Analysis of Buoyancy-Driven Ventilation of Hydrogen from Buildings

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Scope of Work

• Safe building design
• Vehicle leak in residential garage
• Continual slow leak
• Passive, buoyancy-driven ventilation (vs. mechanical)
• Steady-state concentration of $H_2$ vs. vent size
Prior Work

• Modeling and testing with H₂ and He
• Transient H₂ cloud formation

Breitung et al. (2001)
Papanikolaou and Venetsanos (2005)
Our Focus / New Findings

- Slow continual leaks
- Steady-state concentration of $H_2$
- Algebraic equation for vent sizing
- Significant thermal effect (high outdoor temp)
Range of “Slow” Leakage Rates

• **Low end**: 1.4 L/min per SAE J2578 (vehicle manufacture quality control)
• **High end**: 566 L/min automatic shutdown (per Parsons Brinkerhoff for CaFCP)
• **Consider**: Collision damage or faulty maintenance
• Parametric CFD modeling: 5.9 to 82 L/min (12 hr to 7 days/5 kg)
Methods of Analysis

• CFD modeling (FLUENT)
• Simplified, 1-D, steady-state, algebraic analysis
Volume of garage is 146 m³
Volume of 5 kg of H₂ is 60 m³
41% mixture is possible
Well within flammable range
Sample CFD Model Result

CFD modeling used to study \( \text{H}_2 \) cloud. Half of garage is shown. Leak rate is 5 kg/24 hours (41.5 L/min). Vent sizes 790 cm\(^2\). Elapsed time = 83 min. Full scale is 4% \( \text{H}_2 \) by volume.
H₂ concentration at top vent increases monotonically and reaches a steady value in about 90 minutes. A flammable mixture does not occur in this case.
Simulation Setup

- FLUENT version 6.3
- Poly mesh for computational economy
- Grid density study showed solution invariant at approx. 40,000 cells (Avg. ~1.8 L/cell)
- High mesh density near inlet, outlet, gas leak
- Laminar flow model used (more conservative than turbulent models)
- No diffusion across vents at model boundary
Simulation Setup

• Hydrogen concentration at outlet monitored to determine steady state
• 5 kg discharge times from 12 hours to 1 week
• Low speed leak from 8-cm-diameter sphere
• Leak ~1 m above floor, one model near ceiling
• Vent sizes and height varied
Concept of 1-D Model

Typical $\text{H}_2$ stratification determined by CFD model
(steady-state condition)
1-D Parametric Analysis

Pressure Loop / Buoyancy

\[ \Delta P_{1-2} + \Delta P_{2-3} + \Delta P_{3-4} + \Delta P_{4-1} = 0 \]

\[ \Delta P_{1-2} + \Delta P_{3-4} = g \, h \, \rho_{\text{air}} \cdot c_{\text{avg}} \cdot (1-\delta) \]

- \( P \) = Total pressure
- \( h \) = Height between vents
- \( c \) = Concentration of \( \text{H}_2 \), by volume
- \( \rho \) = Density
- \( g \) = Acceleration of gravity
- \( \delta \) = Density of \( \text{H}_2 \) / density of air
1-D Parametric Analysis

Vent Flow vs. Pressure

\[ Q = AD \sqrt{\frac{2\Delta P_{4-1}}{\rho}} \]

Q = Volumetric flow rate
A = Vent area
D = Discharge coefficient

(Similar at bottom vent)
Steady-State Mass Balances

\[ Q_T \, c_T = S \]

\( Q = \) Volumetric flow rate
\( c_T = H_2 \) concentration at top vent, by volume
\( S = \) Volumetric \( H_2 \) source rate
1-D Parametric Analysis

Isothermal Vent-Sizing Equation:

\[ F = \frac{AD}{S} \sqrt{2gh} = \phi^{\frac{1}{2}} \left[ \frac{1 - C_T (1 - \delta) + (1 - C_T)^2}{(1 - \delta) C_T^3} \right]^{\frac{1}{2}} \]

where:

- **F** = Vent sizing factor, dimensionless
- **A** = Vent area (top = bottom), m\(^2\)
- **C_T** = H\(_2\) concentration at top vent, by volume (0-1)
- **D** = Vent discharge coefficient (0-1)
- **S** = Source rate of H\(_2\) (leak rate), m\(^3\)/s
- **g** = Acceleration of gravity = 9.81 m/s\(^2\)
- **h** = Height between vents, m
- **δ** = Ratio of densities of H\(_2\)/Air = 0.0717
- **φ** = Stratification factor = \(C_T/C_{avg}\) (\(C_{avg}\) = average over height)
Curves illustrate isothermal vent-sizing equation. Points 1-7 are CFD results.
# Series of CFD Cases

<table>
<thead>
<tr>
<th>Specifications, Results</th>
<th>CFD Case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Leak-Down Time, hr/5 kg</td>
<td>168</td>
</tr>
<tr>
<td>Vent Size, cm²</td>
<td>788</td>
</tr>
<tr>
<td>Vent Offset, cm</td>
<td>0.0</td>
</tr>
<tr>
<td>Vent Height, m</td>
<td>3.650</td>
</tr>
<tr>
<td>H₂ Conc. at top vent, % Vol</td>
<td>0.47</td>
</tr>
<tr>
<td>Straification Factor (φ)</td>
<td>1.65</td>
</tr>
<tr>
<td>Discharge Coeff. (D*)</td>
<td>0.952</td>
</tr>
</tbody>
</table>

**Note:** The table above lists the specifications and results for a series of CFD cases. Each column represents a different case, with specific values for leak-down time, vent size, vent offset, vent height, hydrogen concentration at the top vent, straification factor, and discharge coefficient.
Ranges of Parameters

- Stratification factor ($\phi$): 1.52 to 1.88
- Apparent discharge coefficient ($D^*$): 0.903 to 0.965
  - $D^*$ higher than typical D (0.60 to 0.70)
  - $D^*$ includes momentum effects
  - Further study needed (experimental)
Reverse Thermocirculation

When outdoor temperature is higher than indoor (garage) temperature, thermal circulation opposes H₂-buoyancy-driven circulation.
Leak rate = 5 kg/12 hours. Vent size = 1,580 cm². 
$T_{\text{amb}} - T_{\text{cond}} = 20^\circ$C. Elapsed time = 3.3 min. 
Full scale = 4% H₂ by volume.
Leak rate = 5 kg/12 hours. Vent size = 1,580 cm².

T_{amb} - T_{cond} = 20°C. Elapsed time = 11.7 min.

Full scale = 4% H₂ by volume.
Leak rate = 5 kg/12 hours. Vent size = 1,580 cm². 
$T_{amb} - T_{cond} = 20°C$. Elapsed time = 15 min. 
Full scale = 4% $H_2$ by volume.
Leak rate = 5 kg/12 hours. Vent size = 1,580 cm². 
\[ T_{\text{amb}} - T_{\text{cond}} = 20°C. \] Elapsed time = 33 min. 
Full scale = 4% H₂ by volume.
Leak rate = 5 kg/12 hours. Vent size = 1,580 cm².
$T_{\text{amb}} - T_{\text{cond}} = 20 ^\circ C$. Elapsed time = 2.8 hr (steady state).
Full scale = 4% $H_2$ by volume.
Thermal Case Study

Leak rate = 5 kg/12 hours. Vent size = 1,580 cm².  
$T_{amb} - T_{cond} = 20^\circ$C.
A Perfect Storm
Extreme thermal scenario

Garage strongly coupled to house & ground
Garage weakly coupled to ambient
Hot day, cool ground, low A/C setpoint
Small vents—sized for 2% H₂ max with 1-D model
A Perfect Storm

Heartland Homes, Pittsburgh, PA
A Perfect Storm
Ambient conditions modeled

- Ambient temp. = 40.6°C (Approx. max. in Denver)
- Ground temp = 10°C  (Denver, mid-April)
- A/C setpoint = 21.1°C (Rather low)
Reverse Flow Scenario
H$_2$ exiting through bottom vent

Case 9. Leak rate = 5 kg/7 days. Vent size = 494 cm$^2$.
Elapsed time = 31 hr (steady state).
Full scale = 1.5% H$_2$ by volume.
A Perfect Storm
Results

• Case 8 (1-day leak):
  Vents from top, 2.3% max

• Case 9 (7-day leak):
  Vents from bottom, 1.0% max

• Case 10 (3-day leak):
  Vents from top, 4.8% max
A Perfect Storm
Worst thermal case we modeled

Case 10. Leak rate = 5 kg/3 days. Vent size = 405 cm$^2$. 
Conclusions

1. The leakage rates that will occur and their frequencies are unknown. Further study of leakage rates is needed to put parametric results into perspective.

2. Our CFD model has not yet been validated against experimental data.
   - Uncertainty in results
   - Future work
Conclusions

3. The 1-D model ignores thermal effects, but otherwise provides a safe-side estimate of H$_2$ concentration by ignoring momentum effects (pending model validation).

4. Indicated vent sizes would cause very low garage temperatures in cold climates, for leak rates of roughly 6 L/min and higher (leak-down in 1 week or less).
Conclusions

5. Reverse thermocirculation:
• Can occur in nearly any climate
• The worst case we modeled increased the expected $\text{H}_2$ concentration from 2% to 5%. This is a significant risk factor,
• Likelihood of occurrence may be low, judging by the lengths we went to in order to identify a significant example.
Conclusions

6. Mechanical ventilation is alternative approach to safety.
   • H₂-sensing fan controller is recommended.
   • Research is needed to develop a control system that is sufficiently reliable and economical for residential use.