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Considerations of Ignition Probability in Turbulent Hydrogen Jets

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Turbulent hydrogen jets issuing into ambient air are relevant to unintended hydrogen releases resulting from a break in high-pressure hydrogen storage or delivery components. Of particular interest to the hydrogen safety codes and standards community is the distance required to mix sufficient air with hydrogen such that a nonflammable mixture is achieved. A question one might further ask is how does the required distance for a hydrogen jet compare with a methane jet. It is important to note that a comparison of methane and hydrogen jet lengths based on the centerline decay of the mean concentration is somewhat simplistic and neglects the important flow dynamics found in turbulent jet flows. For a more realistic and meaningful comparison of these jets, it is necessary to consider the methane jet ignition studies of Birch and coworkers (Birch et al., 1979 and 1981; Smith, 1986). A conclusion of those studies is that, "in a turbulent flow it is not meaningful to consider just the mean concentration in order to define the flammability or probability of ignition". To further examine this important conclusion, it is necessary to describe their experiments in greater detail.

These studies utilized a spark igniter to measure the probability of igniting a flame at various locations in turbulent methane jets. The spark was pulsed at 3 second intervals, and each time an ignition event occurred, it was recorded. From these experiments two probabilities were defined. The first, P_I, is the probability that any _local_ gas ignition occurred. Once local ignition achieved, it was further observed that the initial flame kernel can lead to either upstream flame propagation and a stable fame light-up, or eventual extinction of the flame kernel before any significant flame propagation occurs. Thus, a second probability, P_L, was defined as the probability that the initial local ignition event (i.e. flame kernel) will lead to flame propagation throughout the jet and a stable flame light-up. The igniter was placed at various positions throughout the jet and both P_I and P_L were determined. Some typical results of these methane jet experiments are presented in Fig. 1, where the probabilities of ignition and flame light-up are shown along the jet centerline. Also shown is the centerline decay of the mean jet fluid concentration, X_{CH4} (volume fraction), with the locations at which the mean concentration value equals the methane lean flammability limit, LFL, ($X_{CH4}=0.05$) and the rich flammability limit, RFL, ($X_{CH4}=0.15$). It can be seen that a finite probability ($P_I>0$) of local ignition extends over the entire range of flammable mixtures based on the mean methane concentration and, in fact extends somewhat past both the rich and lean limits. The maximum values of P_I, which approach a value of unity, are also shifted slightly toward the rich flammability limit.

The existence of a finite ignition probability outside the range of flammable mixtures (based on the mean methane concentration) is related to the intermittent nature of

turbulent jet flows. At a single location in the flow, the instantaneous concentration rarely equals its mean value, but rather oscillates, sometimes greatly, about this mean value as turbulent "blobs" of fluid with different concentrations are convected past the selected location. These local variations in methane concentration are reflected in the probability density distributions measured by Birch and coworkers in methane jet flames. Figure 2 shows probability distributions of methane concentration measured at three locations in an unignited methane jet at Reynolds number of 16,000. Figure 2a gives the distribution along the centerline and shows a broad distribution extending from X_{CH4} from 0.8 to 0.3. This location is sufficiently close to the jet exit that the range of concentrations is well above the methane flammability limits that are indicated by the cross-hatched area along the horizontal axis. Farther downstream, as more air is entrained into the jet, the distribution will shift toward leaner mixtures until eventually at least some fraction of the distribution will fall within the flammability limits. Thus even though the mean concentration is outside of the flammability limits, a certain fraction of time a flammable mixture may exist at the measurement location and produce a finite probability of an ignition event. The distributions shown in Figs. 2b and 2c are representative of radial locations away from the jet centerline. Figure 2b, at a normalized radial distance r/D=1.49, is located where the fluctuations in concentration are a maximum. It is characterized by an even broader distribution of methane concentrations and an intermittency spike at $X_{CH4}=0$. This spike is the result of pure air that has not yet mixed with fuel being present in the measurement location. The cross-hatched area again corresponds to the methane flammability limits. Unlike the distribution the centerline, a finite probability exists of the methane concentration at the measurement location falling within the flammability limits. At these times there is also a finite probability of an ignition event occurring. The distribution in Fig. 2c, at r/D=1.8, is farther away from the jet centerline and closer to the air boundary located along the outer edge of the jet. Here, the probability of pure unmixed air occupying the measurement volume is high and the time during which methane mixed with air is present has decreased. Again, a finite probability of a flammable mixture at the measurement location exists.

The flame light-up probabilities seen in Fig. 1 clearly show that not all ignition events lead to a flame light-up. In fact, at some locations all ignition events are extinguished. For example, this situation exists at x/D>100 where P_I has a nonzero value but P_L equals zero, indicating that all ignition events are extinguished. Over the relatively short region from $85 < x/D < 100$, P_L increases from near zero to near unity, where most all local ignition events lead to complete flame light-up.

As noted by Birch and coworkers, whether local ignition results in flame light-up or is extinguished depends on several factors in addition to the local methane concentration. Two of the most important factors include the duration of the concentration fluctuations relative to the chemical ignition time (i.e. if a flammable mixture doesn't exist sufficiently long due to mixing there is insufficient time for the flame to develop) and the probability that the local flow velocity exceeds the flame burning velocity (in which case the flame will be convected downstream and eventually be extinguished by the increased amount of cool air).

Considering this discussion, a perhaps better comparison of unignited hydrogen and methane jet lengths is provided by Fig. 3 where the predicted centerline decay rates for both fuels for a 3.175-mm diameter leak at stagnation pressures of 18.25 bar (250 psig) and 207.85 bar (3000 psig). Also indicated are the lean and rich flammability limits of methane (0.05 and 0.15 mole fraction, respectively) and the lean flammability limits of hydrogen for upward propagating flames (0.04 mole fraction) and downward propagating flames (0.085 to 0.095 mole fraction). It can be seen that while the decay distance to the lower flammability limit for upward propagating hydrogen flames is nearly 3.5 times greater than for methane (which is the predominant component of natural gas), the hydrogen decay distance to the lower flammability limit for downward propagating flames is only about 50 percent greater.

Interpretation of Swains Ignition Measurements in Hydrogen Jets

An interesting observation by Swain (2004) is that it is difficult to ignite a turbulent hydrogen jet at any location where the time-averaged hydrogen concentration less than about 8%. Note that a precise value for the minimum hydrogen concentration at which ignition occurred is difficult to determine since the observed value depended on both ignition energy and spark gap. Thus, depending on the ignition energy and spark gap, a finite probability of ignition less than unity ranged from as low as 5% to as much as 10%. At first appearance this is somewhat surprising since the generally accepted lean flammability limit for H_2 is 4%. Several possibilities were explored to explain this discrepancy. An initial thought was that the flammability limits for H_2 are not sufficiently well established. To resolve this issue a literature search was completed on flammability limits for mixtures of hydrogen and air. Nearly eighty investigations of hydrogen flammability limits were identified between 1920 and 1960. The flammability limits measured in these studies were found to be very consistent once differences in test apparatus were accounted for. Based on this review it was concluded that the flammability limits of hydrogen are well established and do not need further research. However, a unique aspect of hydrogen is that the lean flammability limit is significantly different for upward, downward and sideward propagating flames. This is a buoyancy effect due to the low density of H_2 relative to air. In contrast, the lean flammability limits for conventional hydrocarbon fuels such as methane are independent of flame propagation direction. Although the generally accepted value for the upward-propagating lower flammability limit of hydrogen in air is 4% mole fraction, experimental data in the literature indicate that the limit may be as high as 7.2% for horizontal-propagating flames, and between 8.5% and 9.5% for downward and spherically propagating flames (Coward and Jones, 1952). It is noteworthy that this range of values agrees well with the range of values for hydrogen ignition in turbulent hydrogen jet flows observed experimentally by Swain. Considering the fact that flame propagation from a single ignition point in a turbulent jet is likely to be in a random direction, and not exclusively in an upward direction, the range of ignitable hydrogen concentrations observed by Swain is consistent with the range of lean hydrogen flammability limits found in the literature.

References

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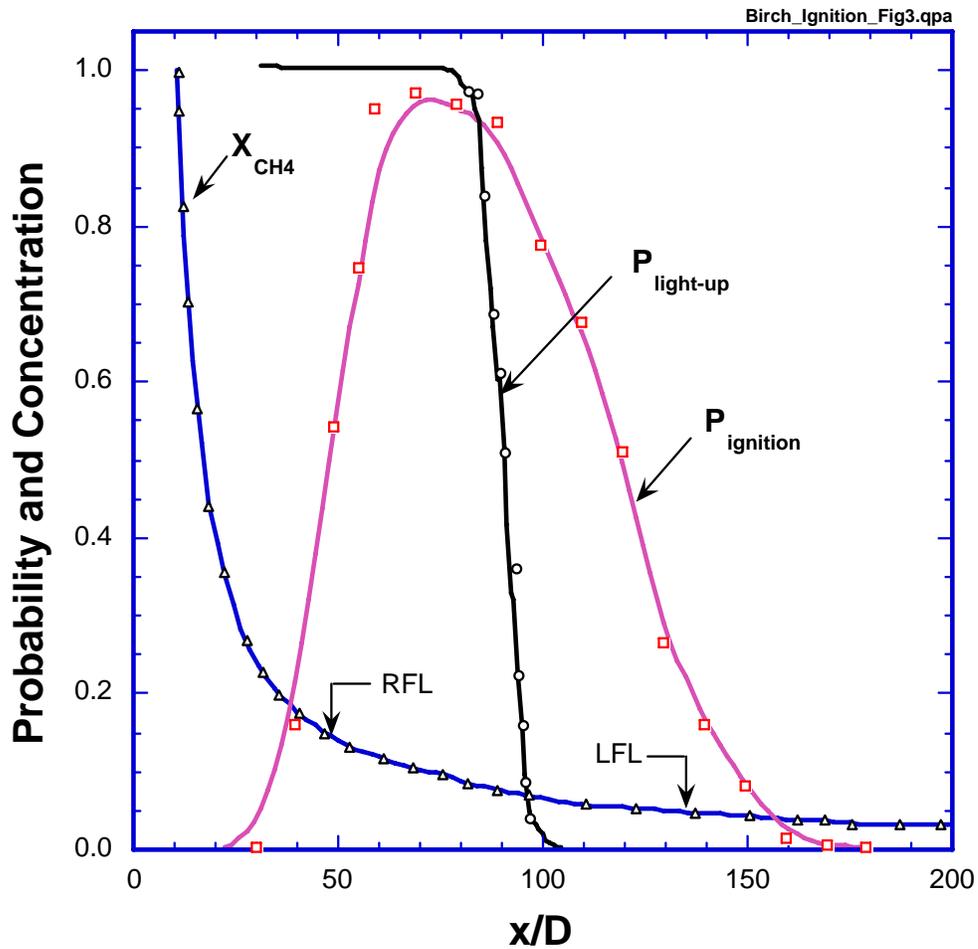
Figure 1. Ignition and light-up probabilities along the centerline of a methane jet. Shown for comparison is the measured centerline distribution of the mean methane concentration. The location of the Rich Flammability Limits (RFL) and Lean Flammability Limits (LFL) based on the mean concentration are also indicated. Jet diameter=12.7 mm and Re=17,400. (From Smith et al., 1986).
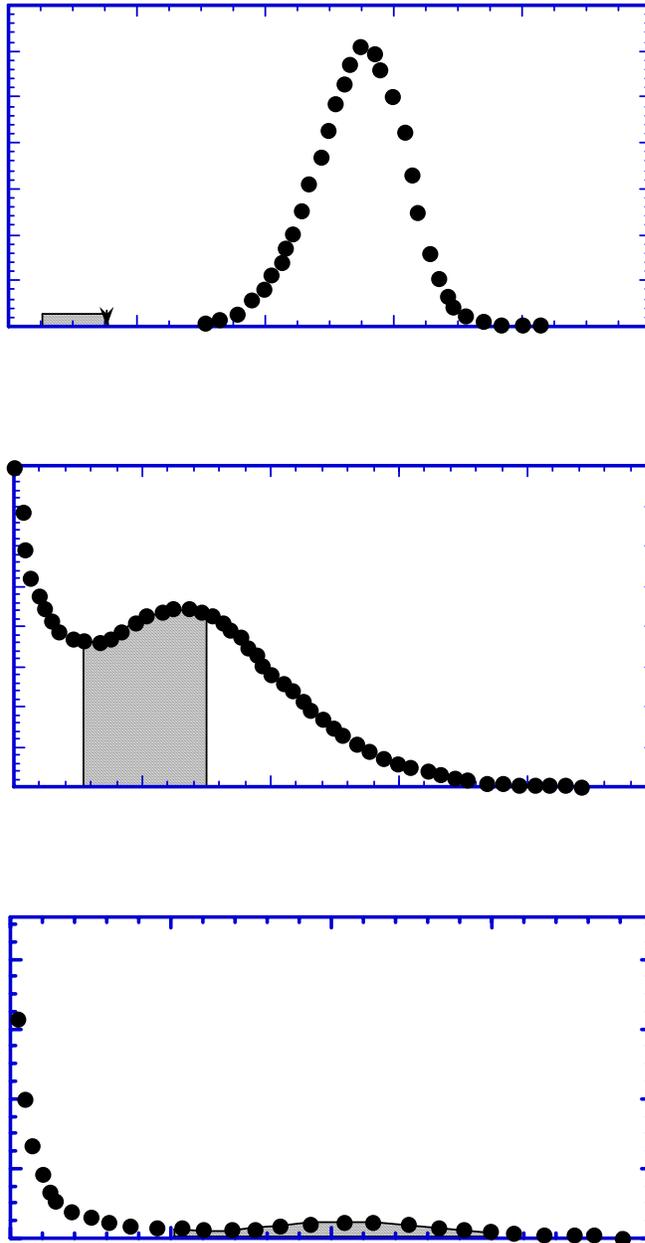
Figure 2. Probability density distributions of methane concentration in unignited CH_4 jet. Distributions are shown at 10 jet diameters downstream of jet exit for radial displacements of a) r/d=0; b) r/d=1.49 and c) r/d=1.80. Jet diameter=12.65 mm and Re=16,000. The mean and rms fluctuations in the CH_4 concentration are indicated in each figure. (From Birch et al., 1979).
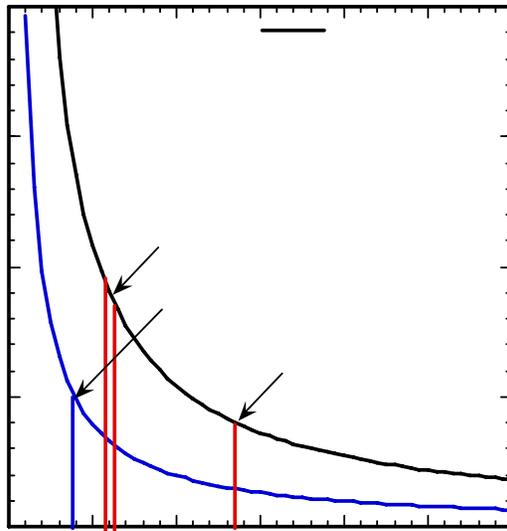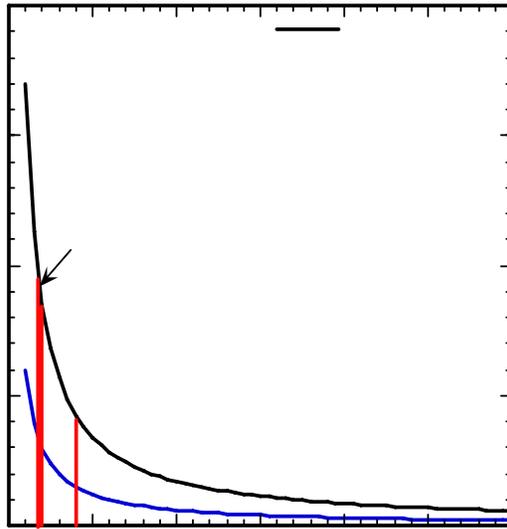
Figure 3. Predicted centerline concentration decay of unignited H_2 and CH_4 jets. a) Stagnation pressure of 250 psig; b) stagnation pressure of 3000 psig. Jet diameter is 3.175 mm.