

*Flammability Limits of Hydrogen/air Mixtures*

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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%. At first appearance this is somewhat surprising since the generally accepted lean flammability limit for hydrogen is 4%. Several possibilities were explored to explain this apparent discrepancy. An initial thought was that the flammability limits for hydrogen are not sufficiently well established and require further research. 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. A detailed analysis of these studies revealed several relevant findings. Experimentally, the determination of flammability limits is not altogether straightforward. Typically flammability limits are determined by confining the fuel/air mixture in a fixed diameter tube or cylinder. Selection of tube dimensions is important since a small diameter will increase heat losses from the flame to the cooler surface and introduce flame-quenching effects at the tube walls. These effects are apparatus specific and can have a significant effect on flammability limit measurements. At present the most accepted standard method for measuring flammability limits is in a vertically orientated, 50-mm diameter by 1.2-m long tube. When differences in experimental apparatus are taken into account, measured flammability limits for various fuels show good agreement. It is thus concluded that the flammability limits for most common fuels *and for hydrogen* are well established and do not need further research

The review of this extensive literature further revealed a unique aspect of hydrogen, which is that the lean flammability limit is significantly different for upward, downward and sideways propagating flames. This is a buoyancy effect due to the low density of hydrogen relative to air. In contrast, the lean flammability limits for conventional hydrocarbon fuels such as methane, which have densities close to that of air, are not impacted by buoyancy and thus are independent of flame propagation direction. A comparison of reported hydrogen flammability limits is given in Table 1 from the review by Coward and Jones, 1952. 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 is as high as 7.2% for horizontal-propagating flames, and between 8.5% and 9.5% for downward and spherically propagating flames. It is noteworthy that this range of values agrees well with the range of values observed experimentally by Swain for hydrogen ignition in turbulent hydrogen jet flows. 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.

Table 1. Limits of Flammability of hydrogen in air

**Upward Flame Propagation**

Tube Dimensions, cm		Firing end	Limits, percent		Water Vapor Content	Reference
Diameter	Length		Lower	Higher		
7.5	150	Closed	4.15	75.0	Half-saturated	356
5.3	150	Open	4.19	74.0	Dried	94
5.3	150	“	4.12	74.2	“	94
5.3	150	“	4.17	74.8	“	94
5.0	150	Closed	4.15	74.5	Half-saturated	356
5.0	150	Open	4.00	72.0	Dried	133
4.8	150	“	4.00	73.8	“	38
4.5	80	Closed	4.10	-----	“	56
4.5	80	“	3.90	-----	“	57

**Horizontal Flame Propagation**

Tube Dimensions, cm		Firing end	Limits, percent		Water Vapor Content	Reference
Diameter	Length		Lower	Higher		
7.5	150	Closed	6.5	-----	Half-saturated	356
5.0	150	“	6.7	-----	“	356
2.5	150	“	7.15	-----	“	356
2.5	150	Open	6.2	-----	Saturated	271
2.5	-----	“	-----	71.4	-----	273
0.9	150	“	6.7	65.7	Saturated	276

**Downward Flame Propagation**

Tube Dimensions, cm		Firing end	Limits, percent		Water Vapor Content	Reference
Diameter	Length		Lower	Higher		

21.0	31	Open	9.3	----	<i>Saturated</i>	63
8.0	37	Closed	8.9	68.8	Half-saturated	324
7.5	150	“	8.8	74.5	“	356
7.0	150	“	-----	74.5	Saturated	115
6.2	33	Open	8.5	----	Partly dried	95
6.0	120	“	9.45	----	“	325

### Propagation in a Spherical Vessel

Capacity, cc	Firing end	Limits, percent		Water Vapor Content	Reference
		Lower	Higher		
Not stated	Closed	9.2	----	<i>Saturated</i>	271
Not stated	“	8.5	67.5	“	82
1,000	“	8.7	75.5	“	95
810	“	5.0	73.5	“	349
350	“	4.6	70.3	“	368
35	“	9.4	64.8	“	297

### References

Coward, H. F. and Jones, G. W., “Limits of Flammability of Gases and Vapors”, U. S. Bureau of Mines, Bulletin 503, 1952.

Swain, M., “Hydrogen Properties Testing and Verification”, presented at Fuel Cell Summit Meeting, Coral Gables, Florida, June 17, 2004.