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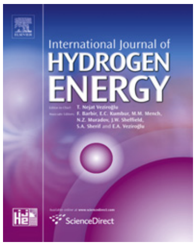

Flammability limits of hydrogen-enriched natural gas

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ABSTRACT

This paper reports both the lower and upper flammability limits of hydrogen-enriched natural gas with hydrogen fractions of 20%, 40%, 60% and 80% respectively as well as these of natural gas and hydrogen, measured by using a constant volume combustion chamber together with a high-speed schlieren photographic system. Based on investigating pressure rise history inside the combustion chamber as well as flame photos, the effect of hydrogen enrichment on the flammability characteristics is discussed. Our experimental results show that the flammability limits of methane–hydrogen mixtures can be used for hydrogen-enriched natural gas as long as their hydrogen fractions are the same. In this paper, the flammability data of methane–hydrogen mixtures available in the literature are reviewed. Correlations for both the lower and upper flammability limits of methane–hydrogen mixtures are summarized.

1. Introduction

Hydrogen is regarded as "an ideal fuel from the point of conservation of the environment" because "the only toxic products of combustion of hydrogen are nitric oxides" [1]. The recent efforts on solar-hydrogen technology lead its way to turn hydrogen energy into a promising renewable energy resource (e.g. [2–4]). This adds measures for the large-scale usage of hydrogen energy in the future. But with our current technologies, widespread application of pure hydrogen in transport engines is still unlikely to happen in the near future, mainly due to infrastructure, transportation and storage constrains [1].

On the other hand, natural gas has been used widely in transportation and industry as well as in domestic applications. To increase its thermal efficiency and reduce unburned hydrocarbon emissions at lean operation conditions, one promising method is to add hydrogen (whose burning velocity is six to seven times as fast as that of natural gas) into natural gas. Experiments showed that by fueling hydrogen-enriched natural gas, automotive engines can operate smoothly at lean conditions with improved engine performance, increased thermal efficiency and reduced emissions (e.g. [5–7]). Therefore, hydrogen-enriched natural gas provides a feasible solution for the high-efficient and environmentally friendly usage of both hydrogen and natural gas.

To safely use hydrogen-enriched natural gas, the knowledge on the explosion hazards of these mixed gaseous fuels is of great importance. Flammability limit (also known as explosion limit) has been widely used as an index for the quantitative risk assessment of the explosion hazard associated with the usage of these fuels. There are two flammability limits named as lower flammability limit (LFL) and upper flammability limit (UFL), referring to the leanest and the

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Nomenclature

LFL	lower flammability limit
p	pressure inside the combustion chamber, MPa
p_i	initial pressure, MPa
p_{max}	maximum pressure inside the combustion chamber, MPa
S_N	standard deviation of experimental and calculated flammability limits data
t	time, s
UFL	upper flammability limit
x	volumetric fraction of hydrogen in hydrogen-enriched natural gas
x_1	measured flammability limits of hydrogen-enriched natural gas
x_2	measured flammability limits of methane–hydrogen mixtures
x_3	calculated flammability limits of methane–hydrogen mixtures
$\bar{x}$	mean value of x_1, x_2 and x_3
Δp	pressure rise inside the combustion chamber $\Delta p = p - p_i$

richest fuel/air mixtures upon which a self-sustainable flame can be initiated respectively.

The flammability limits of methane and hydrogen have been measured and reported intensively [8–16]. For methane–hydrogen mixtures, the available flammability data are relatively limited comparing with that of methane or hydrogen. Table 1 summarizes the available flammability limits of methane–hydrogen mixtures reported in Refs. [17–22]. We noticed that the hydrogen fractions of methane–hydrogen mixtures were different in these references. For example, the hydrogen volume fractions studied were 25%, 50% and 75% in Ref. [19], while in [21] the hydrogen fractions were 20%, 40%, and 60% (See Table 1). Wierzba and Ale studied a wide range of fuel mixtures involving hydrogen, covering hydrogen volume fractions of 20%, 50%, 70%, and 90% [18]. However, only the upper flammability limits were reported. Therefore, it is necessary to conduct a systematic experimental study on the flammability limits of methane–hydrogen mixtures.

Table 1 – Flammability limits of methane–hydrogen mixtures determined by various methods [17–22].

2.7 L chamber[b]

Hydrogen fraction (%)	0	25	50	75
LFL (vol.%)	4.6[a]	4.5[a]	4.4[a]	4.2[a]
UFL (vol.%)	16.5[a]	23[a]	32[a]	43.2[a]

4.2 L sphere[c]

Hydrogen fraction (%)	0	20	40	60
LFL (vol.%)	4.6	4.4	4.6	4.6
UFL (vol.%)	16.0	19.6	25.4	–

Tube with diameter of 50 mm[d]

Hydrogen fraction (%)	23.08	50
LFL (vol.%)	5.0	4.63

Tube with diameters in the range of 18.4–50.2 mm[e]

Hydrogen fraction (%)	0	10	20	30	40
LFL (vol.%)	5.1	5.21	4.54	4.48	4.35

Tube with diameter of 50.8 mm[f]

Hydrogen fraction (%)	0	20	50	70	90	100
UFL (vol.%)	15[a]	18[a]	26[a]	35[a]	51[a]	76[a]

Tube with diameter of 60 mm[g]

Hydrogen fraction (%)	0	20	40	60
LFL (vol.%)	4.4	4.2	4.0	4.0
UFL (vol.%)	15.8	19.0	24.2	32.4

a Values were read from figure(s).
b Pahl (1994), using 10% pressure rise criterion, from Ref. [21].
c Van den Schoor et al (2008), using 5% pressure rise criterion [21].
d Flammability tube (stainless steel) with diameter of 50 mm, vertical upward flame propagation using visual criterion [17].
e Flammability tubes (pyrex) with diameters in the range of 18.4–50.2 mm, vertical upward flame propagation using visual criterion [22].
f Flammability tube (stainless steel) with diameter of 50.8 mm, vertical upward flame propagation using visual criterion [18].
g Flammability tube (glass) with diameter of 60 mm, vertical upward flame propagation using visual criterion [19–21].

We also noticed that it is natural gas that has been used widely in transportation and domestic applications, not pure methane. Although methane is the main constitute of natural gas, are the methane–hydrogen flammability data good enough to represent these of hydrogen-enriched natural gas? Is it appropriate to ignore the effects of other constitutes of natural gas on its combustion under hydrogen-enriched environment? Experimental proof is needed to answer these questions. Therefore, we investigated the flammability characteristics of both hydrogen-enriched natural gas and methane–hydrogen mixtures experimentally in this study. Hydrogen-enriched fuels with hydrogen fractions of 0%, 20%, 40%, 60%, 80% and 100% were tested, aiming at providing a complete picture of the effect of hydrogen addition on its flammability limits.

Generally speaking, there exist two types of apparatus for measuring the flammability limits of a fuel. One is stainless steel or glass tube, usually cylindrical with internal diameter of 5–10 cm [9,14–22]. Usually a mixture is treated as non-flammable if its flame fails to propagate a certain length of distance. The other is spherical or cylindrical internal shaped combustion chamber (also referred to as combustion bomb or explosion vessel) with wide range of internal volume from 1.57 dm^3 (also known as liter) up to 25.5 m^3 [10–13,15,16,19,20]. Spark ignition systems or pyrotechnic igniters are needed to ignite the combustible mixtures; ignition energy should be chosen with care, depending on both chamber dimension and properties of the combustible mixtures. Flammability limits can be determined either by pressure rise criterion or visual criterion. The latter requires one or more glass windows in the combustion chamber.

To standardize test method as well as calculation procedure for measuring the flammability limits of gases and their mixtures, both international and national standards are available. A comprehensive review of international standard,