.043}{28.97 - 2.016} \right)^{\frac{1}{10}} \left( \frac{16.043}{2.016} \right)^{\frac{1}{4}} = 2.3 \]

Inserting values (LFL\textsubscript{CH4} = 4.4 % v/v)

\[ \frac{x_{H2}}{x_{CH4}} = \left( \frac{0.044}{0.040} \right)^{\frac{4}{5}} (2.82)^{\frac{1}{5}} \left( \frac{28.97 - 16.043}{28.97 - 2.016} \right)^{\frac{1}{10}} \left( \frac{16.043}{2.016} \right)^{\frac{1}{4}} = 2.1 \]
When are releases jets or plumes?

Transition from jet to plume is controlled by parameter, $B$

$$B = Fr^{-\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{1}{4}} \frac{x}{D}$$

- $B < 0.5$ the flow is a momentum-dominated jet
- $0.5 < B < 5.0$ the flow is in an intermediate state between jet and plume
- $B > 5.0$ the flow is a buoyancy-dominated plume

Rearrange in terms of distance:

$$\frac{D}{x} = Fr^{-\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{1}{4}} \frac{1}{B}$$

Substitute in jet formula:

$$y = 5.4 \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{2}} \frac{D}{x}$$

To give:

$$y = 5.4 \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{2}} \left[ \frac{\rho_0 U_0^2}{gD(\rho_a - \rho_0)} \right]^{-\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{1}{4}} \frac{1}{B}$$
When are releases jets or plumes?

\[ y = 5.4 \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{2}} \left[ \frac{\rho_0 U_0^2}{gD(\rho_a - \rho_0)} \right]^{\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{1}{4}} \]

Rearrange in terms of release velocity:

\[ U_0 = \frac{5.4 \gamma B}{\rho_0 A} \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{4}} \left[ \frac{gD(\rho_a - \rho_0)}{\rho_0} \right]^{\frac{1}{2}} \]

Equation for subsonic release velocity from BS EN 60079-10-1:

\[ U_0 = \frac{m}{\rho_0 A} = \frac{C_d P}{\rho_0} \sqrt{\frac{M}{ZRT}} \frac{2\gamma}{(\gamma - 1)} \left[ 1 - \left( \frac{P_{atm}}{P} \right)^{(\gamma-1)/\gamma} \right] \left( \frac{P_{atm}}{P} \right)^{1/\gamma} \]

Equate the two equations for the release velocity:

\[ \frac{5.4 \gamma B}{\rho_0 A} \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{4}} \left[ \frac{gD(\rho_a - \rho_0)}{\rho_0} \right]^{\frac{1}{2}} = \frac{C_d P}{\rho_0} \sqrt{\frac{M}{ZRT}} \frac{2\gamma}{(\gamma - 1)} \left[ 1 - \left( \frac{P_{atm}}{P} \right)^{(\gamma-1)/\gamma} \right] \left( \frac{P_{atm}}{P} \right)^{1/\gamma} \]
When are releases jets or plumes?

\[
\frac{5.4}{yB} \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{4}} \left[ \frac{gD(\rho_a - \rho_0)}{\rho_0} \right]^{\frac{1}{2}} = \frac{C_dP}{\rho_0} \sqrt{\frac{M}{ZRT(\gamma - 1)}} \left[ 1 - \left( \frac{P_{atm}}{P} \right)^{(\gamma - 1)/\gamma} \right] \left( \frac{P_{atm}}{P} \right)^{1/\gamma}
\]

Rearrange for the release diameter as a function of pressure:

\[
D = \left[ \frac{\rho_0}{g(\rho_a - \rho_0)} \right] \left( \frac{yB}{5.4} \right)^2 \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{1}{2}} \left( \frac{C_dP}{\rho_0} \right)^2 \left\{ \frac{M}{ZRT(\gamma - 1)} \left[ 1 - \left( \frac{P_{atm}}{P} \right)^{(\gamma - 1)/\gamma} \right] \right\} \left( \frac{P_{atm}}{P} \right)^{2/\gamma}
\]

This equation is used to draw the line for subsonic releases at the boundary between jet and intermediate.

\[ B = 0.5 \] at boundary
When are releases jets or plumes?

Now for choked releases, using the Birch et al. (1987) pseudo-source model

\[ B = Fr^{\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{4}} \frac{x}{D_{eff}} \]

Rearrange in terms of distance:

\[ \frac{D_{eff}}{x} = Fr^{\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{4}} \frac{1}{B} \]

Substitute in choked jet formula:

\[ y = 5.4 \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{2}} \frac{D_{eff}}{x} \]

To give:

\[ y = 5.4 \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{2}} \left[ \frac{\rho_0 U_0^2}{gD_{eff}(\rho_a - \rho_0)} \right]^{-\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{1}{4}} \frac{1}{B} \]

Rearrange in terms of release velocity:

\[ U_0 = \frac{5.4}{yB} \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{4}} \left[ \frac{gD_{eff}(\rho_a - \rho_0)}{\rho_0} \right]^{\frac{1}{2}} \]
When are releases jets or plumes?

\[ U_0 = \frac{5.4}{\gamma B} \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{4}} \left[ gD_{eff} \left( \frac{\rho_a - \rho_0}{\rho_0} \right) \right]^{\frac{1}{2}} \]

Equation for expanded jet velocity from BS EN 60079-10-1:

\[ U_0 = \frac{\dot{m}}{\rho_0 A_{eff}} = \frac{C_d P}{\rho_0 A_{eff}} \sqrt{\gamma \frac{M}{ZRT} \left( \frac{2}{\gamma + 1} \right)^{\frac{(\gamma+1)}{(\gamma-1)}}} \]

Birch et al. (1987) effective source diameter:

\[ \frac{D_{eff}}{D} = C_{eff} = \left[ \frac{C_d}{P_a} \left( \frac{2}{\gamma + 1} \right)^{\gamma-1} \right]^{\frac{1}{2}} \left\{ \frac{C_d}{\gamma^2 C_d} \left[ 1 - \frac{P_c}{P} \right] \right\}^{-\frac{1}{2}} \]

Equating the velocities:

\[ \frac{5.4}{\gamma B} \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{4}} \left[ gD_{eff} \left( \frac{\rho_a - \rho_0}{\rho_0} \right) \right]^{\frac{1}{2}} = \frac{C_d P}{\rho_0 C_{eff}^2} \sqrt{\gamma \frac{M}{ZRT} \left( \frac{2}{\gamma + 1} \right)^{\frac{(\gamma+1)}{(\gamma-1)}}} \]
When are releases jets or plumes?

\[
\frac{5.4}{yB} \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{4}} \left[ \frac{gD_{\text{eff}} (\rho_a - \rho_0)}{\rho_0} \right]^{\frac{1}{2}} = \frac{C_d P}{\rho_0 C_{\text{eff}}^2} \sqrt{\frac{M}{\gamma ZRT} \left( \frac{2}{\gamma + 1} \right)}^{\frac{\gamma + 1}{\gamma - 1}}
\]

Rearranging the equation into orifice diameter and a function of pressure:

\[
D = \frac{1}{C_{\text{eff}}} \left[ \frac{\rho_0}{g (\rho_a - \rho_0)} \left( \frac{yB}{5.4} \right)^2 \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{1}{2}} \left( \frac{C_d P}{\rho_0 C_{\text{eff}}^2} \right)^2 \left[ \frac{M}{\gamma ZRT} \left( \frac{2}{\gamma + 1} \right) \right]^{\frac{\gamma + 1}{\gamma - 1}} \right]
\]

where:

\[
C_{\text{eff}} = \left[ C_d \frac{P}{P_a} \left( \frac{2}{\gamma + 1} \right)^{\frac{1}{\gamma - 1}} \left\{ C_d + \frac{1}{\gamma C_d} \left[ 1 - \frac{P_c}{P} \right] \right\}^{-1} \right]^{\frac{1}{2}}
\]

This equation is used to draw the line for choked releases at the boundary between jet and intermediate.

\[B = 0.5\] at boundary
When are releases jets or plumes?


Same derivation as before to give the orifice diameter in terms of pressure:

\[
D = \frac{1}{C_{eff}} \left[ \frac{\rho_0}{g(\rho_a - \rho_0)} \right] \left( \frac{yB}{4.99} \right)^2 \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{1}{2}} \left( \frac{C_d P}{\rho_0 C_{eff}^2} \right)^2 \left[ \frac{M}{ZRT} \right] \left( \frac{2}{\gamma + 1} \right)^{(\gamma+1)/(\gamma-1)}
\]

Note that Ewan and Moodie use \( k = 4.99 \) instead of 5.4 in the concentration-decay formula.

Ewan & Moodie (1986) effective source diameter:

\[
\frac{D_{eff}}{D} = C_{eff} = \left( \frac{P_e}{P_{atm}} \right)^{\frac{1}{2}}
\]

Exit pressure:

\[
P_e = P \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma-1}}
\]

Pseudo-source density:

\[
\rho_0 = \rho_g \left( \frac{2}{\gamma + 1} \right)^{-1}
\]

where \( \rho_g \) is the gas density at ambient temperature.

The above equations are used to draw the line for choked releases at the boundary between jet and intermediate.

\( B = 0.5 \) at boundary.
When are releases jets or plumes?

Why does the trend change at the critical pressure from increasing \( D \) with \( P \) to decreasing \( D \) with \( P \)?

Below the critical pressure (\( P < P_{\text{crit}} \)), the boundary between jet and plume is defined by parameter \( B \) as follows:

\[
B = \left[ \frac{\rho_0 U_0^2}{gD(\rho_a - \rho_0)} \right]^{\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{4}} \frac{x}{D}
\]

Substituting the concentration decay formula for jets:

\[
y = 5.4 \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{2}} \frac{D_{\text{eff}}}{x}
\]

The resulting equation rearranged is:

\[
U_0 = \frac{5.4}{yB} \left( \frac{\rho_0}{\rho_a} \right)^{\frac{1}{4}} \left[ \frac{gD(\rho_a - \rho_0)}{\rho_0} \right]^{\frac{1}{2}}
\]

So an increase in pressure, which causes an increase in velocity \( U_0 \) is balanced by an increase in diameter \( D \) and we have the positive slope to the line in the diagram.
When are releases jets or plumes?

Above the critical pressure \((P > P_{\text{crit}})\), the diameter in parameter \(B\) becomes the pseudo-source diameter, \(D_{\text{eff}}\):

\[
U_0 = \frac{5.4}{yB} \left(\frac{\rho_0}{\rho_a}\right)^{\frac{1}{4}} \left[ gD_{\text{eff}} (\rho_a - \rho_0) \right]^{\frac{1}{2}} \rho_0
\]

Diameter \(D_{\text{eff}}\) is a function of pressure. In the Ewan & Moodie (1986) model \(D_{\text{eff}} \propto DP^{\frac{1}{2}}\)

\[
U_0 = c \frac{5.4}{yB} \left(\frac{\rho_0}{\rho_a}\right)^{\frac{1}{4}} \left[ gDP^{\frac{1}{2}} (\rho_a - \rho_0) \right]^{\frac{1}{2}} \rho_0
\]

The flow is choked and so \(U_0\) is not a function of pressure. Rearranging the above equation:

\[
\frac{1}{P^{\frac{1}{4}}} = c \frac{5.4}{yB U_0} \left(\frac{\rho_0}{\rho_a}\right)^{\frac{1}{4}} \left[ gD (\rho_a - \rho_0) \right]^{\frac{1}{2}} \rho_0
\]

So an increase in pressure \(P\) is balanced by a decrease in diameter \(D\), hence the negative slope to the line in the diagram.
When are releases jets or plumes?

Is the velocity $U_0$ really independent of pressure when the flow is choked?

Equation for expanded jet velocity from BS EN 60079-10-1:

$$U_0 = \frac{\dot{m}}{\rho_0 A_{eff}} = C_d P \frac{A}{\rho_0 A_{eff}} \sqrt{\frac{M}{ZRT}} \left( \frac{2}{\gamma+1} \right)^{\frac{(\gamma+1)}{(\gamma-1)}}$$

Ewan & Moodie (1986) pseudo-source diameter

$$\frac{D_{eff}}{D} = \left( \frac{P_e}{P_{atm}} \right)^{\frac{1}{2}} = \left( \frac{P}{P_{atm}} \right)^{\frac{1}{2}} \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma}{2(\gamma-1)}}$$

$$\frac{A}{A_{eff}} = \frac{\pi D^2/4}{\pi D_{eff}^2/4} = \left( \frac{D}{D_{eff}} \right)^2$$

So the area ratio $A/A_{eff}$ is proportional to $1/P$, which cancels the pressure term in the equation for the pseudo-source velocity, $U_0$, i.e. the velocity $U_0$ is not a function of pressure.
How is the plume boundary calculated?

Starting from the parameter $B$, which takes a value of 5.0 at the plume boundary

$$B = Fr^{-\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{1}{4}} \frac{x}{D}$$

Chen & Rodi (1980) correlation for concentration decay in plumes:

$$C^* = 9.35 Fr^\frac{1}{3} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{1}{3}} \left( \frac{x}{D} \right)^{-\frac{5}{3}}$$

Combining the two equations:

$$C^* = 9.35 Fr^\frac{1}{3} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{1}{3}} \left[ Fr^{-\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{1}{4}} \frac{1}{B} \right]^\frac{5}{3}$$
When are releases jets or plumes?

\[ C^* = 9.35 Fr^\frac{1}{3} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{1}{3}} \left[ Fr^{-\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{1}{4}} \frac{1}{B} \right]^3 \]

Rearranging:

\[ C^* = 9.35 Fr^{\frac{2}{6}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{4}{12}} Fr^{-\frac{5}{6}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{5}{12}} \left( \frac{1}{B} \right)^{\frac{5}{3}} \]

\[ C^* = 9.35 \left[ \frac{\rho_0 U_0^2}{g D (\rho_a - \rho_0)} \right]^{-\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{3}{4}} \left( \frac{1}{B} \right)^{\frac{5}{3}} \]

\[ U_0 = \frac{9.35}{C^*} \left[ \frac{g D (\rho_a - \rho_0)}{\rho_0} \right]^{\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{3}{4}} \left( \frac{1}{B} \right)^{\frac{5}{3}} \]
When are releases jets or plumes?

\[ U_0 = \frac{9.35}{C^*} \left[ \frac{gD(\rho_a - \rho_0)}{\rho_0} \right]^{\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{3}{4}} \left( \frac{1}{B} \right)^{\frac{5}{3}} \]

Equation for subsonic release velocity from BS EN 60079-10-1:

\[ U_0 = \frac{m}{\rho_0 A} = \frac{C_a P}{\rho_0} \sqrt[2]{\frac{M}{ZRT (\gamma - 1)}} \left[ 1 - \left( \frac{P_{atm}}{P} \right)^{(\gamma - 1)/\gamma} \right] \left( \frac{P_{atm}}{P} \right)^{1/\gamma} \]

Equating these two equations for the velocity gives:

\[ \frac{9.35}{C^*} \left[ \frac{gD(\rho_a - \rho_0)}{\rho_0} \right]^{\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{3}{4}} \left( \frac{1}{B} \right)^{\frac{5}{3}} = \frac{C_a P}{\rho_0} \sqrt[2]{\frac{M}{ZRT (\gamma - 1)}} \left[ 1 - \left( \frac{P_{atm}}{P} \right)^{(\gamma - 1)/\gamma} \right] \left( \frac{P_{atm}}{P} \right)^{1/\gamma} \]

And rearranging:

\[ D = \left[ \frac{\rho_0}{g(\rho_a - \rho_0)} \right] \left( \frac{C^*}{9.35} \right)^2 \left( \frac{\rho_0}{\rho_a} \right)^{\frac{3}{2}} \left( \frac{1}{B} \right)^{-\frac{10}{3}} \left( \frac{C_a P}{\rho_0} \right)^2 \left[ \frac{M}{ZRT (\gamma - 1)} \right]^{2/\gamma} \left[ 1 - \left( \frac{P_{atm}}{P} \right)^{(\gamma - 1)/\gamma} \right] \left( \frac{P_{atm}}{P} \right)^{2/\gamma} \]
When are releases jets or plumes?

How is the plume boundary calculated when the flow is choked?

Starting from the equation for velocity presented previously for subsonic plumes, but using the pseudo-source diameter, $D_{eff}$:

$$U_0 = \frac{9.35}{C^*} \left[ \frac{g D_{eff} (\rho_a - \rho_0)}{\rho_0} \right]^{\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{3}{4}} \left( \frac{1}{B} \right)^{\frac{5}{3}}$$

The equation for the choked flow velocity is:

$$U_0 = \frac{C_d P}{\rho_0} \frac{1}{C_{eff}^2} \sqrt{\gamma \frac{M}{ZRT} \left( \frac{2}{\gamma + 1} \right)^{\frac{(\gamma+1)}{(\gamma-1)}}}$$

Combining these two equations for the velocity gives:

$$\frac{9.35}{C^*} \left[ \frac{g D_{eff} (\rho_a - \rho_0)}{\rho_0} \right]^{\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{-\frac{3}{4}} \left( \frac{1}{B} \right)^{\frac{5}{3}} = \frac{C_d P}{\rho_0} \frac{1}{C_{eff}^2} \sqrt{\gamma \frac{M}{ZRT} \left( \frac{2}{\gamma + 1} \right)^{\frac{(\gamma+1)}{(\gamma-1)}}}$$
When are releases jets or plumes?

\[
\frac{9.35}{C^*} \left[ \frac{gD_{eff} (\rho_a - \rho_0)}{\rho_0} \right]^{\frac{1}{2}} \left( \frac{\rho_0}{\rho_a} \right)^{\frac{3}{4}} \left( \frac{1}{B} \right)^{\frac{5}{3}} = \frac{C_d P}{\rho_0} \frac{1}{C_{eff}^2} \sqrt{\frac{M}{ZRT} \left( \frac{2}{\gamma + 1} \right)^{(\gamma + 1)/(\gamma - 1)}}
\]

\[
\left[ \frac{gD_{eff} (\rho_a - \rho_0)}{\rho_0} \right]^{\frac{1}{2}} = \frac{C^*}{9.35} \left( \frac{\rho_0}{\rho_a} \right)^{\frac{3}{4}} \left( \frac{1}{B} \right)^{\frac{5}{3}} \left( \frac{C_d P}{\rho_0} \frac{1}{C_{eff}^2} \right) \sqrt{\frac{M}{ZRT} \left( \frac{2}{\gamma + 1} \right)^{(\gamma + 1)/(\gamma - 1)}}
\]

Rearranging using the relation \(D_{eff} = C_{eff} D\):

\[
D = \frac{1}{C_{eff}} \left[ \frac{\rho_0}{g(\rho_a - \rho_0)} \right] \left( \frac{C^*}{9.35} \right)^2 \left( \frac{\rho_0}{\rho_a} \right)^{\frac{3}{2}} \left( \frac{1}{B} \right)^{\frac{10}{3}} \left( \frac{C_d P}{\rho_0} \frac{1}{C_{eff}^2} \right)^2 \sqrt{\frac{M}{ZRT} \left( \frac{2}{\gamma + 1} \right)^{(\gamma + 1)/(\gamma - 1)}}
\]

The equations presented previously from Birch et al. (1987) or Ewan & Moodie (1986) are then used for \(C_{eff}\) in the above expression.