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# Experimental results of hydrogen enrichment of ethanol in an ultra-lean internal combustion engine

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ABSTRACT

An investigation was made to determine the effects of hydrogen enrichment of ethanol at ultra-lean operating regimes utilizing an experimental method. A 0.745 L 2-cylinder SI engine was modified to operate on both hydrogen and ethanol fuels. The study looked at part throttle, fixed RPM operation of 0%, 15%, and 30% hydrogen fuel mixtures operating in ultra-lean operating regimes. Data was collected to calculate NO and HC emissions, power, exhaust gas temperature, thermal efficiency, volumetric efficiency, brake-specific fuel consumption, and Wiebe burn fraction curves.

It was shown that hydrogen enrichment of ethanol demonstrated an ability to reduce $NO_x$ and stabilize and accelerate the combustion process. The experiments showed that operating near the LOL at both 15% and 30% hydrogen by volume reduced engine out $NO_x$ emissions by more than 95% as compared to stoichiometric gasoline operation. This reduction is comparable to the efficiency of modern three-way catalyst and could offer an alternative to current $NO_x$ reduction technologies. Power, thermal efficiency, and volumetric efficiency were not affected by the hydrogen mixture at a given equivalence ratio. However, hydrogen addition allowed an increase in the lean operating limit which helped further reduce $NO_x$ emissions, but also at reduced power and thermal efficiency.


## Introduction

### *Background*

Because of growing concerns about energy security and emissions, ethanol fuel has received significant attention in the past few years. Ethanol has shown promise as a domestically produced alternative to fossil fuels. This is because it is a liquid simplifying distribution and has relatively low toxicity. Ethanol has also shown promise in helping to reduce greenhouse gases; especially if the ethanol is produced by sugarcane or cellulosic feedstocks [1–4].

Hydrogen ($H_2$) enrichment, which is the addition of small amounts of hydrogen to internal combustion engines, has also shown great promise. Hydrogen enrichment has been shown

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to enable lean or dilute combustion regimes that potentially reduce emissions and increase efficiency in spark ignition internal combustion engines using a variety of different primary fuels [5–24]. Hydrogen enrichment has been applied to natural gas and methanol fuels in many studies [5,7–10,13,15,20,21] and has been applied to gasohol (less than 30% Ethanol) fueled engines with demonstrated effects in both emissions and efficiency [16–19].

### Objective

Although some experimental work has taken place on the subject of hydrogen enrichment of gasohol fueled engines, there has been little work to predict and validate the behavior of hydrogen enrichment of neat ethanol.

The purpose of this research is to investigate the feasibility of hydrogen-enrichment as a method to enhance ethanol combustion in internal combustion engines, specifically to:

1. Modify a small IC engine to run on ethanol with hydrogen enrichment.
2. Empirically determine the effects of hydrogen enrichment and equivalence ratio on efficiency, power, and emissions for ethanol fueled engines.

### Ethanol and hydrogen in IC engines

Ethanol fuel has been shown in numerous works to offer some significant benefits over gasoline. Ethanols high octane rating gives the ability to operate at higher compression ratios without pre-ignition [25]; ethanols greater latent heat of vaporization gives a higher charge density through increased charge cooling [26]; and ethanols higher laminar flame speed and lower flammability limit allows it to be run with leaner, or more dilute, air–fuel mixtures [27]. In addition, ethanol fuels generally yield lower criteria pollutant emissions than gasoline [28,29]; lower evaporative emissions due to somewhat lower vapor pressures [30]; and, when certain renewable feedstocks are used, lower life-cycle greenhouse gas emissions [1–4]. Table 1 compares some of the physiochemical characteristics of ethanol and gasoline.

**Table 1 – Physiochemical characteristics of gasoline, ethanol, and hydrogen [14,33–39].**

| Physiochemical characteristics | Gasoline | Ethanol | Hydrogen |
|---|---|---|---|
| Formula | $C_nH_{1.87n}$ | $C_2H_5OH$ | $H_2$ |
| Molecular weight | 110 | 46.07 | 2.02 |
| Density, g/cm$^3$ | 0.72–0.78 | 0.785 | 0.00009 |
| Boiling point, °C | 27–227 | 78 | −253 |
| Reid vapor pressure, kPa @ 37.8 °C | 54.3 | 14.3 | – |
| Octane no., (RON + MON)/2 | 86–94 | 100–114 | 130 |
| Viscosity, centipoise (cP) @ 20 °F | 0.37–0.44 | 1.19 | 0.0088 |
| Flashpoint, °C | −43 | 13 | −253 |
| Autoignition temp., °C | 440 | 558 | 572 |
| Minimum ignition energy, mJ | 2.4 | 0.7 | 0.02 |
| Peak flame temperature, °C | 2030 | 1920 | 2210 |
| Flammability limits[c], vol% | 1.4–7.6% | 3.3–19% | 4.1–75% |
| Lean limit[b] (Equivalence ratio) | (0.6) | (0.49) | (0.1) |
| Stoichiometric air/fuel ratio | 14.6 | 8.93 | 34.3 |
| Max flame speed[b], m/s | 0.57 | 0.61 | 1.7 |
| (Stoichiometric flame speed) | (1.06) | (1.1) | (230) |
| Diffusion coefficient in air[e], cm$^2$/s | 0.012 | 0.021 | 0.096 |
| Quenching distance[d], mm | 2.84 | 0.9 | 0.64 |
| Latent heat of vaporization, kJ/kg @ 25 °C | 350 | 838 | 446 |
| Lower heating value, MJ/kg | 44.5 | 26.9 | 119.9 |
| Energy density LHV[a,b], MJ/m$^3$ | 31,380–34,320 | 15,840 | 11 |

[a] Calculated from specific energy LHV; density of hydrogen used was from Ref. [31].
[b] Calculated at 1 atm, 273 K.
[c] Calculated from information in Ref. [15] at 1 atm, 373 K.
[d] Calculated from information in Ref. [15].
[e] Calculated at 1 bar, 300 K using Wilke and Lee method in Ref. [32]; average gasoline density was used.

However promising, there are some disadvantages to using ethanol fuel. Dedicated ethanol fueled engines using a high compression ratios have faced a persistent challenge with hydrocarbon emissions during cold start [40]. Such challenges may be mitigated somewhat through secondary air injection [26] or with more volatile fuel additives such as gasoline [40] or hydrogen [41,42]. Additionally, hydrogen enrichment may further increase efficiency and solve the cold starting issues with ethanol fuel.

Internal combustion engine operation on pure hydrogen has been investigated extensively due to the potential for high thermal efficiency, near zero emissions of HC and CO, and low $NO_x$ emissions. Unfortunately, there are many drawbacks to using hydrogen as a fuel, such as fuel storage, production and availability, and pre-ignition. Although ultra-lean combustion increases thermal efficiency and decreases emissions, it also typically decreases power output.

### Hydrogen enrichment

Hydrogen addition to another primary fuel (hydrogen enrichment) eliminates many of the drawbacks of utilizing hydrogen as an energy carrier. Addition of hydrogen in small to moderate amounts with other fuels, such as alcohols, gasoline, or natural gas allows for the following when compared to pure hydrogen operation:

- A reduction in pre-ignition caused by hot spots in the cylinder.
- Lower $NO_x$ emissions and more efficient engine operation without severe power decreases seen in pure hydrogen engines.
- Smaller quantities of hydrogen needed for similar combustion enhancement, reducing either the hydrogen storage tank size or weight or reducing reformer size and complexity.
- Less energy losses from hydrogen production due to lower hydrogen demand.

Hydrogen enrichment, the addition of small amounts of hydrogen, has been shown to enable lean or dilute