DETERMINATION OF CLEARANCE DISTANCES FOR VENTING OF HYDROGEN STORAGE

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ABSTRACT

This paper discusses the results of computational fluid dynamics (CFD) modeling of hydrogen releases and dispersion outdoors during venting of hydrogen storage in real environment and geometry of a hydrogen refueling or energy station for a given flow rate and dimensions of vent stack. The PHOENICS CFD software package was used to solve the continuity, momentum and concentration equations with the appropriate boundary conditions, buoyancy model and turbulence models. Also, thermal effects resulting from potential ignition of flammable hydrogen clouds were assessed using TNO "Yellow Book" recommended approaches. The obtained results were then applied to determine appropriate clearance distances for venting of hydrogen storage for contribution to code development and station design considerations. CFD modeling of hydrogen concentrations and TNO-based modeling of thermal effects have proven to be reliable, effective and relatively inexpensive tools to evaluate the effects of hydrogen releases.

1.0 INTRODUCTION

During operation of hydrogen energy stations for transportation and stationary power applications, sometimes it might be necessary to safely vent stored hydrogen to ambient in case of emergency. The venting of hydrogen results in a large combustible cloud, which, if ignited, may be harmful to both personnel and station equipment.

Fire codes prescribe regulations consistent with notionally recognized good practice for the safeguarding to a reasonable degree of life and property from the hazards of fire explosion arising from the venting of hydrogen storages. For example, Section 2209 of 2003 International Fire Code (IFC), Table 5.4.1 [1] addresses the separation distances from the leak location versus vent pipe diameters and hydrogen venting flow rates as shown in Figure 1. Personnel on the ground or on the building/equipment are assumed to be able to leave the hazardous zone for a shielded area within 3 minutes to get protection from thermal effects resulting from hydrogen cloud potential ignition. The analysis reflected in this table does not permit hydrogen air mixtures that would exceed 50% of Lower Flammable Limit (LFL) for hydrogen (2% H_2 vol.) at the building or equipment, including the case of 30 ft/sec. wind [1].

However, the mandatory separation distances required by the existing Codes and Standards are generally conservative and can be relaxed if risk analysis is based on the quantitative CFD techniques. Understanding hydrogen cloud behaviour, its combustion and thermal effects during and after the venting from storage device is essential to the development of CFD models for the gas release and dispersion and to the development of installation codes and risk mitigation requirements.

In this paper, cloud extents arising from the hydrogen venting were investigated using computational fluid dynamics (CFD) techniques implemented through the PHOENICS software package [2], and the resulting thermal effects from the combustion of flammable hydrogen clouds were investigated using TNO "Yellow Book" recommended approaches [3].

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TABLE 2209.5.4.1
VENT PIPE HEIGHT AND SEPARATION DISTANCE
VERSUS HYDROGEN FLOW RATE AND VENT PIPE DIAMETER[a,b,c,d,e,f]

HYDROGEN FLOW RATE	0-500 CFM at NTP		500-1000 CFM at NTP		1,000-2,000 CFM at NTP		2,000-5,000 CFM at NTP			5,000-10,000 CFM at NTP			10,000-20,000 CFM at NTP	
Vent Diameter (inches)	1	2	1	2	1	2	1	2	3	1	2	3	2	3
Height (ft)	8	8	8	8	12	12	17	12	13	25	25	22	36	36
Distance (ft)	13	13	15	17	22	26	39	36	40	53	53	53	81	81

For SI: 1 inch = 25.4 mm, 1 foot = 304.8 mm, 1 Btuh/ft^2 = 3.153 W/m^2, 1 foot/second = 304.8 mm/sec.

a. Minimum distance to lot line is 1.25 times the separation distance.

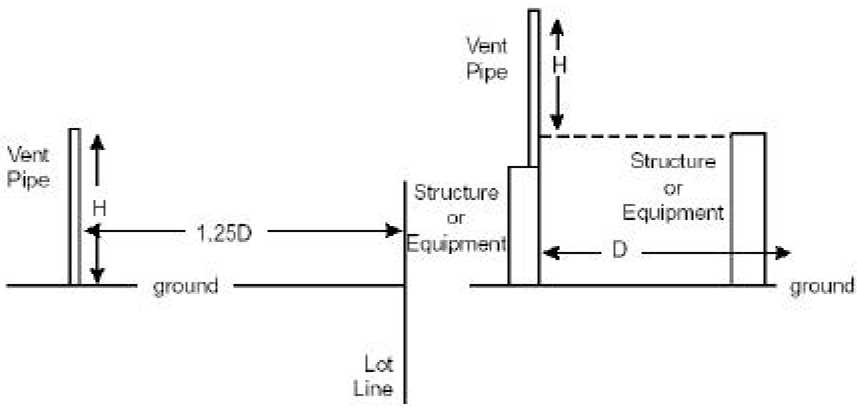
b. Designs seeking to achieve greater heights with commensurate reductions in separation distances shall be designed in accordance with accepted engineering practice.

c. With this table, personnel on the ground or on the building/equipment are exposed to a maximum of 1,500 Btuh/ft.^{2}, and are assumed to be provided with a means to escape to a shielded area within 3 minutes, including the case of a 30 ft./sec. wind.

d. Designs seeking to achieve greater radiant exposures to noncombustible equipment shall be designed in accordance with accepted engineering practice.

e. The analysis reflected in this table does not permit hydrogen air mixtures that would exceed one-half of the lower flammable limit (LFL) for hydrogen (2 percent by volume) at the building or equipment, including the case of a 30 ft./sec. wind.

f. See Figure 2209.5.4.1.



H = Minimum height in feet of vent pipe above the ground or above any structure or equipment within distance (D) where personnel might be present.

D = Distance in feet to adjacent structure or equipment where personnel might be present.

Figure 1. Section 2209 of 2003 International Fire Code (IFC), Table 5.4.1

The PHOENICS software package [2] contains a number of validated turbulence models that allow for modeling of complex flow conditions. The LVEL model, built in PHOENICS, was selected for the computational task as it allows for both laminar and turbulent flow conditions to be considered within one model. The time-dependent computation was applied to the hydrogen releases and cloud dispersion, accounting for the transient behaviour of all calculated variables (pressure, gas density, velocity and hydrogen concentration) and the movement of hydrogen clouds with time. To account for the effect of hydrogen buoyancy, the density difference model implemented in the PHOENICS was used. The dispersed hydrogen was driven by the buoyancy force caused by the density difference between the local mixed gas density and the standard reference air density. The Thornton model (Chamberlain, 1987) was programmed and used to calculate the flame parameters and the thermal flux [3]. The model has been validated for natural gas and is considered reliable for hydrocarbon gases. We should note that this model is usually applied to large scale flares (the TNO example is for a 30 kg/second outflow). It predicts shorter flame lengths for flares in the presence of a crosswind. The thermal flux is computed from the surface emissive power and the view factor for a tilted cylinder elevated by a distance equal to the stack height plus the lift-off of the flame. The surface emissive power is proportional to the mass flow rate, the heat of combustion and the fraction of heat radiated. It is inversely proportional to the surface area of the flame, so for a given mass flow rate, conditions that would lead to longer flames also lead to a smaller surface emissive power. For a given volumetric flow rate, hydrogen will emit less radiation than propane or methane. Although the heat of combustion of hydrogen is 3 times higher than methane or propane, the density of hydrogen is much lower: 0.0838 kg/m^3 for H_2 vs 0.65 kg/m^3 for methane and 1.82 kg/m^3 for propane at NTP. Methane is 8 times heavier than hydrogen, while propane is 22 times heavier than hydrogen. The Thornton-Shell model predicts that the surface emissive power of methane flames is 2.6 larger than hydrogen and that the surface emissive power of propane is 8 times larger than hydrogen (for similar values of the fraction of heat released).

The correlation of thermal flux to specific consequences is shown in Table 1 [4].

Table 1. Thermal Level Standards for Hazard Assessment

Flux(kW/m^2)	Damage to Equipment	Damage to human beings
37.8	Damage to process equipment	1% mortality in 10 sec
25	Minimum energy required to ignite wood at indefinitely long exposure.	Significant injury in 10 sec
12.6	Plastic tubing melts	1st degree burns in 10 sec
9.5		Immediate skin reactions
4.7		Pain threshold
1.6		Safe level

2.0 INVESTIGATION TOPICS

Both combustion and non-combustion of hydrogen dispersion cloud are considered in this paper. Four vertical venting releases are assumed with hydrogen flow rates of 2000, 5000, 10000 and 20000 SCFM according to Section 2209 of 2003 International Fire Code (IFC), Table 5.4.1.

As we know, the venting rate of hydrogen will increase if the pressure difference over the pipe increases, and thus also the hydrogen release velocity. Flow of compressible hydrogen may become critical. The so-called critical (choked) outflow is reached when the upstream pressure is high enough for that the release velocity of hydrogen to reach the speed of sound in the mixture, which is the maximum flow velocity possible. For a given constant upstream stagnation state, further lowering of the downstream pressure does not increase the mass flux, but will only lead to steep pressure drops in the opening to the ambient. When the upstream pressure increases, the critical mass flow rate will increase but only due to the increasing density of the release hydrogen. For a given constant downstream pressure, namely, standard atmosphere pressure for venting scenarios, further lowering of the upstream stagnation pressure will decrease the mass flux from the choked (sonic) release to subsonic releases, in which the release velocity is below the local sonic speed for the gas mixture. Therefore, the current CFD modeling considers two release categories, which are choked releases and subsonic releases for different pipe diameters, and simulates hydrogen gas releases and dispersion of non-burning, expanding clouds as well as the resulting thermal effects when hydrogen is combusted during the venting of hydrogen storage at a constant release rate and a constant downstream pressure (a standard atmosphere). Different stack orifice diameters for each scenario cause either choked or subsonic release, which is fully investigated at 9 m/s (30 ft/sec) horizontal wind. The thermal flux at ground level, and at a typical human height of 1.8 meters for the same stack configurations (i.e. 1.8 meters above ground) are investigated with the Thornton model. The maximum thermal flux exceeding the 4.7 kW/m^2 threshold is associated with pain in human beings (Table 1) so the minimum stack height required to limit this pain threshold is calculated for each scenario.

3.0 BOUNDARY CONDITIONS AND NUMERICAL APPROACHES

Hydrogen density, $r^0_{H_2}$, is equal to $0.0838\,\dfrac{\text{kg}}{\text{m}^3}$ at the NTP of T=T_0=293.15K and P_0=101.3 kPa. The mass flow rate can be determined as $\dot{m} = r^0_{H_2} Q$ (Q is the standard flow rate). For a flow rate corresponding to 2000 SCFM (Q=0.944 m^3/sec), the mass flow rate is $\dot{m} = 0.0791\ \text{kg}/\text{s}$. The sonic speed in hydrogen at this condition is $c = \sqrt{g_{H_2} R_{H_2} T_0} = \sqrt{1.41 \times 4124 \times 293.15} = 1305.61 \,\mathrm{m/s}$. The hydrogen venting should be considered under either choked or subsonic release according to the venting stack size. The hydrogen leak from a 2”-stack orifice is a subsonic flow as $\dfrac{Q}{\mathrm{Area}\,(f = 2")} = \dfrac{0.9439\ \mathrm{m^3/sec}}{0.002\ \mathrm{m^2}} = 465.7 \,\mathrm{m/s}$ $< 1305.61 \,\mathrm{m/s}$ (sonic speed), but it becomes a choked flow if hydrogen leaks at the same flow rate from a 1”-orifice, as $\dfrac{Q}{\mathrm{Area}\,(f = 1")} = \dfrac{0.9439\ \mathrm{m^3/sec}}{5.0671 \times 10^{-4}\ \mathrm{m^2}} > 1305.61 \,\mathrm{m/s}$. The mass flux for 2000 SCFM from 1” orifice is about $156.1 \dfrac{kg}{m^2 s}$ (corresponding to P^* = 144.55 kPa at the leak orifice) and the local hydrogen density at the orifice is $0.1196 \dfrac{kg}{m^3}$. Note that it was assumed that the critical leak temperature is equal to the ambient temperature, $T^* \cong T_0$. In reality, $T^* \cong 0.83 T_{storage}$. The above isothermal assumption can bring 9% greater velocity at the orifice than the non-isothermal model. The buoyancy force was calculated according to the density difference between the hydrogen/air mixture density (r_{mix}) and the reference air density ($r^0_{air} = 1.209 \dfrac{\mathrm{kg}}{\mathrm{m^3}}$). The isothermal compressible model and the incompressible model were used for the calculations of hydrogen/air mixture density.

3.1. The isothermal compressible model

In this model,

$$r = r_{mix} = a r^0_{H_2} + (1-a) r^0_{air} = \frac{P_{Total}}{\{(1-C)R_{air} + C R_{H_2}\} T}, \tag{1}$$

where P is the gas mixture pressure, C the mass concentration of hydrogen and a the hydrogen volumetric concentration. This model assumes that the mixture density is a function of the local pressure, temperature and hydrogen concentration (mass concentration, C).

3.2. The incompressible model

For simplicity, we also used an increased orifice approach and the incompressible model, in which the mixture density is defined as a function of the hydrogen mass concentration, C, i.e. an inverse linear function of C depending on standard air and hydrogen densities: $\dfrac{1}{r_{mix}} = \dfrac{1-C}{r^0_{air}} + \dfrac{C}{r^0_{H_2}}$. (Here $r^0_{air} = 1.209 \,\mathrm{kg/m^3}$ and $r^0_{H_2} = 0.0838 \,\mathrm{kg/m^3}$). The increased orifice, or “artificial” orifice diameter, is calculated by $d = \sqrt{\dfrac{4\dot{m}}{p r^0_{H_2} c}}$ so that the mass flow rate at the orifice is accurately addressed if the leak is choked. Therefore, the compressible Navier-Stokes equations are simplified to the incompressible equations, which are much easier and quicker to solve numerically.

To fully understand the relations among the momentum, viscosity, buoyancy and compressibility effects in the hydrogen venting release, the Reynolds number (Re), the Richardson number (Ri) and the Mach number (Ma) are introduced and defined as follows [5]:

$$\mathrm{Re} = \frac{r_{H_2} w d}{m}, \ \mathrm{Ri} = \frac{(r_{air} - r_{H_2}) g d}{r_{H_2} w^2}, \ \mathrm{Ma} = \frac{w}{c} = \frac{w}{\sqrt{g_{H_2} R_{H_2} T}} = \frac{w}{1305.61},$$

where w is the vertical release velocity of hydrogen, c the sonic speed in hydrogen ($c = 1305.61\,\mathrm{m/s}$), g_{H_2}=1.41 and R_{H_2} the gas constant for hydrogen. Table 2 shows the boundary conditions for the hydrogen venting rates of 2000 to 20000 SCFM and the corresponding Reynolds, Richardson and Mach numbers.

Table 2. CFD input data and dimensionless parameters

Flow rate, Q	2000 SCFM (0.9439 m^3/s)		
Mass flow rate, $\dot{m}$	0.07910 kg/s		
Model	Compressible	Incompressible	
Type of leak	Choked	Choked	Subsonic
Leak velocity, w, ()	1305.61 m/s	1305.61 m/s	465.7 m/s
Leak orifice, Ø	1”	1” (needs increase)	2”
Density (orifice)	0.1196 kg/m^3	0.0838 kg/m^3	
Reynolds number (Re)	3.9744×10^{5}	3.3293×10^{5}	1.9875×10^{5}
Richardson number (Ri)	1.1795×10^{-6}	2.0786×10^{-6}	2.7343×10^{-5}
Mach number (Ma)	1.0	1.0	0.3567
Flow rate, Q	5000 SCFM (2.3597 m^3/s)		
Mass flow rate, $\dot{m}$	0.19774 kg/s		
Model	Incompressible		
Density (orifice)	0.0838 kg/m^3		
Type of leak	Choked	Subsonic	
Leak velocity, w	1305.61 m/s	517.44 m/s	
Leak orifice, Ø	1” (needs increase)	3”	
Reynolds number (Re)	5.2617×10^{5}	3.3124×10^{5}	
Richardson number (Ri)	3.2851×10^{-6}	3.3222×10^{-5}	
Mach number (Ma)	1.0	0.3963	
Flow rate, Q	10000 SCFM (4.7195 m^3/s)		
Mass flow rate, $\dot{m}$	0.3954 kg/s		
Model	Incompressible		
Density (orifice)	0.0838 kg/m^3		
Type of leak	Choked	Subsonic	
Leak velocity, w	1305.61 m/s	1034.9 m/s	
Leak orifice, Ø	2” (needs increase)	3”	
Reynolds number (Re)	7.4409×10^{5}	6.6251×10^{5}	
Richardson number (Ri)	4.6457×10^{-6}	8.3053×10^{-5}	
Mach number (Ma)	1.0	0.7927	
Flow rate, Q	20000 SCFM (9.4389 m^3/s)		
Mass flow rate, $\dot{m}$	0.79098 kg/s		
Model	Incompressible	Compressible	
Density (orifice)	0.0838 kg/m^3	0.1328 kg/m^3	
Type of Leak	Choked		
Leak velocity, w	1305.61 m/s		
Leak orifice, Ø	3” (needs increase)	3”	
Reynolds number (Re)	1.052×10^{6}	1.325×10^{5}	
Richardson number (Ri)	6.571×10^{-5}	3.148×10^{-5}	
Mach number (Ma)	1.0	1.0	

4.0 NUMERICAL RESULTS

4.1. Non-burning hydrogen cloud dispersion

Hydrogen cloud sizes and extents are closely related to the venting rates, so computational domain sizes for hydrogen dispersion simulations were selected differently according to the release rates to avoid the boundary effects on the hydrogen concentration distributions. For 2000 SCFM release, the domain size was 27m×27m×27m with the grid of 42×18×27, while for 20000 SCFM, the domain was 60m×27m×30m with the grid of 59×18×29. Table 4 shows the domain sizes and computational grids used for the current simulations. According to Section 2209 Table 5.4.1, the stack heights for 2000, 5000, 10000 and 20000 SCFM releases are 3.658, 5.182, 7.62 and 10.973 m, respectively.

The CFD simulations obtained with PHOENICS 3.5 show that the numerical results obtained with the incompressible model are close to those obtained with the compressible model for choked hydrogen release under the current low venting pressure. The horizontal hydrogen extent corresponding to the 2000 SCFM release and the 1”-orifice is 0.7 m for 200% of LFL, 1.9 m for LFL and 5.5 m for 50% of LFL when using the compressible model. The hydrogen extent obtained with the incompressible model is 0.7 m for 200% of LFL, 2.0 m for LFL and 5.5 m for 50% of LFL. Table 3 shows the comparison of the numerical results obtained by the incompressible model and the compressible model for the release rates of 2000 and 20000 SCFM. Note that the incompressible model needs “artificial” increasing of the orifice size in the simulations so as to compensate the mass release rate under the choked leak condition.

The hydrogen cloud does not change after 10 seconds and it is assumed that the system reaches the steady state.

Table 3. Hydrogen cloud extents 10 seconds after the onset of the release

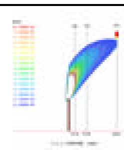
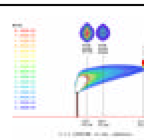
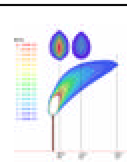
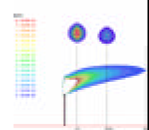
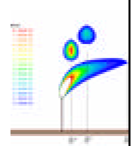
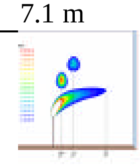
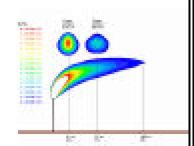
Rates	2000 SCFM		20000 SCFM	
Model	Compressible	Incompressible	Compressible	Incompressible
Orifice size	2.54 cm (1”)	2.69 cm*	7.62 cm (3”)	8.5 cm*
200% of LFL	0.7 m	0.7 m	3.1 m	3.5 m
LFL	1.9 m	2.0 m	8.7 m	8.9 m
50% of LFL	5.5 m	5.5 m	19.2 m	19.5 m

* The increased orifice, or “artificial” orifice diameter, was calculated as $d = \sqrt{\frac{4\dot{m}}{\pi \rho^0_{H_2} c}}$.

However, the hydrogen cloud caused by the subsonic release is quite different from that caused by the choked release even if the release rate is the same. The numerical results show that the horizontal hydrogen cloud extent for the subsonic release of 2000 SCFM from a 2”-orifice is 1.5 m for 200% of LFL, 4.0 m for LFL and 9.7 m for 50% of LFL. For choked release with the same flow rate, the cloud extent is 0.7 m for 200% of LFL, 1.9 m for LFL and 5.5 m for 50% of LFL. Simulation results for the other scenarios also indicate that the subsonic release results in larger hydrogen clouds in comparison to the choked releases. We believe that the vertical release velocity component plays an important role in the formation of the hydrogen cloud and the determination of the separation distance.

The cells marked by “IFC” in Table 4 also shows the separation distances as well as minimum distances to lot lines based on 2% vol. hydrogen concentration envelopes prescribed by the International Fire Code (IFC) as compared to the numerical results obtained for the hydrogen dispersion in different scenarios (cells marked by “CFD Dispersion”). It can be seen that the IFC requirements lack consistency since they demand having max 2% vol. hydrogen concentration at two different distances (D and 1.25 D) simultaneously. Clearly, if the requirement is to have maximum hydrogen concentration at the lot line (1.25 D) of 2% by volume, then its concentration at distance D will be greater than 2%. Taking the largest separation distances required by the IFC as benchmarks it can be seen that these distances are substantially larger than those obtained in numerical simulation results, particularly for chocked flow releases.

Table 4. Summary of hydrogen cloud dispersion and potential thermal effects analysis

Flow rate		2000 SCFM		5000 SCFM		10000 SCFM		20000 SCFM
		0.949 m^3/sec		2.360 m^3/sec		4.720 m^3/sec		9.439 m^3/sec
Mass flow rate		0.079 kg/s		0.198 kg/s		0.395 kg/s		0.791 kg/s
Stack height		3.658 m		5.182 m		7.620 m		10.973 m
IFC	Distance 1D	7.92 m		12.19 m		16.15 m		24.69 m
IFC	Lot line 1.25D	9.9 m		16.12 m		20.19 m		30.86 m
Leak type		Choked	Subsonic	Choked	Subsonic	Choked	Subsonic	Choked
Stack diameter		1”	2”	1”	3”	2”	3”	3”
CFD Dispersion	Domain size	27×27×27 m^3		32×27×29 m^3		50×27×30 m^3		60×27×30 m^3
CFD Dispersion	Coarse grid	42×18×27		49×18×28		56×18×29		59×18×29
CFD Dispersion	2% vol.	5.5 m	9.7 m	9.2 m	13.5 m	14.4 m	16.0 m	19.5 m
CFD Dispersion	4% vol.	2.0 m	4.0 m	3.4 m	6.2 m	5.9 m	7.1 m	8.9 m
CFD Dispersion	Non-burning H_2 cloud concentration extents							
Flame	Net length [2]	3.17 m	3.32 m	3.17 m	6.09 m	6.63 m	5.40 m	10.81 m
Flame	Min diameter [3]	0.094 m	0.15 m	0.094 m	0.24 m	0.21 m	0.23 m	0.32 m
Flame	Max diameter	1.01 m	1.30 m	1.01 m	1.87 m	1.89 m	1.96 m	2.73 m
Flame	Lift-off height	0.60 m	0.54 m	0.60 m	0.82 m	1.13 m	1.11 m	1.63 m
Flame	Tilt angle	20.06 °	32	20.06 °	27	17.00 °	19	15.47 °
Gnd [1]	Max rad. [4]	1.94	--	3.02	--	2.19	--	1.96
Gnd [1]	Dis. Max flux [5]	3.32 m	--	4.13 m	--	7.04 m	--	10.58 m
Gnd [1]	Distance 1.6 [6]	5.86 m	--	11.30 m	--	14.27 m	--	18.78 m
1.8 m [7]	Max rad. [4]	4.22	6.93	5.37	5.06	3.074	3.51	2.45
1.8 m [7]	Dis. Max flux [5]	2.31 m	2.18 m	3.18 m	3.87 m	6.00 m	5.67 m	9.49 m
1.8 m [7]	Distance 1.6 [6]	7.81 m	9.69 m	12.54 m	14.82 m	16.30 m	16.84 m	21.42 m
1.8 m [7]	Distance 4.7 [8]	--	4.78	5.10	5.57	--	--	--
Pain Threshed Cal.		Max radiation flux at ground level: 4.7 kW/m^2						
Pain [9]	Stack height	3.46 m	4.46 m	5.55 m	5.43 m	5.77 m	6.36 m	6.8 m
Pain [9]	Dis. Max flux [5]	2.18 m	2.58 m	3.37 m	4.01 m	4.86 m	4.95 m	6.79 m
Pain [9]	Distance 1.6 [6]	7.94 m	9.33 m	12.33 m	14.68 m	16.30 m	17.69 m	25.07 m

[1] Gnd: thermal flux at ground level from stacks, flare in the presence of a 9 m/sec crosswind and jet exit temperature is 293 K. The view factor is calculated as follows: The flame is considered to be a tilted cylinder located at height h, where h is equal to the stack height plus the lift-off height.

[2] Net length: Flame net length.

[3] Min diameter: Min flame diameter.

[4] Max rad.: Max radiation flux at ground level or at 1.8 m above ground respectively (kW/m^2).

[5] Dis. Max flux: Distance to the maximum flux.

[6] Distance 1.6: Distance to 1.6 kW/m^2.

[7] 1.8 m: Thermal flux at a height of 1.8 m from the ground from stacks, flare in the presence of a 9 m/sec crosswind and jet exit temperature is 293 K. The view factor is calculated as follows: The flame is considered to be a tilted cylinder located at a height, which is equal to the stack height plus the lift-off height minus 1.8 m.

[8] Distance 4.7: Distance to 4.7 kW/m^2.

[9] Pain: Minimum height to 4.7 kW/m^2, (pain threshed) 1.8 m from the ground from stacks, flare in the presence of a 9 m/sec crosswind and jet exit temperature is 293 K. The view factor is calculated as follows: The flame is considered to be a tilted cylinder located at a height, which is equal to the stack height plus the lift-off height minus 1.8 m.

4.2. Thermal effects from hydrogen combustion

In the thermal flux calculations, the emissive power is calculated using the high heating value for the heat of combustion of hydrogen 1.419×10^8 Joules/kg. Ambient conditions are set to 293 K and 101.3 KPa. The expression used to compute the fraction of heat released in this paper is the one recommended in references [3] and [4], $F_r = 0.21\exp(-0.00323u) + 0.11$, where u is the gas velocity at the nozzle. This correlation was established for hydrocarbon fuels, which generally tend to exhibit larger values of F_r than hydrogen and is expected to overestimate somewhat the thermal radiation. Values of F_r for hydrogen reported in the literature lie in the range 0.15-0.17 [4]. The fraction of heat released for hydrogen is similar to methane (0.15-0.16), although smaller than natural gas (0.19-0.23) and than most hydrocarbon fuels (0.33 for propane, 0.30 for butane, 0.38 for ethylene).The thermal flux from a flare was calculated assuming a 9 m/sec crosswind towards a vertical target surface area. Table 4 concerns stack diameters which lead to choked flows or subsonic flows for the four typical volumetric flow rates. The cells marked by "Gnd [1]" in Table 4 show the ground level thermal flux obtained from the Thornton model. The height of the stacks increases as the flow rate is increased. For the stack height/diameter chosen, the maximum flux obtained is 3.02 kW/m^2. Distance to the safe level of 1.6 kW/m2 varies from 5.86 m to 18.78 m. The cells marked by "1.8 m [7]" in Table 4 show the thermal flux calculated for a typical human height of 1.8 m for the same stack configurations (i.e. 1.8 m above ground). The maximum flux obtained is then 6.93 kW/m^2. Distance to 1.6 kW/m^2 increases from 7.81 to 21.42 m depending on flow rate. As an example, the maximum flux for the 2000 CFM subsonic flow rate reaches 6.93 kW/m^2 at 2.18 m, which leads to a distance of 4.78 meters associated with the pain threshold level of 4.7 kW/m^2. The minimum stack heights required to limit the thermal flux to the 4.7 kW/m^2 threshold are shown in the bottom section of Table 4. Note that the thermal fluxes obtained from the combustion of the subsonic hydrogen releases tend to be somewhat larger, leading to slightly larger clearance distances than those of the choked counterparts. The minimum height required to maintain the flux below 4.7 kW/m^2 also tends to be larger. This suggests that stack diameters leading to choked flows would lead to somewhat shorter clearance distances.

Based on the above discussion, we suggest that the clearance distances required for venting of hydrogen be based on the CFD hydrogen dispersion results and the thermal effects from burning H_2/air mixtures.

5.0 RECOMMENDED CLEARANCE DISANCES FOR HYDROGEN VENTING

CFD modeling results (as illustrated by the pictures incorporated in the Table 4) clearly show that due to hydrogen properties and even at 9.14 m/s (30 ft/s) wind, hydrogen clouds extend above the level of the vent stack outlet. Hence, only air intakes and ignition sources located ABOVE the vent stack should be of concern from the clearance distances prospective. In other words, clearance distances should not be applicable to any objects BELOW the level of the top of a vent stack.

There are different schools of thought regarding the selection of an appropriate hydrogen concentration that could serve as a "safe level" for this purpose. The traditional conservative approach (used, for example, in IFC Section 2209) is 2% vol. concentration of H_2 in air or 50% of LFL. This means that an air intake or an ignition source must have such a clearance distance that they would not be exposed to a hydrogen concentration greater than 50% of LFL under any flow rate of hydrogen and the wind velocity up to 9.14 m/s (30 ft/s).

We think, however, that this approach is overly conservative. Experiments conducted by Prof. Mike Swain from University of Miami (and reported at Hydrogen and Fuel Cell Summit VIII in Miami in June 2004) show that under real conditions of gas flow it is impossible to ignite hydrogen concentrations below 7% vol. Taking this information into account, we recommend considering LFL hydrogen concentration (or 4% H_2 vol. in air) as a "safe level" for the purpose of determining clearance distances for air intakes and ignition sources outdoors. As an additional precaution, a "safety factor" (say, 25% extent) may be applied. It is also recommended to select such diameters of vent stacks (up to 3" or 75 mm in diameter) so to ensure initial exiting velocities as close to sonic speed as possible. (The fact that the subsonic concentration extents are larger than the sonic ones supports the idea of designing the vent stacks in such a way that the resulting release velocity will be as close as possible to sonic speed.) The recommendation is to use subsonic numbers for 4% extents and apply 25% "safety factor" on top for determining safety clearance distances for air intakes and ignition sources located ABOVE the top of the vent stacks.

To estimate extents of concentration envelopes for smaller flow rates of hydrogen venting (below 2,000 CFM or 0.94 m3/s), a simple analysis was performed using the interpolation and extrapolation with Microsoft Excel. The summary tables and the graphs are shown below.

Table 5. Clearance distances based on hydrogen dispersion

Flow, CFM	500	1000	2000	5000	10000	20000
Flow, m^3/s	0.25	0.5	1	2.5	4.75	9.5
2% extent (sonic), m	2.6	4	5.5	9.2	14.4	19.5
2% extent (subsonic), m	5.5	7	9.7	13.5	16	21.5
4% extent (sonic), m	0.8	1.2	2	3.4	5.9	8.9
4% extent (subsonic), m	2.5	3	4	6.2	7.1	9.7
Vent Diameter, mm	25	25	25-50	25-75	50-75	75

Note: highlighted numbers are predicted by their respective trend lines as shown in Figure 2.

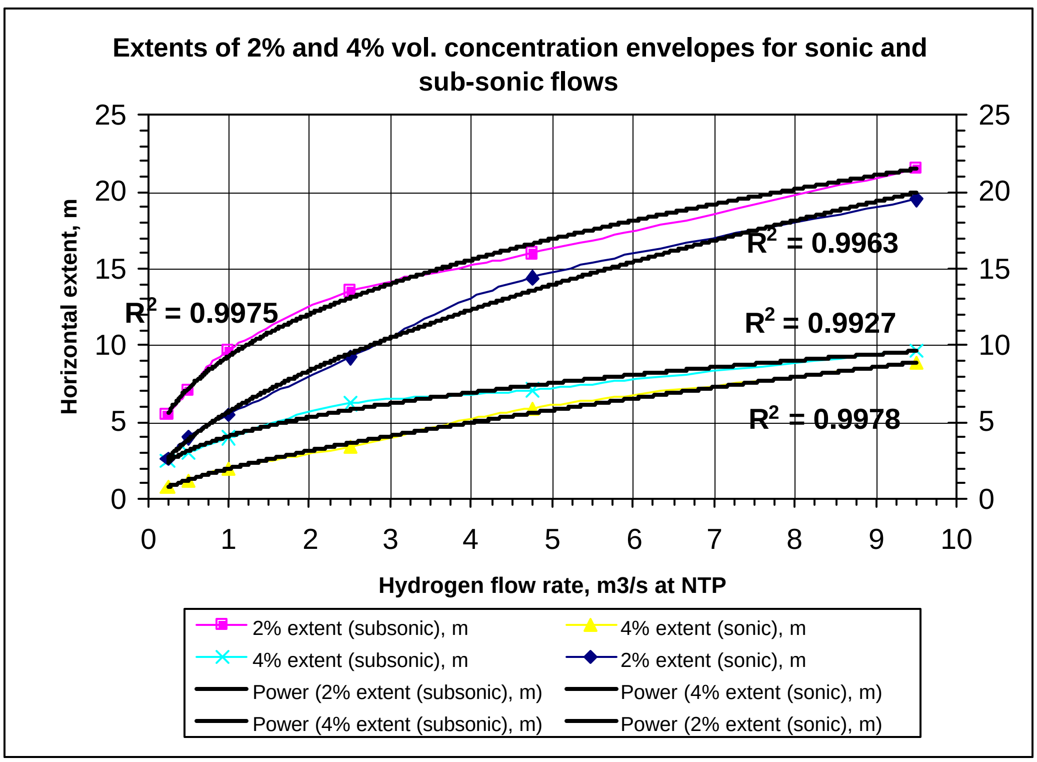


Figure 2. Extents of 2% and 4% vol. concentration envelopes for sonic and sub-sonic flows

Based on the numbers obtained for 4% vol. extent for subsonic flow, Table 6 is derived for the recommendation for the clearance distances for air intakes and ignition sources located above the top of the vent stack.

Table 6. Recommended clearance distances for ignitions sources above the top of the vent stack

Approach: Applying Subsonic Data	Reasonably Conservative (Metric Units)					
Flow, CFM	500	1000	2000	5000	10000	20000
Flow, m^3/s	0.25	0.5	1	2.5	4.75	9.5
2% LFL extent (subsonic), m	5.5	7	9.7	13.5	16	21.5
4% LFL extent (subsonic), m	2.5	3	4	6.2	7.1	9.7
Clearance Distance, m	3.1	3.8	5.0	7.3	9.0	12.0
Vent Diameter, mm	25	25	25-50	25-75	50-75	75

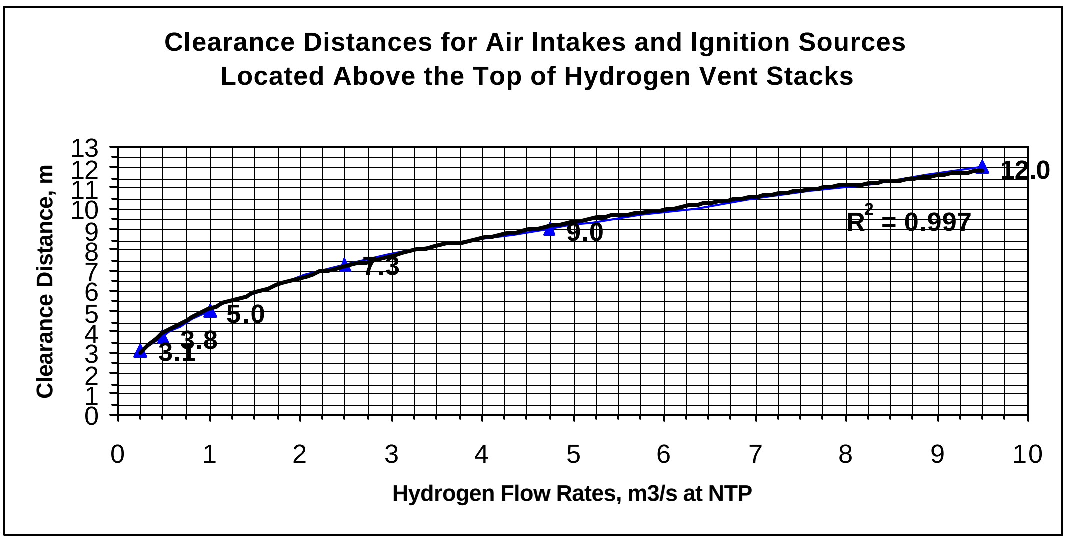


Figure 3. Clearance distances for air intakes and ignition sources located ABOVE the top of vent stacks

Table 7 summarizes the data obtained from Table 4 in regards to vent stack heights, diameters and clearance distances, i.e. distances to 4.7 kW/m^2 thermal flux boundary at the height of 1.8 m above ground, expressed in both imperial and metric units.

Table 7. Clearance distances based on the calculation of thermal effects

Sonic + Subsonic Flow - Imperial Units										
H2 Flow Rate	< 2,000 CFM			< 5,000 CFM				< 10,000 CFM		< 20,000 CFM
Vent Diameter, in	1	2	2	1	1	3	3	2	3	3
Height, ft	11.4	12	14.6	17	18.2	17	17.8	19	20.9	22.3
Clearance Distance, ft	7.2	15.7	8.5	16.7	11.1	18.3	13.2	16	16.2	22.3
Sonic + Subsonic Flow - Metric Units										
H2 Flow Rate	< 0.94 m^3/s			< 2.36 m^3/s				< 4.72 m^3/s		< 9.44 m^3/s
Vent Diameter, mm	25	50	50	25	25	75	75	50	75	75
Height, m	3.46	3.66	4.46	5.18	5.55	5.18	5.43	5.77	6.36	6.8
Clearance Distance, m	2.18	4.78	2.58	5.1	3.37	5.57	4.01	4.86	4.95	6.79

Sonic flows correspond to lowest stack diameter in each flow rate range. It is interesting that the best sonic (coloured green) and subsonic (coloured blue) results in terms of clearance distances for each flow rate range are quite close to each other. This indicates that if an appropriate height of the vent stack is selected, the stack orifice will not materially affect the clearance distance. Of course, it should be noted that the preferred selection of the vent stack diameter is the one that provides for sonic or near sonic velocity of hydrogen release. Based on these considerations and using reasonably conservative approach, the following clearance distances to personnel are recommended in Table 8.

Table 8. Recommended clearance distances based on thermal effects

Approach: Averaging Sonic and Subsonic Data, Reasonably Conservative (Imperial Units)						
Flow, CFM	500	1000	2000	5000	10000	20000
H, ft	11	13	15	18	21	24
D, ft	6	8	10	14	18	23
Vent Dia, in	1	1	1 - 2	1 - 3	2 - 3	3
Approach: Averaging Sonic and Subsonic Data, Reasonably Conservative (Metric Units)						
Flow, m3/s	0.25	0.5	1	2.5	4.75	9.5
H, m	3.5	4	4.6	5.5	6.2	7
D, m	1.8	2.4	3	4.3	5.5	7
Vent Dia, mm	25	25	25-50	25-75	50-75	75

Note: highlighted numbers are predicted by their respective trend lines as shown in Figure 4 and Figure 5.

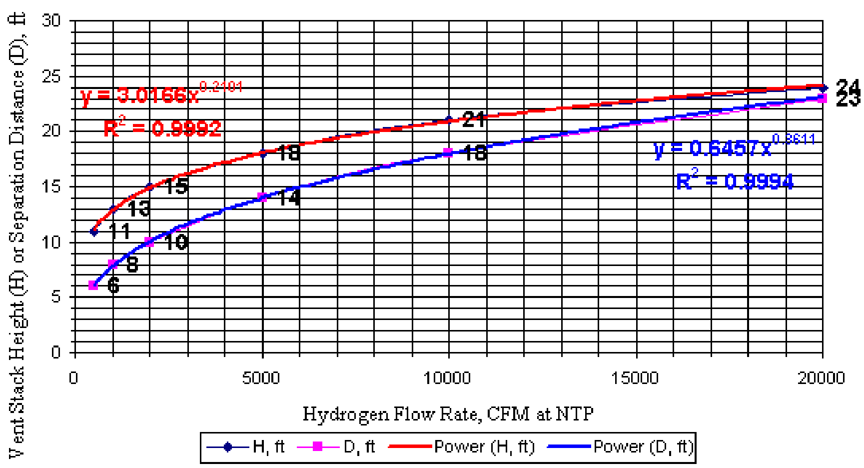


Figure 4. Minimum vent stack height and separation distance vs hydrogen flow rate (imperial units)

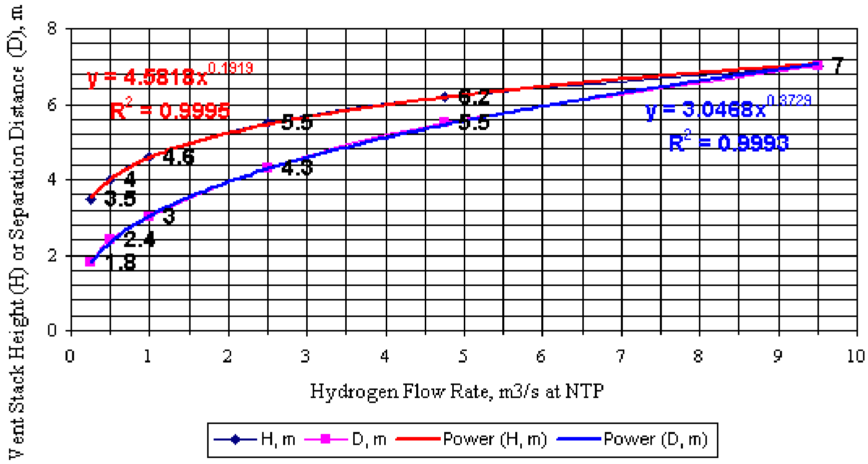


Figure 5. Minimum vent stack height and separation distance vs hydrogen flow rate metric units

As it can be seen from the above graphs, the obtained correlations fit the power function extremely well. As a result, the above figures provide a tool for design engineers to select appropriate dimensions of their vent stacks depending on ANY predicted flow rate of hydrogen between 0 and 9.5 m3/s (or 0 and 20,000 CFM).

It should also be noted that suggested clearance distances are substantially smaller that those suggested by IFC Table 2209.5.4.1.

6.0 CONCLUSION

Clearance distances related to venting of hydrogen storage were derived using both thermal effects and concentration envelope approaches. Obtained tables and graphs were based on thermal effects analysis using TNO "Yellow Book" recommendations and CFD modeling of hydrogen releases and dispersion, implemented through the PHOENICS software package. Obtained results provide comprehensive guidance to both design engineers and regulatory authorities to design and provide regulatory approvals for placement of hydrogen storage systems vent stacks.

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