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Extremely weak hydrogen flames

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ABSTRACT

Hydrogen jet diffusion flames were observed near their quenching limits. These involved downward laminar flow of hydrogen from a stainless steel hypodermic tube with an inside diameter of 0.15 mm. Near their quenching limits these flames had hydrogen flow rates of 3.9 and 2.1 μg/s in air and oxygen, respectively. Assuming complete combustion, the associated heat release rates are 0.46 and 0.25 W. To the authors' knowledge, these are the weakest self-sustaining steady flames ever observed.

1. Introduction

This study is motivated by a concern of fire hazards associated with small leaks in hydrogen systems and the design of microcombustors. Butler et al. [1] examined fire hazards of small hydrogen leaks. They observed quenching limits of diffusion flames in air on round burners and found the quenching mass flow rates for hydrogen to be about an order of magnitude lower than for methane and propane. These hazards are now acknowledged in an SAE technical information report [2], which requires hydrogen vehicles not to have localized leaks in excess of the measured quenching limits of Ref. [1].

The lowest quenching limits measured by Ref. [1] were for hypodermic tube burners with downward discharge. Six different tube diameters were considered. The lowest quenching flow rate was observed for an inside diameter of 0.15 mm, while smaller and larger tubes yielded higher quenching limits. This flame, and its counterpart burning in pure oxygen, are further considered here.

Microcombustors have potential advantages over batteries in terms of power generation per unit volume and energy storage per unit mass [3]. Recent developments in micro-electro-mechanical systems (MEMS) have enabled microcombustors with dimensions on the order of 1 mm [3]. Weak but stable flames [4,5] are beneficial for microcombustors and may allow flames to serve as permanent pilots.

Several studies have identified very weak self-sustaining flames. Saito and co-workers [6,7] observed and predicted the behavior of small hydrocarbon diffusion flames and predicted the existence of flames as weak as 0.4 W [7]. Ronney et al. [8] observed microgravity premixed flame balls with heat release rates as low as 0.5–1 W. Matta et al. [9] observed weak propane jet flames with heat release rates as low as 1 W.

2. Experimental methods and results

The experiments involved two hydrogen laminar jet diffusion flames, one burning in air and the other in oxygen. The hydrogen jets issued downward. The burner was a stainless steel hypodermic tube with an inside diameter of 0.15 mm and an outside diameter of 0.30 mm. Tests with platinum tubes of similar dimensions had nearly identical quenching limits, suggesting that any surface reactions were insignificant.

A pure oxygen ambient was obtained by placing the burner tip 40 mm above a 100 mm diameter supply of O_2 flowing upward at 20 mm/s through a plenum and a ceramic honeycomb flow straightener. There was no measurable change in the quenching limit with changes in oxygen velocity.

The flames (and any glowing of the burner tip) were not visible even in a darkened laboratory and hence were detected with a thermocouple placed 10 mm above the burner tip. After ignition, the hydrogen flow rate was reduced slowly until each flame was extinguished at its quenching limit. Hydrogen flow rates were measured with a rotameter. Uncertainties in the quenching limit flow rates are estimated at ±10%.

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Fig. 1. Images of hydrogen jet flames near their quenching limits in air (left) and in O_2 (right). The word WE from a US dime is shown at the same scale as the flames.

Color images of the two hydrogen flames slightly above their quenching limits are shown in Fig. 1. These were recorded with a Nikon D100 camera at ISO 200, f/1.4, and a shutter time of 30 s. The test conditions are given in Table 1. The word "WE" on a US dime is included at flame scale to show that the flames are smaller than the smallest letters on US coins. The flames are hazy, suggesting distributed reaction zones rather than thin flame sheets. The flames' diameters are seen to be smaller than 0.5 mm and the tube is seen to glow dimly for the hydrogen/air flame.

The quenching limits, i.e., the lowest hydrogen mass flow rates that can sustain steady flames in air and in oxygen, are provided in Table 1. These limits are 3.9 and 2.1 μg/s, respectively. The reduced quenching limit in oxygen is attributed to increased adiabatic flame temperature.

Under the assumption of complete combustion and a lower heating value of 120 kJ/g, these limits correspond to upper bounds of heat release rate (HRR) of 0.46 and 0.25 W. It is not expected that H_2 can leak across the flame zone. Indeed, computations of methane micro diffusion flames near their quenching limits [10] found negligible fuel leakage across the reaction zone. However, fuel can leak between the flame and the tube. Matta et al. [9] used propane experiments and an analytical model to estimate that 25% of the fuel was unburned near microflame quenching limits. Computations by Nakamura et al. [7] for methane microflames near their quenching limits on an isothermal 0.04 mm burner found that about 80% of the fuel flow rate contributed to the HRR.

Table 1
Measured quenching limits of hydrogen jet flames.

Oxidizer	$\dot{m}_{H_2}$ (μg/s)	HRR (W)	u (m/s)	Re	Fr	Pe
Air	3.9	0.46	2.5	3.96	4251	5.3
O_2	2.1	0.25	1.4	2.13	1331	3.0

Also included in Table 1 are the Reynolds, Froude, and Peclet numbers:

$$\mathrm{Re} = ud/\nu; \quad \mathrm{Fr} = u^2/gd; \quad \text{and} \quad \mathrm{Pe} = \mathrm{Re}(l_D/d)\mathrm{Sc}, \tag{1}$$

where u is mean hydrogen velocity in the burner, d is burner inside diameter, ν is kinematic viscosity, g is acceleration of gravity, l_D is a characteristic diffusion length scale, and Sc is Schmidt number. Here l_D is approximated as 1 mm, and Sc is 0.204 and 0.22 for H_2/air and H_2/O_2 flames, respectively [11]. The viscosity and velocity in Eq. (1) pertain to H_2 at laboratory pressure and temperature. The low Peclet and high Froude numbers of these flames indicate that diffusion dominates over momentum, which in turn dominates over buoyancy [7].

The quenching limit mechanisms of micro diffusion flames are complicated, and their understanding continues to evolve. Diffusion and reaction times are similar near the limits [7], indicating kinetic extinction. Flame heights at the limits are comparable to the quenching distance for premixed flames [1,7,9]. Burner heat loss has been found numerically to affect the limits [7,12]. Methane [12] and hydrogen [10] limit flames were found to behave like diffusion and premixed flames, respectively, while propane [9] yielded flat premixed flame behavior. Our preliminary numerical results for hydrogen limit flames indicate that O_2 leaks across the reaction zone, but H_2 does not. The small scales of micro diffusion flames result in many unusual phenomena.

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