Calculation of Radiant Heat Intensity from Remote Vent Stack

Prepared for: Sandia National Laboratories
Project Number: PL-00742
Project: Hydrogen Station Equipment Performance Device (HyStEP)
Report Number: TR00742-02-R01

OBJECTIVES
- To calculate the radiant heat intensity (K) from the HyStEP device's vent stack in the event of ignition while venting and compare that with the acceptable limits outlined in ANSI/API 521 [1].
  - Calculation was conducted in order to meet CGA-G-5.5-2014, which states that the vent stack must "be elevated sufficiently to reduce thermal radiation doses to levels recommended in ANSI/API 251" [2: Section 6.2.3].

SCHEMATIC

Figure 1: Simplified Diagram of the HyStEP Defuel System

ASSUMPTIONS
1. The fraction of heat radiated is 0.17, which is the maximum value for hydrogen flames [3]
2. The maximum flow rate is 0.007898 kg/s which is the maximum flow rate from 3 defuel tests with safety factor of 2.5 (see attached calculation)
3. A lower heating value of 120.21 MJ/kg was used (@ 0°C and 1 atm. from the Hydrogen Analysis Resource Center)
4. The fraction of radiated heat transmitted through the atmosphere (τ) is 1 (conservative approach, since the equations referenced in API 521 are not applicable for hydrogen)
5. Assume the operator is 7 ft. tall (2.1336m) and standing directly below the vent stack
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APPROACH
1. The radiant heat intensity at the vent stack outlet was calculated using Equation 45 [1: Section 5.7.2.3.3], shown re-arranged to calculate for $K$ below.

$$ K = \frac{\tau \cdot F \cdot Q}{D^2 \cdot 4\pi} = \frac{1 \cdot 0.17 \cdot 949.36 \text{ kW}}{(3.1242 \text{ m})^2 \cdot 4\pi} = 1.3158 \text{ kW/m}^2 $$

Where:
- $D =$ the minimum distance from the epicenter of the flame to the object being considered, expressed in meters
- $\tau =$ the fraction of radiated heat transmitted through the atmosphere
- $F =$ the fraction of heat radiated
- $Q =$ the heat release based on the lower heating value, expressed in kW
- $K =$ the radiant heat intensity expressed in kW/m$^2$

   a. To calculate $D$, the height of the vent stack was subtracted from the height of the operator (see assumption 5): 17' 9" - 6' - 7" = 10' 3" = 3.1242 m
   b. $\tau$ was set to 1 (see assumption 4)
   c. $Q$ was calculated using the equation below. The mass flow rate ($m$) was determined from test data obtained while defueling the device. The systems hydrogen mass was calculated before and after defueling and the time recorded to calculate the mass flow rate (see assumption 2). As it is possible to have higher flow rates than observed in the test, a safety factor of 2.5 was used. A lower heating value of 120.21 MJ/kg was used (see assumption 3).

$$ Q = m \cdot LHV = 0.007898 \frac{kg}{s} \cdot \frac{120.21 \text{ MJ/kg}}{kg} = 949.36 \text{ kW} $$

2. With the radiant heat intensity ($K$) calculated, this value was compared with the "Recommended Design Thermal Radiation for Personnel" from Table 12 [1: Section 5.7.2.3.1] to determine if it was acceptable.

3. The radius from the vent stack where the maximum radiant heat intensity is located that personnel with appropriate clothing can be exposed to was calculated using Equation 45. For this $K = 1.58 \text{ kW/m}^2$ as is outlined in Table 12 of API 521 [1].

$$ D = \sqrt{\frac{\tau \cdot F \cdot Q}{4\pi \cdot K}} = \sqrt{\frac{1 \cdot 0.17 \cdot 949.36 \text{ kW}}{4\pi \cdot 1.58 \text{ kW/m}^2}} = 2.851 \text{ m} = 9.35 \text{ ft} $$

RESULTS
The radiant heat intensity calculated was $K=1.3158 \text{ kW/m}^2$ (Calculations shown in attached Appendix). In Table 12 of API 521, a permissible design level of $K = 1.58 \text{ kW/m}^2$ is the "maximum radiant heat intensity at any location where personnel with appropriate clothing* can be continuously exposed" [1]. Therefore the thermal radiation is within the acceptable limits outlined in API 521.

An operator with appropriate clothing can work up to a 9.35 ft (2.851 m) radius from the vent stack outlet (as hatched area in the Figure 1).

*Note: API defines "appropriate clothing" as "hard hat, long-sleeved shirts with cuffs buttoned, work gloves, long legged pants, and work shoes. Appropriate clothing minimizes direct skin exposure to thermal radiation" [1: pg. 106]
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REFERENCES

Prepared By: Liam Quinlan, E.I.T.  Reviewed By: Brad Wong, P.Eng
Date: Dec 17/15  DEC 17 2015
COMPUTATION SHEET

Project: **Hystep PL-00742**
Sheet: 1 of 4

**Computation of:** Radiant Heat Intensity on Hystep Vent Stack

**Computed by:** Liam Aquino, E.I.T.
Date: Oct 28/15, updated Dec 16/15

**Problem:** For the Hystep Device's vent stack to meet CGA-G-5.5, vents shall be elevated sufficiently to reduce thermal radiation due to levels recommended in ANSI/API 521 (6.3.3.6A-6.5.5, 2014). This calculation uses Equation #45 in ANSI/API 521 to calculate the Radiant Heat Intensity \( K \) if the hydrogen gas were to ignite while venting using Hystep's vent system. This is compared with Table 12 (5.7.2.3.1, ANSI/API 521, 2014) to determine if it is within acceptable limits.

**Schematic:**

![Schematic Diagram]

**Assumptions:**
1. The fraction of heat radiated is the maximum value for hydrogen flames.
2. Maximum flow rate from 3 defuel tests is representative of the maximum defueling flow rate.
3. The vent stack outlet is at 1 atm and 0°C with a Lower Heating value of 120.2 kJ/kg.
4. The fraction of radiated heat transmitted through the atmosphere (T) is 1 (assumed) since the equation referenced in ANSI/API 521 are not applicable for hydrogen.
5. Assume the vent is 7 ft tall (2.1336m) and standing directly below the vent stack.

**Analysis:**

Use Equation 45 from section 5.7.2.3.3 of ANSI/API 521 to calculate Radiant Heat Intensity \( K \).

\[
D = \sqrt{\frac{C \cdot F \cdot Q}{4 \pi \cdot k}}
\]

Solve for \( K \):

\[
D^2 = \frac{C \cdot F \cdot Q}{4 \pi \cdot k} \implies K = \frac{C \cdot F \cdot Q}{D^2 \cdot 4 \pi}
\]

**Where:**

\( D \) = minimum distance from flame to center of object being considered (m)

\( k \) = height of vent stack - height of operator, with assumption 5 \( D = 5.1336m - 0.1524m - 2.1336m = 3.05 \) m

\( F \) = Fraction of Heat Radiated, found using Table 13 in 5.7.2.3.3

For conservative analysis, assume the fraction of heat radiated is the maximum value for use with hydrogen.

\[ F = 0.17 \]

(Also see "Applied Process Design for Chemical 
& Petroleum Plants" by Ernest E. Ludwig for the range of \( F \) values)
Q = \text{Heat released based on the lower heating value} = m \cdot \text{LHV}

\text{Lower Heating Value at } H_2 = 120.21 \text{ MJ} \cdot \text{kg}^{-1} \text{ at } 32^\circ F (0^\circ C) \text{ in air}

\text{(Based on Hydrogen Analysis Results cont.)}

\text{Mass Flow Rate was determined from data obtained while defrosting:}

\textbf{Test Data:}

\textbf{Test 1: } 3 tanks, 22.8 L

<table>
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<th>Time</th>
<th>Pressure (MPa)</th>
<th>Temp (°C)</th>
<th>SOC</th>
</tr>
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<td>0</td>
<td>1.82</td>
<td>-10.6</td>
<td>3.7</td>
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<tr>
<td>3:06.55</td>
<td>14.9</td>
<td>-16</td>
<td>3.21</td>
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<th>SOC</th>
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<td>48.4</td>
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<td>20.5</td>
<td>-6.5</td>
<td>41.4</td>
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</table>

\textbf{Test 3: } 1 tank (76 L) until 62.4 MPa, Then 2 tanks (152 L) until 11.5 MPa, Then 3 (22.8 L)

<table>
<thead>
<tr>
<th>Time</th>
<th>P_1</th>
<th>P_2</th>
<th>P_3</th>
<th>T_1</th>
<th>T_2</th>
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<td>62.9</td>
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<td>12.7</td>
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<td>11.5</td>
<td>42.5</td>
<td>42.6</td>
<td>13.4</td>
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<td>14:08</td>
<td>11.5</td>
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<td>18.2</td>
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<td>12.6</td>
<td>8.5</td>
<td>8.8</td>
<td>8.8</td>
</tr>
</tbody>
</table>

\textbf{Mass Flow Rate Calculation:}

\textbf{Test 1: } P_1 = 18.2 \text{ MPa}, P_2 = 14.9 \text{ MPa},
\text{ T}_1 = -10.6, \text{ T}_2 = -16^\circ C = 257 \text{ K}
\Delta T = 3:06.55 = 186.555
\text{ Volume } = 0.228 \text{ m}^3 = V

\text{Using W.A.S.T. Table:}
\text{ P}_1 = 14.971 \text{ kg} \cdot \text{m}^{-3}, \quad \text{ P}_2 = 12.764 \text{ kg} \cdot \text{m}^{-3}

\text{System mass } m = \text{ P} \cdot V = 0.228 \text{ m}^3 \cdot 14.971 \text{ kg} \cdot \text{m}^{-3} = 3.41239 \text{ kg}

\text{ m} = \frac{0.5032 \text{ kg}}{1 \text{ kg}} = 0.005032 \text{ kg}

\text{ m} = \frac{0.328 \text{ kg} \cdot \text{m}^{-3} \cdot 12.764 \text{ kg} \cdot \text{m}^{-3}}{2.91019 \text{ kg}} = 0.003267 \text{ kg}
Mass Flow Rate Calculation (cont):  

**Test 2:**  
\[ P_1 = 262 \text{ kPa}, \quad P_2 = 20.5 \text{ kPa} \]  
\[ T_1 = 2.8^\circ \text{C}, \quad T_2 = -6.5^\circ \text{C} \]  
\[ \Delta t = 3.5791 = 237.915 \]  

**Using NIST Tables:**  
\[ P_1 = 19.612856 \text{ kPa}, \quad P_2 = 16.38587 \text{ kPa} \]  
\[ m = P_1 \cdot V = 4.47 \text{ kg}, \quad m_2 = 3.7358 \]  
\[ m_{\text{net}} = m - m_2 = 0.73575 \text{ kg} \]  
\[ \dot{m} = \frac{0.73575}{237.915} = 0.003093 \text{ kg/s} \]  

**Test 3:**  
Using data from 13:58 to 14:08 since a. B a 10 minute average the entire time  
\[ V = 0.158 \text{ m}^3 \]  
\[ P_1 = 43.5 \text{ kPa}, \quad P_2 = 19.3 \text{ kPa} \]  
\[ T_1 = -1.85^\circ \text{C (average)}, \quad T_2 = -30.8^\circ \text{C (average)} \]  
\[ \Delta t = 14:08 - 13:58 = 10 \text{ minutes} = 600 \text{ s} \]  

**Using NIST Tables:**  
\[ P_1 = 29.35809 \text{ kPa}, \quad P_2 = 16.88829 \text{ kPa} \]  
\[ m = P_1 \cdot V = 4.46243 \text{ kg}, \quad m_2 = 3.567 \text{ kg} \]  
\[ m_{\text{net}} = m - m_2 = 0.8954 \text{ kg} \]  
\[ \dot{m} = \frac{0.8954}{600} = 0.003159 \text{ kg/s} \]  

** Calculation of Q:**  
Based on assumption 2, use the highest mass flow rate with a safety factor of 3.5  
\[ Q = \dot{m} \cdot \text{LHV} = 0.003159 \text{ kg/s} \cdot 120.21 \times 10^6 \frac{\text{J}}{\text{kg}} = 949.358 \frac{\text{J}}{\text{s}} \]  
\[ \Rightarrow Q = 949.36 \text{ kW} \]
Determination of $C$:

$$C = \text{The fraction of the radiated heat transmitted through the atmosphere}$$

(see C.3.3.6.3 in API 521)

Calculation in Annex 1 is only applicable when a luminous flame. No flame is non-luminous (see Annex 4)

Set $C = 1$ for conservative approach

Calculation of $K$:

$$K = \frac{C \cdot F \cdot Q}{D^2 \cdot 4\pi}$$

$$\Rightarrow K = \frac{1.017 \cdot 9.4936 \text{ kW}}{(3.124 \text{ m})^2 \cdot 4\pi} = 1.3158 \text{ kW/m}^2$$

$$K = 1.3158 \text{ kW/m}^2$$

Table 12 in API 521 shows the recommended design thermal radiation for personnel. The permissible design level for $K$ (kW/m²) where the "maximum radiant heat intensity at any location where personnel with appropriate clothing can be continuously exposed" is 1.58 kW/m².

Since $K = 1.3158 \text{ kW/m}^2 < 1.58 \text{ kW/m}^2$, thermal radiation is within acceptable limits.

Calculation of $R$ where $K = 1.58 \text{ kW/m}^2$:

Using Eqn 45:

$$D = \sqrt{\frac{C \cdot F \cdot Q}{4\pi \cdot K}} = \sqrt{\frac{1.017 \cdot 9.4936 \text{ kW}}{4\pi \cdot 1.58 \text{ kW/m}^2}}$$

$$= 2.851 \text{ m} = 9.35 \text{ feet}$$

Therefore, personnel with appropriate clothing can be continuously exposed up to 9.35 feet from the vent.