Fire Safety of Hydrogen Leaks

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Abstract

Quenching limits of hydrogen diffusion flames on small burners were observed. Four burner types, with diameters as small as 8 μm, were considered: pinhole burners, curved-wall pinhole burners, tube burners, and leaky fittings. In terms of mass flow rate, hydrogen had a lower quenching limit and a higher blowoff limit than either methane or propane. Hydrogen flames at their quenching limits were the weakest flames recorded to date, with mass flow rates and heat release rates as low as 3.9 μg/s and 0.46 W. The quenching limits were generally independent of hole diameter and burner orientation, and generally decreased with increased surface curvature. The quenching limit for a hydrogen flame at a 6 mm leaky compression fitting was found to be 28 μg/s. This limit was independent of supply pressure (up to 131 bar) and about an order of magnitude lower than the corresponding limits for methane and propane.

1. Introduction

Hydrogen is attractive as an energy carrier for highway vehicles. It can power fuel cells or engines with only water vapor as exhaust. Hydrogen could help mitigate concerns over fossil fuel consumption [1,2]. Hydrogen can be stored as a gas, liquid, or a solid (in metal hydrides), and can be transported using pipelines, tankers or rail trucks [3]. It is anticipated that hydrogen could be produced efficiently using nuclear sources or renewable sources such as wind [4].

Hydrogen is an unusual fuel. It has a high leak propensity and wide flammability limits, 4 – 75% by volume [5]. Hydrogen is the lightest fuel and has the lowest quenching distance (0.51 mm) and smallest ignition energy of any fuel in air (28 μJ), the lowest auto-ignition temperature of any fuel ignited by a heated air jet (640 ºC), the highest laminar burning velocity of any fuel in air (2.91 m/s), and the highest heat of combustion (119.9 kJ/g) [5]. Hydrogen flames are the dimmest of any fuel. Hydrogen embrittles metals more than any other fuel does.

Hydrogen may ultimately prove to be no more hazardous from a fire safety standpoint than gasoline or diesel. However, gasoline and diesel underwent over a century of widespread vehicle use, and this has resulted in codes and standards that have yielded an acceptable fire safety record. Further research is necessary if hydrogen is to be rapidly introduced with a similar safety record. It is expected that existing codes and standards will need to be updated [6] to ensure safe use of hydrogen in vehicles.

The goal of present study is to investigate small hydrogen flames that could be characterized as "leak flames," i.e., small flames that could result from hydrogen leaking from a containment vessel. The scenario of concern is that a small leak in a hydrogen system could ignite, burn undetected for a long period of time, and potentially degrade surrounding materials, or ignite secondary fires.

Several studies have been conducted to evaluate the characteristics the hydrogen leak itself. Lee *et al.* [15] conducted leak rate experiments on micromachined orifices of different sizes and shapes. They examined the differences in flow rates among circular, square, and elliptical slit orifices as a function of pressure, and in most cases the flow was choked. Helium was used as a substitute for hydrogen for safety reasons. Schefer *et al.* [16] investigated leaks where the flow was due to pressure-driven convection and permeation through metals. They obtained analytical relationships for flow rates of choked flows, subsonic laminar flows, and turbulent flows. Hydrogen leakage in stainless steel threaded pipe fittings was considered by Ge and Sutton [17]. They found that a larger tightening torque is less important in leak prevention than choice and proper application of thread sealant. The tests were run up to 70 bar and typical hydrogen leak rates through these fittings were found to be 1 μg/s.

Studies have also evaluated the risks of hydrogen leaks with respect to accumulation and explosion of hydrogen [7,8]. Swain and Swain [18] evaluated the safety risks associated with leaks of hydrogen, methane, and propane into an enclosed area. They modeled and measured leak rates for diffusion, laminar, and turbulent flow regimes and found that, for a given supply pressure, hydrogen had a significantly higher volumetric flow rate than methane or propane. They also found that combustible mixtures resulted more quickly for propane and hydrogen leaks than for methane leaks.

Leak flames resemble the micro diffusion flames that have been observed in other laboratories and while only one previous study specifically evaluated leak flames [20], there have been many studies of micro diffusion flames [9-14]. Micro diffusion flames are typically associated with an application, e.g., a microcombustor for power generation. Nonetheless, it is possible that they could arise unexpectedly. For example, if a leak from a crack or hole in a fitting, tube or storage vessel of a plumbing system were ignited, this could be characterized as a micro diffusion flame.

Ban *et al.* [10] investigated micro diffusion flames that were 2 – 3 mm long on round burners with inner diameters of 0.15 – 0.4 mm. Three fuels were considered: ethane, ethylene and acetylene. The experiments agreed with predictions of flame shapes in the absence of buoyancy. The flames were nearly spherical and their shapes were unaltered when burner orientation was changed with respect to gravity. Cheng *et al.* [11] performed detailed measurements and computations on small hydrogen flames burning on similar burners. Buoyancy was found to be insignificant for these flames. Nakamura *et al.* [12] simulated methane micro diffusion flames supported on circular burners with diameters less than 1 mm. They, too, found nearly spherical flames, associated with weak buoyancy forces. They also considered quenching limits of the flames. Baker *et al.* [9] studied micro-slot burners (with port widths of 0.1 – 0.76 mm) and developed a flame height expression for purely diffusion-controlled propane/air nonpremixed flames.

Quenching and blowoff limits refer to flames with the smallest and highest fuel flow rates for sustained burning. Matta *et al.* [13] measured quenching limits for propane on small round burners. Similar experiments were performed by Cheng *et al.* [14] for methane. Both studies found that quenching mass flow rate was largely independent of burner diameter. Prior to the present work, quenching flow rates had not been measured for hydrogen. Blowoff limits for micro diffusion flames have been measured for a variety of fuels by several researchers [13,19].

Thus motivated, this study includes experiments and analysis to identify which hydrogen leaks can support flames. A scaling analysis is presented to estimate the fuel mass flow rate at the quenching limit. Measured mass flow rates, both at the quenching and blowoff limits, are presented for hydrogen, methane and propane on round-hole burners. Flame quenching limits for leaky compression fittings are also presented.

2. Scaling for Flame Quenching Limits

A scaling analysis is presented here for flame quenching limits. This is similar to past work of Matta *et al.* [13]. The stoichiometric length L_f of laminar gas jet diffusion flames on round-hole burners is given by:

$$L_f / d = a \, \mathrm{Re} = 4 \, m_{fuel} \, a / (\pi \, \mu \, d) \quad (1)$$

where d is the burner inside diameter, a is a fuel-specific coefficient, Re is fuel port Reynolds number, m_{fuel} is the fuel mass flow rate, and μ is fuel dynamic viscosity. The scaling of Equation (1) arises from many theoretical and experimental studies, including Roper [21], Sunderland *et al.* [22], and references cited therein.

The base of an attached jet diffusion flame is quenched by the burner and is premixed. Its standoff distance can be approximated as one half of the quenching distance of a stoichiometric premixed flame. Quenching distances typically are reported as the minimum tube diameter or plate separation distance, L_q, through which a premixed flame can pass. It is assumed here that a jet flame is above its quenching limit if its stoichiometric length exceeds half this quenching distance:

$$L_f > L_q / 2 \quad (2)$$

Combining Equation (1) and (2), yields the fuel mass flow rate at the quenching limit:

$$m_{fuel} = \pi \, L_q \, \mu / (8 \, a) \quad (3)$$

Equation (3) predicts that the fuel mass flow rate at the quenching limit is a fuel property that is independent of burner diameter, which was similarly predicted by [13]. When measured values of L_q, μ, and a (see Table 1) are inserted into Equation (3), the predicted fuel mass flow rates at the quenching limit are obtained and are listed in Table 1.

Table 1. Selected properties of hydrogen, methane, and propane and predicted quenching mass flow rates. Values for a are from [22], L_a and S_L (laminar burning velocity) are from [5], and μ is from [23]. The quantity m_{fuel} is predicted from Equation (3).

Fuel	A	L_q (mm)	S_L (cm/s)	μ (g/m-s)	m_{fuel} (µg/s)
H_2	0.236	0.51	291	8.76E-3	8
CH_4	0.136	2.3	37.3	1.09E-2	85
C_3H_8	0.108	1.78	42.9	7.95E-3	63

3. Experimental

Two different burner configurations are considered in this study: round-hole burners and leaky compression fittings.

3.1 Round-Hole Burners

Three types of round-hole burners were considered: pinholes, and curved-wall pinholes, and tubes, as illustrated in Figure 1. Each type included various hole diameters, given in Table 2. The pinhole burners were stainless steel nozzles that were manufactured for solid-stream spray generation. The top surface of each burner (except for the two smallest ones) is a curved surface (radius of curvature of 4.3 mm) with a hole passing through its axis, as shown in Figure 1. The top surfaces of the two smallest pinhole burners were planar, not curved, surfaces. The pinhole burners represent pinhole leaks in pressure vessels where the radius of curvature of the wall is large or infinite.

The curved-wall pinhole burners were constructed from stainless steel tubes with two outside diameters: 1.6 and 6.4 mm. A radial hole was drilled in each tube. These burners represent pinhole leaks that might occur in fuel supply tubing.

The tube burners were made from stainless steel hypodermic tubes. Although they do not represent practical leak flames, they are a fundamental configuration that leads to a flame from a wall where the radius of curvature approaches zero. Their observation should also lead to an improved understanding of microinjectors in small-scale microelectro-mechanical power generators [13].

Fuel was delivered via a pressure regulator and a needle valve, and all tests were performed at normal lab pressure and temperature. Measuring the small flow rates at the quenching limits required special procedures. A glass soap-bubble meter was installed upstream of the burners. Quenching flow rates were measured by establishing a small flame near the quenching limit and gradually decreasing the flow rate until the flame extinguished. The fuel flow rate was then measured using the soap-bubble meter.

Determining the existence of hydrogen flames near their quenching limits was complicated by their small size and low luminosity. These flames were detected with a K-type thermocouple positioned 10 mm above each burner.

Burners were allowed to warm slightly above room temperature to prevent water condensation. This was necessary because water condensation was found to disturb the flows from the small burners, sometimes extinguishing the flames. Using similar burners, Takahashi *et al.* [20] also reported complications of water condensation. Tests performed at different burner temperatures, up to about 200 °C, found quenching flow rate to be largely independent of burner temperature provided condensation was avoided. Tests were also conducted with varying ambient humidity, and quenching limits were found to be generally independent of the relative humidity of the air in the range of 46 – 90%.

Hydrogen flow rate at blowoff was measured with a soap bubble meter. A stable flame was established and then the flow rate was increased until the flame first lifted and then extinguished. For blowoff tests the flames were detected visually. Hearing protection was required for the blowoff tests for the larger burners.

Additional tests were performed to consider buoyancy effects. To this end. quenching flow rates were found for pinhole and tube burners in the vertical, horizontal, and inverted orientations.

3.2 Leaky Fittings

Quenching limits were also measured for leaky compression fittings. The tests involved leaks between Swagelok® stainless steel tube union compression fittings and stainless steel tubes. Tube diameters were 3.2, 6.4, and 12.7 mm. The end of each union opposite the tube was sealed. New tubes and fittings were assembled according to manufacturer instructions and were rejected if bubbles appeared in an applied soap water solution when pressurized with hydrogen to 8 bar absolute. Leaks were then introduced in one of three ways: by reducing the torque on the threaded nut, by over tightening the nut, or by scratching the front ferrule sealing surface. These types of leaks are occasionally encountered in plumbing systems. The three leak types were found to yield the same flame quenching limits, so only results for reduced torque

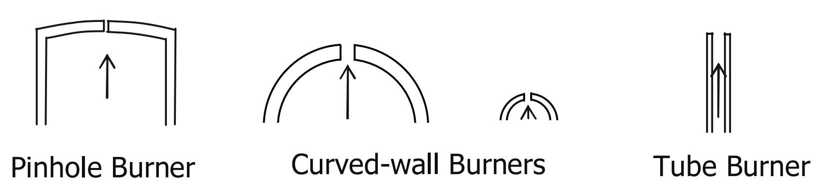

Figure 1. Schematics of the present round-hole burners. Arrows show the fuel flow direction. Burner dimensions are given in Table 2.

Table 2. Hole diameters (mm) for the present round-hole burners.

Pinhole	Curved wall[a]	Curved wall[b]	Tube
0.008	0.41	0.41	0.051
0.13	0.53	1.75	0.152
0.36	0.74	2.46	0.406
0.53	0.86	3.12	0.838
0.71	1.02		1.194
0.84			2.21
1.01			
1.40			
1.78			
2.39			
3.18			

[a]For tube diameter of 1.6 mm.
[b]For tube diameter of 6.4 mm.

fittings are presented here. Reduced torque fittings allow quenching limits to be measured for different upstream pressures by adjusting the torque, i.e., an increased torque requires an increased upstream pressure at the quenching limit. Most tests were performed with the burner in the vertical orientation, with the leaky fitting at the top end of the tube. Horizontal and inverted orientations also were considered for some tests.

Quenching limits were found by igniting the fuel (with an external flame) and then reducing fuel flow rate until extinction. Fuel flow rate was controlled with upstream pressure, primarily, and with torque on the threaded nut. Upstream absolute pressure was set with a pressure regulator. When a quenching limit was established, any flame was extinguished and a plastic tube was installed over the fitting such that the leak flow was measured with a downstream soap bubble meter at laboratory pressure. The quenching limits were obtained with burners at nearly laboratory temperature.

The hydrogen flames generally were not visible even in dark conditions. As with the round-hole burners, the presence of hydrogen flames was determined with a thermocouple positioned 10 mm above the flame position. Quenching limits for methane and propane were identified visually because thermocouples confirmed these flames to be visible in all cases.

Uncertainties for the present round-hole and leaky fitting tests are estimated at ±5% for hole diameter, fuel flow rate, and upstream pressure.

4. Results

4.1 Round-Hole Burners

Figure 2 shows an image of a hydrogen flame burning slightly above its quenching limit on a 0.36 mm pinhole burner. The flame appearance is similar to that of all the quenching limit hydrogen flames on round-hole burners. The hydrogen quenching distance of Table 1 suggests steady hydrogen diffusion flames should be anchored about 0.26 mm from the burner surface. Figure 2 indicates this is reasonable for the present hydrogen flames near their quenching limits. Because the maximum flame dimension is comparable to its standoff distance, this flame closely resembles a flat premixed flame [13].

Measured quenching limits for hydrogen, methane, and propane on tube burners are shown in Figure 3. Consistent with Equation (3), for each fuel the mass flow rate at quenching is nearly independent of burner diameter. The mean quenching limit flow rates are shown and are in reasonable agreement with the predictions of Table 1. The mean quenching limits for hydrogen are about an order of magnitude lower than those of the other fuels. Table 1 and Equation (3) indicate this arises from hydrogen's short quenching distance (primarily) and from its large flame length relative to its mass flow rate (i.e., large coefficient *a*).

Figure 3 also shows measured blowoff limits. The mass flow rate at blowoff increases with tube diameter because for these flames blowoff occurs when the local velocity exceeds the local premixed flame speed. The blowoff limits for hydrogen are about an order of magnitude larger than those of the other fuels, largely owing to the high burning velocity of hydrogen. Regardless of tube diameter, the limits of stable combustion of hydrogen are much wider than those for propane or methane. The limits narrow with decreasing tube diameter, as was shown for propane in [13], but they never meet.

Figure 4 shows the hydrogen quenching limits for the three types of round burners. Figure 4 indicates that, in general, quenching limits are somewhat affected by burner type and diameter for the smaller burner diameters. Where the limits are affected by burner type, the differences can largely be attributed to varying amounts of heat loss, as discussed next. An increase in heat loss requires a higher quenching flow rate to sustain the flame.

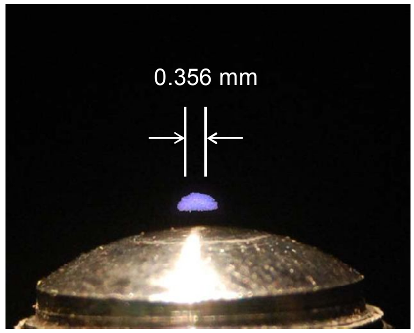

Figure 2. Color image of a hydrogen flame slightly above its quenching limit of 7.5 µg/s. The burner is a 0.36 mm pinhole burner and is oriented vertically. The image was recorded in a dimly lit room at *ƒ*/4.2 with an exposure time of 30 s.

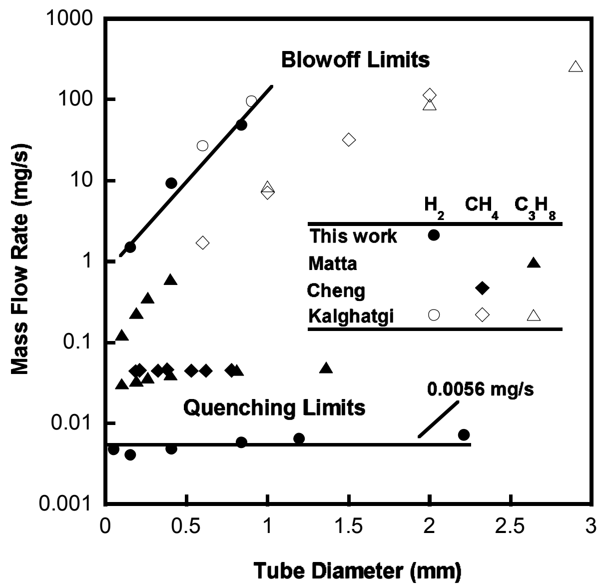

Figure 3. Quenching and blowoff limits for tube burners. Hydrogen quenching and blowoff limits include best fit lines. Past measurements shown are from [13,14,19].

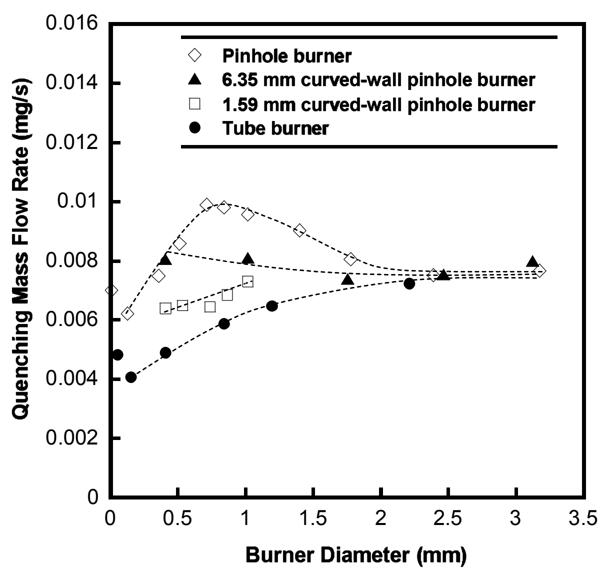

Figure 4. Quenching mass flow rates for hydrogen for various burner types and diameters.

For burner diameters below 1.5 mm, pinhole burners have the highest quenching flow rates, while tube burners have the lowest. Pinhole burners have greater heat losses owing to their shape and mass. Heat conducted to the pinhole burners is mostly transferred to the ambient and constitutes a loss of enthalpy from the system. On the other hand, much of the heat conducted to the tube burners is transferred to the fuel and oxidizer and thus is not intrinsically lost from the system. For tube burners the primary heat losses are expected to be radiation from the tube.

The effects of burner curvature on heat loss were investigated by observing curved-wall pinhole burners. An increase in curvature is expected to reduce wall heat loss. Indeed the 1.59 mm curved-wall pinhole burners yield quenching limits approaching those of the tube burners, whereas the 6.35 mm burners have quenching limits closer to those of the pinhole burners.

Burner diameter has interesting effects on the quenching limits of Figure 4. For tube burners quenching flow rate generally increases with increasing burner diameter. This also was observed for propane by Matta *et al.* [13], as shown in Figure 3. This is attributed to increasing heat loss with increasing burner diameter. In contrast pinhole burners do not exhibit this trend because their heat loss is nearly independent of burner hole size. The reason for the local maximum in Figure 4 for pinhole burners is unknown. For burner diameters above 1.5 mm, the quenching flow rates for both pinhole and tube burners agree with the 8 μg/s prediction of Table 1.

Quenching mass flow rates show a small increase for hole diameters less than 0.2 mm for both pinhole and tube burners. It is likely that the flow field is affecting the quenching limits at these very small sizes. In particular, the measured quenching flow rates for these two burners indicate sonic velocities. For the next larger hole sizes velocities are well below sonic. While exit velocities are high, the hole size is sufficiently small that the Reynolds numbers are all small and less than 10.

While the results above are for vertical burner orientation (upward flowing fuel), hydrogen quenching limits also were measured for inverted and horizontal orientations. The results, shown in Figures 5 and 6, reveal that quenching limits for the pinhole and tube burners are not dependent on orientation. Thus these limit flames are not affected significantly by buoyancy. This can be elucidated by considering their Froude numbers, given by:

$$\mathrm{Fr} = u^2 / (g\, d) \tag{4}$$

where u is the fuel velocity at the burner port and g is the acceleration of gravity. For the present quenching limit flames on pinhole and tube burners, the Fr range is 0.17 – 39. These are not in the buoyancy-controlled regime of Fr ≤ 0.1 [10]. Thus flame structure at the quenching limits should not vary with orientation. Furthermore, as mentioned in the experimental section, small changes in burner temperature do not affect the quenching limits, so any effects of orientation on burner heating should not affect these limits.

The above results demonstrate that flame quenching limits depend on fuel type and mass flow rate, with burner type, diameter, and orientation having far less significant effects. For a given fuel the mass

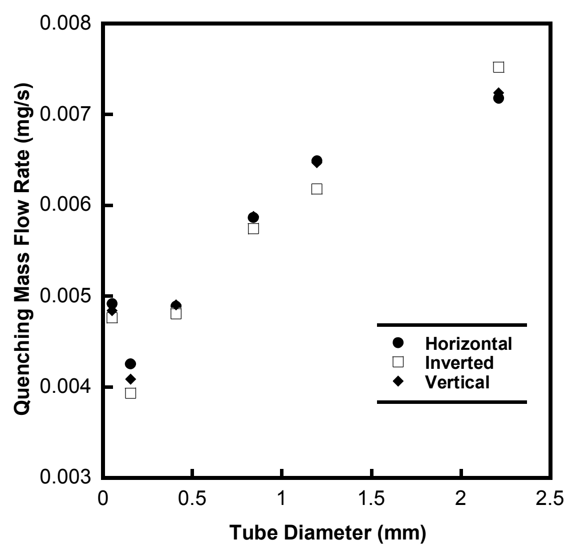

Figure 5. Quenching mass flow rates for tube burners in horizontal, inverted, and vertical orientations.

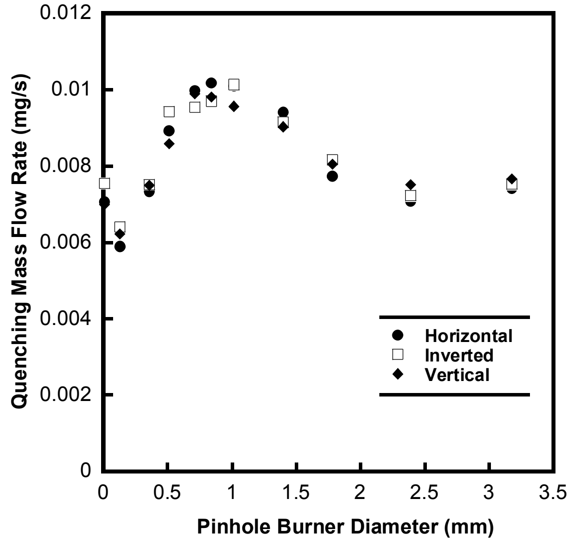

Figure 6. Quenching mass flow rates for pinhole burners in horizontal, inverted, and vertical orientations.

flow rate out of the leak is a function of the leak geometry and the upstream pressure. This relationship depends whether the leak regime is diffusional, subsonic laminar, subsonic turbulent, isentropic choked, supersonic, etc., as considered by Schefer *et al.* [16]. While the leaks considered here would not be considered isentropic, insight into the present quenching limits can be obtained by considering isentropic choked flows through round holes at the quenching limits. This could, for example, be relevant to a pinhole leak in a thin wall tube. Under these conditions the fuel flow rate is linear with respect to leak area A and upstream absolute pressure p_0 as follows [16]:

$$m_{fuel} = A\, p_o \left(\frac{k\, MW}{T_0\, R_u}\right)^{1/2} \left(\frac{2}{k+1}\right)^{\frac{k+1}{2(k-1)}} \tag{5}$$

where k is fuel specific heat ratio, MW is fuel molecular weight, T_0 is upstream stagnation pressure, and R_u is the universal gas constant.

Insight into the present quenching limits is obtained by considering isentropic choked flows through round holes at the quenching limits. For a given fuel and upstream pressure, Equation (5) can predict the hole diameter (the quenching diameter) associated with the quenching limit. The results of these predictions are shown in Figure 7. For this plot the quenching limit flow rates were taken as the average values for tube burners in Figure 3. Each line in Figure 7 starts at the minimum upstream pressure for choked flow and ends at the maximum pressure anticipated in alternative fuel vehicles. This plot predicts that for a given storage pressure, hydrogen is susceptible to flaming leaks for hole diameters that are smaller than those for methane or propane. Furthermore, at hydrogen's maximum anticipated storage pressure of 690 bar (10,000 psi), a hole diameter of just 0.4 µm is predicted to support a flame.

The limit flames in this study are believed to be among the weakest steady flames ever recorded. The weakest of these had a hydrogen flow rate of 3.9 µg/s (see Figure 5), or a heat release rate of 0.46 W based on hydrogen's lower heating value of 119.9 kJ/g. Previously, Ronney *et al.* [24] documented hydrogen flame balls produced under microgravity conditions with a power output of about 1 W. In subsequent tests they achieved flames as weak as 0.5 W. These were believed to be the weakest flames ever recorded.

Flame balls were first predicted by Zeldovich [25], who proposed that a solution exists to the steady heat and mass conservation equations corresponding to a stationary, spherical premixed flame. This solution was termed a flame ball, and the phenomena was discovered forty years after Zeldovich's work by Ronney *et al.* [26] in drop tower experiments with lean hydrogen-air mixtures. The microgravity environment was necessary to obtain the spherical symmetry and to avoid extinction brought on by buoyancy. Flame balls have only been achieved in microgravity conditions with very lean hydrogen mixtures. With no mechanism other than radiative heat loss, and this being low for hydrogen flames, it was reasonable to assume that these flames were the weakest possible flames. The present results indicate that, despite the possibility of heat loss to the tube, the present diffusion flame geometry is actually slightly more resistant to extinction than a flame ball. As noted earlier, heat transfer to the hypodermic tube does not intrinsically imply a significant loss of enthalpy as most of this heat preheats the reactants.

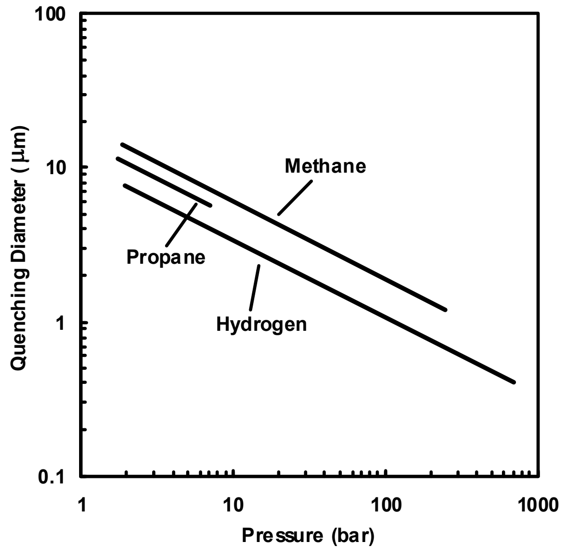

Figure 7. Minimum diameter of a circular port for flaming (quenching diameter) as a function of upstream absolute pressure assuming isentropic choked flow.

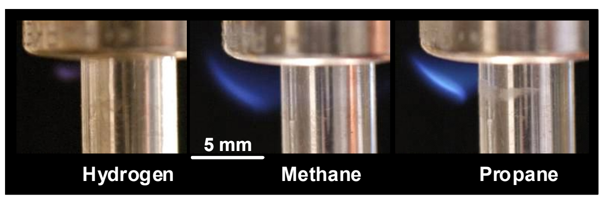

Figure 8. Flames near extinction on leaky compression fittings for hydrogen, methane, and propane (original in color). Also visible here is the 6.3 mm tube and the threaded nut. The fitting was vertically oriented and the upstream absolute pressure was 4 bar.

4.2 Leaky Fittings

Figure 8 shows photographs of hydrogen, methane, and propane flames on 6.3 mm leaky compression fittings in the vertical orientation. These images were recorded slightly above the quenching limits. Near their quenching limits the flames did not burn along the entire fitting annulus. The hydrogen flame is significantly smaller and dimmer than the others. For all three flames the shortest distance between the flame and the metal material is approximately 50% of the quenching distance given in Table 1. No yellow soot luminosity was visible in any of the present flames near their quenching limits. The leaks associated with the images of Figure 8 produced readily visible bubbles when soap water solution was applied.

An audible pop occurred upon hydrogen ignition, but not upon ignition of methane or propane. When the external flame was removed, ignition was quickly followed by extinction for fuel flow rates below the quenching limit. For fuel flow rates above the quenching limit, ignition was followed by a stable flame.

Figure 9 shows measured quenching limits for hydrogen, propane, and methane for 6.3 mm fittings in the vertical orientation. The data at the higher line pressures were obtained by increasing the torque on the fitting, and thus reducing the leak size. The upper limit on line pressure for propane is lower than that of the others because the vapor pressure of propane is only 9.1 bar (142 psia) at 25 °C.

Within experimental uncertainties, the quenching limits of Figure 9 are independent of line pressure for each fuel. This suggests that, as anticipated from the round-hole burner results of Figure 4, the key parameter controlling quenching limits is the fuel mass flow rate. For these low flow rates and small leak sizes the line pressure does not have a significant effect on the velocity field in the flame region.

The mean hydrogen flow rate at the quenching limit is about an order of magnitude lower than for the other fuels, which is consistent with the results of Figure 3. For leaky fittings, the quenching flow rates for hydrogen, methane, and propane are about an order of magnitude higher than the corresponding flows for round-hole burners (Figure 4). This is attributed to additional burner heat losses in the leaky fittings, where the flames burn near concave metal surfaces.

The effects of orientation of leaky fittings are investigated in Figure 10. Fitting orientation had little or no effect on the quenching limits of hydrogen flames. This is anticipated as these flames are small at their limits and is the results are consistent with the round-hole hydrogen measurements of Figures 5 and 6. Nonetheless, burner orientation did have an effect on the quenching limits of propane and methane flames, with the inverted limits averaging 20% lower than the vertical limits. These flames are larger than the corresponding hydrogen flames such that buoyancy is beginning to have a significant effect on the flow field. The inverted orientation has the fitting below the tube, and this minimizes the surface area of the flame impingement, leading to a reduced heat loss and thus lower quenching limits.

The effects of fitting diameter on quenching limits are examined in Figure 11. Diameter had a significant impact on the quenching limits in all cases; on average as tube diameter doubles, the fuel mass flow rate at quenching increases 30%. This is attributed to increased heat losses associated with larger fittings.

This study has identified new questions that warrant further study. For example, what corrosive effects do leak flames have on containment materials? Can permeation leaks support flames? Can surface coatings, e.g., intumescent paints, be applied that will increase the fuel flow rate at quenching? An improved understanding of hydrogen leaks is necessary to ensure safe use of hydrogen in the commercial sector.

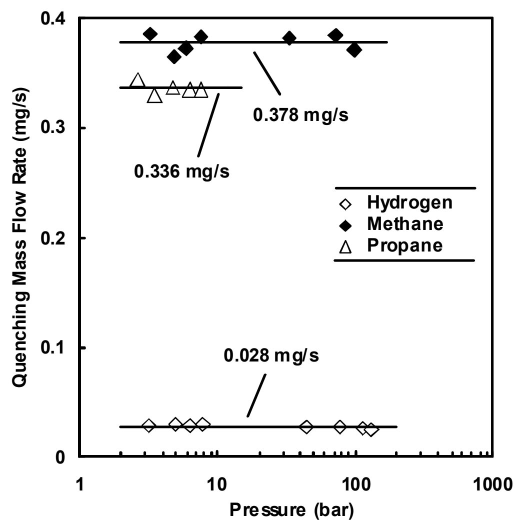

Figure 9. Quenching limit (minimum flaming flow rate) versus upstream absolute pressure for a 6.3 mm leaky compression fitting in the vertical orientation. The line fits represent mean values of the measured quenching limits.

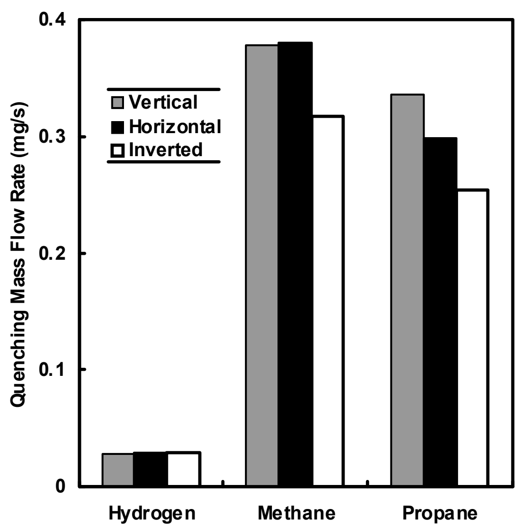

Figure 10. Quenching limits for a 6.3 mm leaky compression fitting in vertical, horizontal and inverted orientations. The upstream absolute pressure was 4 bar.

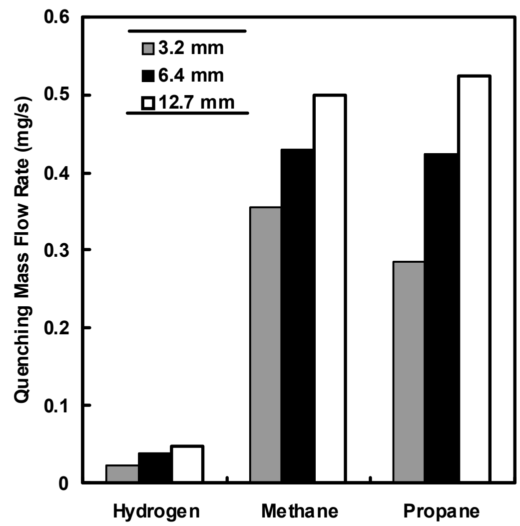

Figure 11. Quenching limits for leaky compression fittings for tube diameters of 3.1 mm, 6.3 mm and 12.6 mm. The fittings were vertically oriented and upstream absolute pressure was 4 bar.

5. Conclusions

Flame quenching and blowoff limits were measured for diffusion flames results from fuel issuing out of small burners. Hydrogen fuel was emphasized, and was compared with methane and propane for a variety of burner types that characterized a range of heat losses. The key findings are as follows:

1. Flame quenching limits for round-hole burners are nearly independent of burner diameter. These limits are reasonably predicted by a simple model presented here. The quenching limit mass flow rate of hydrogen, 5.6 μg/s, which is only is about one-tenth of that of methane and propane.
2. Existing codes and standards require leak rates below 200 mL/h (36 μg/s) for natural gas and 20 mL/h (0.46 μg/s) for hydrogen [20]. The measurements show that these flow rates are well below the associated quenching limits.
3. The mass flow rate at blowoff increases with burner diameter, and for hydrogen is about 10 times that for methane and propane for the same diameter burner. Thus the limits of stable combustion are much wider for hydrogen than for the other fuels.
4. For round-hole burners, the quenching flow rate was found to depend weakly on burner type, and to be independent of burner orientation. These observations are consistent with known wall heat loss and buoyancy effects.
5. For an isentropic choked leak, hydrogen is susceptible to flaming leaks for hole diameters that are smaller than those for methane or propane. This suggests that for hydrogen stored at 690 bar, a pinhole leak as small as 0.4 μm could support a stable flame.
6. The weakest hydrogen flame found in this study, which was generated with a hypodermic needle with an inner diameter of 0.152 mm, is believed to be the weakest flame ever observed, with a fuel flow rate of 3.9 μg/s and a heat release rate of 0.46 W.
7. The minimum flow rate necessary for sustaining a hydrogen flame on a leaky 6.3 mm tube compression fitting is 28 μg/s. This is about an order of magnitude lower than for propane or methane. The minimum mass flow rate for all fuels is independent of upstream (line) pressure, and is sufficient to produce bubbles when a soap-water solution is applied.
8. Fitting orientation had about a 20% effect on the quenching limits of the leaky compression fittings considered here, while a doubling of tube size on average results in a 30% increase in quenching flow rate.

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