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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

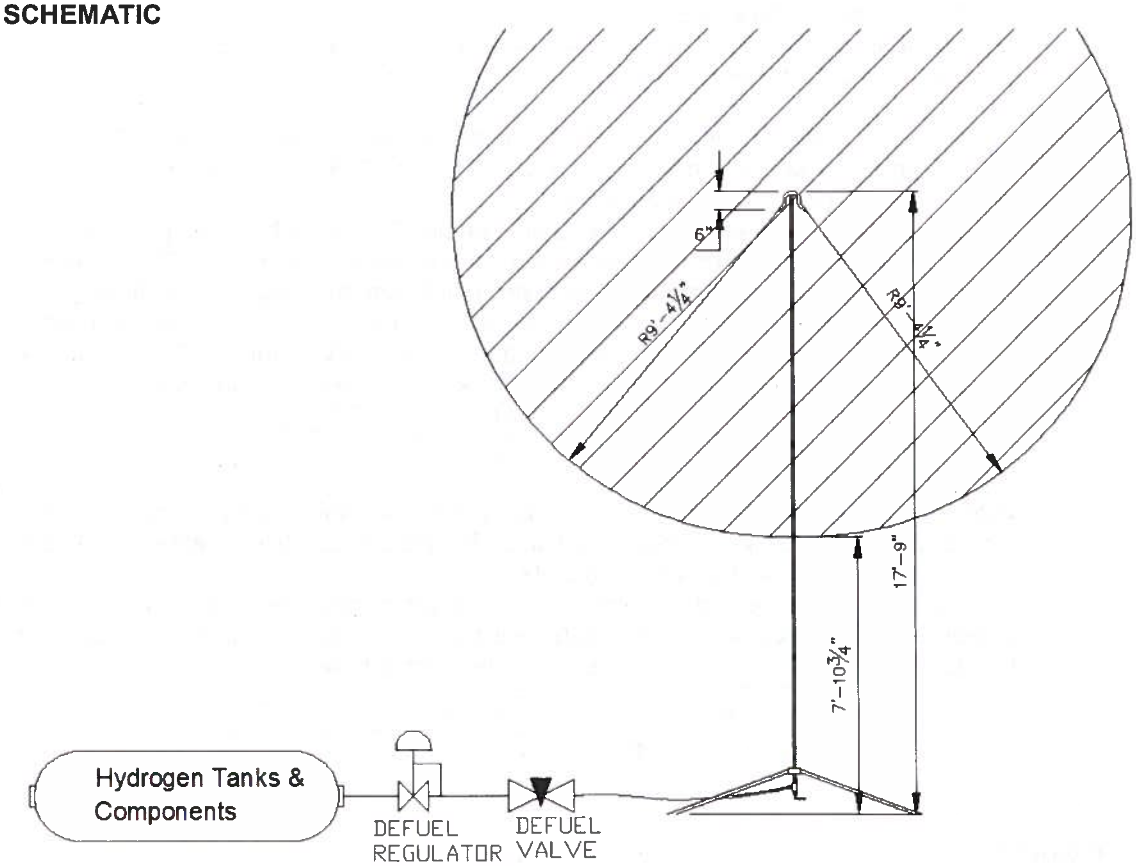

Figure 1: Simplified Diagram of the HyStEP Defuel System

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.

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

Where:

D = the minimum distance from the epicenter of the flame to the object being considered, expressed in meters
τ = 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. τ was set to 1 (see assumption 4)
   c. Q was calculated using the equation below. The mass flow rate ($\dot{m}$) 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).

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

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 kW/m^2 as is outlined in Table 12 of API 521 [1].

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

RESULTS

The radiant heat intensity calculated was K=1.3158 kW/m^2 (Calculations shown in attached Appendix). In Table 12 of API 521, a permissible design level of K = 1.58 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

[1] American Petroleum Institute. "Pressure-relieving and Depressuring Systems, API Standard 521, Sixth Edition." United States. January 2014

[2] Compressed Gas Association. "CGA-G-5.5-2014 Hydrogen Vent Systems, Third Edition." United States, 2014

[3] Ernest E. Ludwig. *Applied Process Design for Chemical and Petrochemical Plants, Volume 1, Third Edition*. Houston, TX: Gulf, 1999, pp. 530

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Date: Dec 17/15	DEC 17/2015

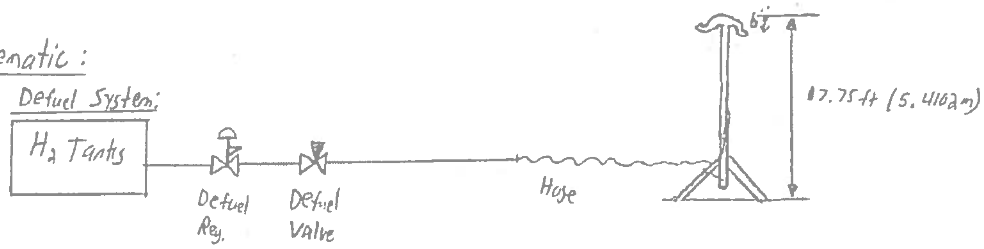
Project HyStEP PL-00742 Sheet 1 of 4

Computation of Radiant Heat Intensity on HyStEP Vent Stack

Computed by Liam Quinlan, 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 doses to levels reccomended in ANSI/API 521 (6.2.3, CGA-G-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:



Assumptions:
1. Assume the fraction of heat radiated is the maximum value for hydrogen flames with a safety factor of 2.5 (LQ, Dec 15/15)
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 & 0°C with a Lower Heating value of 120.21 MJ/kg
4. The fraction of radiated heat transmitted through the atmosphere (τ) is 1 (conservative) since the equations referenced in ANSI/API 521 are not applicable for Hydrogen.
5. Assume the operator is 7ft 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.

Eqn. 45 $$D = \sqrt{\frac{\tau \cdot F \cdot Q}{4\pi \cdot k}}$$

solve for k: $$D^2 = \frac{\tau \cdot F \cdot Q}{4\pi \cdot K} \Rightarrow \boxed{K = \frac{\tau \cdot F \cdot Q}{D^2 \cdot 4\pi}}$$

where:

D = minimum distance from flame epicenter to object being considered (m)
= Height of vent stack − height of operator, using assumption 5 D = 5.4102m − 0.1524m − 2.1336m = 3.121 (Added Dec 17/15 LQ)

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

$\therefore$ F = 0.17

(Also see "Applied Process Design for Chemical & petrochemical Plants" by Ernest E. Ludwig for the range of F values)

LQ

Project HySTEP, PL-00742

Computation of Radiant Heat Intensity on HySTEP's Vent Stack

Computed by Liam Quinlan, E.I.T. Date Oct 28/15

$Q =$ Heat released based on the Lower Heating value $= \dot{m} \cdot LHV$

Lower Heating Value of $H_2 = 120.21 \frac{MJ}{kg}$ @ 32°F (0°C) & 1atm (Based on Hydrogen Analysis Resource center)

Mass Flow Rate was determined from data obtained while defueling:

Test Data:

Test 1: 3 tanks, 228L

Time	Pressure (mPa)	Temp (°C)	SOC
0	182	-10.6	37
3:06.55	14.9	-16	32.1
Test 2: (3 Tanks)			
0	26.2	+2.8	48.4
3:57.91	20.5	-6.5	41.4

Test 3: 1 tank (76L) until 62.4mpa, Then 2 tanks (152L) until 11.5mPa, Then 3 (228L

Time	P_1	P_2	P_3	T_1	T_2	T_3	
13:48	11.5	67.6	62.4	13.1	12.7	12.4	
13:58	11.5	42.5	42.6	13.4	-1.5	-2.2	
14:08	11.5	19.2	19.2	13.4	-30.1	-31.5	← Pause defuel
14:18	11.5	19.3	19.2	13.1	-18.4	-19.4	← restart
14:21	12.2	12.6	12.7	8.1	-27.8	-29.2	← stop device due to low temp
14:32	12.1	13.5	13.6	9.5	-8.8	-9.1	← restart

Mass Flow rate Calculation:

Test 1: $P_1 = 18.2 mPa$, $P_2 = 14.9 mPa$

$T_1 = -10.6 = 262.4 K$, $T_2 = -16°C = 257 K$

$\Delta t = 3:06:55 = 186.55 s$

Volume $= 0.228 m^3 = V$

Using NIST Tables:

$\rho_1 = 14.971 \frac{kg}{m^3}$, $\rho_2 = 12.764 \frac{kg}{m^3}$

System mass $m_1 = \rho_1 \cdot V = 0.228 m^3 \cdot 14.971 \frac{kg}{m^3} = 3.41339 kg$

$m_2 = \rho_2 \cdot V = 0.228 m^3 \cdot 12.764 \frac{kg}{m^3} = 2.91019 kg$

$\dot{m} = \frac{0.5032 kg}{186.555} = 0.002697 \frac{kg}{s}$

LQ

Mass Flow Rate Calculation (cont):

Test 2: $P_1 = 26.2$ MPa, $P_2 = 20.5$ MPa

$T_1 = 2.8°C$, $T_2 = -6.5°C$

$\Delta t = 3:57.91 = 237.91$ s

Using NIST Tables:

$\rho_1 = 19.612856$ kg/m³, $\rho_2 = 16.385877$ kg/m³

$\therefore m_1 = \rho_1 \cdot V = 4.47$ kg $m_2 = 3.73598$

$m_{vented} = m_1 - m_2 = 0.73575$ kg

$\dot{m} = \frac{0.73575 \text{ kg}}{237.91 \text{ s}} = \underline{0.003093 \text{ kg/s}}$

Test 3: using data from 13:58 to 14:08 since 2 Tanks will be open the entire time

$V = 0.152$ m³

$P_1 = 42.5$ MPa, $P_2 = 19.2$ MPa

$T_1 = -1.85$ (average), $T_2 = -30.8°C$ (average)

$\Delta t = 14:08 - 13:58 = 10$ minutes $= 600$ s

Using NIST Tables:

$\rho_1 = 29.35809$ kg/m³, $\rho_2 = 16.88829$ kg/m³

$\therefore m_1 = \rho_1 \cdot V = 4.46243$ kg, $m_2 = 2.567$ kg

$m_{vented} = m_1 - m_2 = 1.8954$ kg

$\dot{m} = \frac{1.8954 \text{ kg}}{600 \text{ s}} = \underline{0.003159 \text{ kg/s}}$

Calculation of Q: (Dec 16, 15 updated LQ.)

Based on Assumption 2, use the highest mass flow rate with a safety factor of 2.5

$\therefore Q = \dot{m} \cdot LHV = 0.003159 \frac{kg}{s} \cdot 120.21 \times 10^6 \frac{J}{kg} \cdot 2.5 = 949,358 \frac{J}{s}$ (W)

$\Rightarrow \underline{Q = 949.36 \text{ kW}}$

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Determination of τ:

τ = The fraction of the radiated heat transmitted through the atmosphere (see C.2.3.6.3 in API 521)

Calculation in Appendix C is only applicable when a luminous flame, H_2 flame is non-luminous (see Assumption 4)

∴ set $\tau = 1$ for conservative approach

Calculation of K: updated Dec 16, 15 L.Q.

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

$$\Rightarrow K = \frac{1 \cdot 0.17 \cdot 949.36\ kW}{(3.1242m)^2 \cdot 4 \cdot \pi} = 1.3158\ \frac{kW}{m^2}$$

$$\boxed{K = 1.3158\ \frac{kW}{m^2}}$$

Table 12 in API 521 shows the Recommended Design Thermal Radiation for Personnel. The permissible design level for K (kW/m^2) where the "Maximum radiant heat intensity at any location where personnel with appropriate clothing can be continuously exposed" is 1.58 kW/m^2.

Since $K = 1.3158\ kW/m^2 < 1.58\ kW/m^2$ Thermal Radiation is within acceptable limits

Calculation of Radius where $K = 1.58\ kW/m^2$:

Using Eqn 45 : $D = \sqrt{\frac{\tau \cdot F \cdot Q}{4\pi \cdot K}} = \sqrt{\frac{1 \cdot 0.17 \cdot 949.36\ kW}{4\pi \cdot 1.58\ kW/m^2}}$

$= 2.851\ m = 9.35$ feet

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

LQ