HHO and Diesel Technology

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Abstract

Background: HHO is a mixture of hydrogen and oxygen gas produced by water electrolysis that is purported to increase efficiency of internal combustion engines when fed into the air intake. Available data indicates that this is true. This report attempts to determine whether HHO gas injection can serve as a cost-effective method for reducing vehicle fuel costs.

Methods: The results of eight investigations are analyzed. In all studies, the method of determining the effect of HHO on fuel consumption is roughly the same. Fuel consumption of a Diesel engine on a dynamometer test stand is measured at different HHO gas feed rates. In this way, tests are performed under a relatively controlled set of conditions.

Results: The additional amount of energy produced per mass units of hydrogen gas was calculated at various speeds and loads. This determination, called a yield value, was useful for comparing results against various thresholds. A yield of approximately 9 megajoules per gram of H_2 is needed for cost effective reduction of vehicle fuel costs. Only three of the eight investigations met this requirement.

Conclusions: A restricted HHO feed rate was one factor common to the three investigations with higher yield values. A wet cell reactor of similar design was also used. The issue of whether there might be some variability in the composition of the HHO gas itself is also addressed.

Practical Implications: Yield values for some of these studies probably do not exceed an economic break even point. Thus, they should *not* be used to indicate that HHO injection can serve as a cost effective technology for reduction of vehicle fuel costs. Also, the studies that do indicate a cost effective fuel cost reduction are not found in peer reviewed literature. The validation and development of HHO technology requires much more data of better quality. It also requires better evaluation of this data.

Key Words: Brown's gas, oxyhydrogen, HHO, diesel, fuel efficiency, fuel consumption

Background.

Because of its energy efficiency and widespread fuel availability, Diesel technology serves as the primary power source used for surface transportation of bulk, freight and containerized cargo. Therefore, the surface network of the global logistics system is powered largely by Diesel technology. It also powers the majority of industrial construction, agricultural and mining equipment.

HHO gas injection is a a largely undeveloped technology that could very possibly be used to increase efficiency of Diesel technology resulting in billions of dollars in reduced fuel costs. In this study, we shall evaluate available data obtained from laboratory tests of the effect of HHO on Diesel engine efficiency to determine how effective HHO injection might be for reducing vehicle fuel costs. The application used to calculate a performance threshold for cost effectiveness shall be a Class 8 truck or "semi" traveling over 100,000 miles per year.

Methods.

Brake-Specific Fuel Consumption.

A laboratory evaluation of the effect of HHO gas injection on fuel consumption requires a very specific definition of fuel consumption. Brake specific fuel consumption (BSFC) is expressed in units of grams per kilowatt hour (g/kW hr) or in the US, pounds per horsepower hour (lbs / hp hr). A typical BSFC value for a Diesel engine is 0.35 lbs / hp hr. [1] As the name implies, BSFC is specific to engine load. The engine is set on a dynamometer test stand that applies a load to the engine and regulates the speed. Engine load in horsepower is given by the equation:

$$\frac{RPM \times torque}{5252.113} = brake\, horsepower \qquad (1)$$

where RPM is engine speed in revolutions per minute and torque is output torque of the engine measured in foot pounds. The exact value for the denominator of the horsepower equation is $220 \times 150 \div 2\pi$ which comes from the observation of James Watt that a mine pony harnessed to a winch could haul 150 lbs. up a mine shaft at 220 feet per minute.

The quantity of fuel is given as weight as opposed to volume. The amount of fuel in a unit of volume varies with density which is affected by temperature. Also, weight can generally be measured more precisely. A common procedure is to measure the weight of the fuel container before and after a timed test run and calculate the difference.

Evaluations.

The evaluations analyzed were published either in peer-review literature or on-line.[1] All analysis was performed using Open Office 3.3 spread sheet functions. These spread sheets can be found on-line at hho-research.org . In some cases, data was given in tabular form and could be copy/pasted into the spread sheet. In other cases, data was presented as a graph, in which case, pixel positions of the data points were used to calculate the value of the data point. Modified images can be found on-line at hho-research.org .

The types of engine and test conditions for each study are listed as follows:

- Yilmaz [2, 10] Engine: Four-stroke, four cylinder, direct injection with glow plug, 3.57 L, HHO reactor: specially made parallel plate type. Flow rate: 4 lpm.

- Milen and Kiril Engine: [3] Single cylinder, 98 mm bore, 130 mm stroke, direct injection. HHO reactor: not specified. Flow rate: 4 lpm.

- Purdue University [4] Engine: 4.5 L John Deere tractor engine. HHO reactor: Commercially available SS-20. Flow rate: Approx. 2 lpm.

- Fox Valley Technical College [5] Engine: Caterpillar C15 turbocharged truck engine. HHO reactor: Commercially available SS-40. Flow rate: approx. 4 lpm. Estimate based on measured reactor current and reactor specifications.

- Univ. of Northwest Ohio [6] Engine: 2004 Detroit Diesel 14 L Series 60 truck engine, 515 hp capacity. HHO reactor; Commercially available SS-40. Flow rate: Approx. 4 lpm. Estimate based on 32 amp and 46 amp supplied by a current regulator and reactor specifications.

- Bari and Esmaeil [7] Engine: Direct injection, 4 cylinder, 4.009 L. HHO reactor: Epoch EP-500. Flow rate: 10-60 lpm.

- Wang, et. al. [8] Engine: Cummins B5.9-160, six-cylinder four strokes, direct injection, 5.88 L HHO reactor: Epoch 560A. Flow rate: 10-60 lpm.

- Birtas, et.al., [9] Direct injection, 4 cylinder in line. 3.76 L tractor engine. HHO reactor: not specified. Flow rate: 0.111 to 0.153 kg/hr.

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[1] In the case of the on-line studies, both Univ. of Northwest Ohio and Fox Valley Technical College were contacted by email and they did confirm that such evaluations were actually performed. The Purdue study was a student project and could not be confirmed because of privacy policies.

Flow Rate Measurement.

Measurement of HHO gas flow rate is relevant to this analysis. A mass flow measurement is preferred since a volume measurement is affected by pressure and temperature. Mass flow measurement was used in only one of the investigations. Grams of hydrogen were estimated for the other studies assuming 760 mm Hg pressure and 298 degrees Kelvin temperature using the ideal gas equation and assuming an average molecular weight of 12 amu. Although this is an approximation, any error introduced would be comparatively small and could not account for the disparity of results obtained by this analysis. In one investigation [11] average molecular weight of HHO was found to be 12.3 amu. The study states that the same value was obtained for 2 different samples at the Adsorption Research Laboratory, Dublin Ohio on June 30, 2003 although it does not state the method used to make the measurements. In future investigations, a precise measurement of the rate at which water is used by the HHO reactor as well as measurements of relatively humidity, pressure, temperature and volumetric flow rate might be used to estimate mass flow and the average molecular weight of the gas.

Calculations.

The equation used for the energy yield value when the dynamometer test stand had a regulated load capability is given by:

$$\frac{E}{m_g}\,[1-r] \;=\; energy\,yield \tag{2}$$

where E is total energy produced in a unit time period in mega joules (MJ), m_g is grams of hydrogen (H_2) injected during the same time period and r is a dimensionless ratio equivalent to $\frac{m_1}{m_2}$ where m_1 is the mass flow rate of fuel with gas injection and $m_2$is the mass flow rate of fuel without HHO gas injection.

In some cases, the dynamometer load was adjustable and measured but it did not have a feedback loop to regulate it. In that case, yield value is given as:

$$\frac{E_{avg}}{m_g}\,[1-k\,r] \;=\; energy\,yield \tag{3}$$

where k is a dimensionless correction ratio equivalent to $\frac{E_2}{E_1}$ where E_1 is energy output with gas injection, E_2 is energy output without gas injection and E_{avg} is the average of E_1 and E_2 at a given engine speed. This is generally acceptable if E_1 and E_2 are close enough together. In all cases, engine speed is regulated by an automatic feedback loop. These Eqns. 2 and 3 are derived in Appendix A.

Study	**Average**	**Max.**
Bari [7]	0.081	0.257
Birtas [9]	0.034	0.042
Milen [3]	0.149	0.233
FVTC [4]	6.545	13.263
Purdue [5]	2.639	12.415
UNOH [6]	6.529	19.797
Wang [8]	0.034	0.044
Yilmaz [10, 2]	0.541	1.054

Table 1: Energy yields (MJ/grams H_2)

Results.

Table 1 gives average and maximum energy yield value estimates for the various evaluations. Eqn. 3 was used to estimate yields for the Milen, FVTC, and Yilmaz studies. Eqn. 2 was used for the rest.)

There is an implied protocol here that the test with and without HHO injection should be run under the same conditions, namely engine speed and load. If the test conditions are substantially different, then fuel consumption measurements are meaningless since fuel consumption is affected mostly by engine speed and load. In fact, it is common to create maps of BSFC as a function of engine speed and load. These diagrams always show a great deal of variation in the BSFC over the mapped range of speed and load.

Particularly in the case of the studies done by Milen and Yilmaz, the authors apparently did not understand the need for such a protocol. With these studies, it was necessary to correlate two different tables, one for speed and one for load. It is not entirely clear that the tables were necessarily correspondent.

However, it had to be assumed that they were in order to do the calculation. Regardless, the yields were rather meager and there is no reason to suppose that better testing would have had much of an effect on the results.

Discussion of results.

Break even values.

Yield values can be compared break even values. The practical break even value is the amount of yield needed to exceed the total amount of energy needed to generate a gram of hydrogen. The heat of combustion of hydrogen is 0.118 MJ/gram. The SS-40 HHO reactor used for the FVTC and UNOH studies is about 70% efficient. An automotive alternator is about 55% efficient. So there is a practical break even value of 0.31 MJ/gram = 0.118 / (0.7 x 0.55).

An economic break even value is the amount of yield needed to cost justify use of the HHO injection technology. This is a more complex value. Cost of installation of the technology, type of vehicle, fuel cost, vehicle use conditions and required pay back period should all be identified. A typical set of inputs might be:

- **Installation cost**: High end HHO injection system labor and parts = 5,000 USD.
- **Vehicle:** Class 8 truck. Gross Vehicle Weight Rating = 33,000 lbs. Typical = 65,000 lbs.
- **Use conditions:** long haul. 100,000 miles per year. Typical mileage: 6 mpg or 0.167 gallons per mile. Average engine load: 200 Hp. or 520.5 MJ/hr. (200 x 723 x 3600)
- **Fuel type and cost:** No. 2 Diesel. 4.00 USD per gallon.
- **Pay back period:** 6 months

Total annual fuel cost would be 100,000 x 0.167 x 4 = 66,800 USD. This requires a 15% reduction in fuel costs since 0.15 x 66,800 = 10,000. Yield value is based on a fuel weight ratio so yield needed to achieve a 15% reduction of 520.5 MJ/hr would be 520.5 x 0.15 = 78 MJ. A feed rate of 8 grams of hydrogen per hour would require a yield of 9.76 MJ/gram. This is within the range of the SS-40 used in the FVTC and UNOH evaluations. It is also helpful that both these evaluations were performed on Diesel truck engines typically used in the example given here. This is a rather approximate estimate. More detailed modeling has been done indicating that a 30% reduction in fuel cost is perhaps possible. [12]

Yield values.

The range in the values listed in Table 1 is notable. A common characteristic of the high yield evaluations is a lower feed rate in comparison to the size of the engine, about 0.5 to 1 lpm per 100 hp of engine capacity. Such a large effect on engine performance in comparison to the small amount of gas injected suggests a free radical chain reaction mechanism that is perhaps similar to the effect of tetra ethyl lead on engine knocking in spark ignition engines. See Appendix B for further discussion of reasons why HHO increases the efficiency of Diesel engines.

A commonly held idea is that HHO is in some way different from a 2 to 1 molar mixture of molecular hydrogen and oxygen gases. This is suggest by the appearance of the flame of HHO (Fig. 1) [13] versus that of hydrogen (Fig. 2) [14] .

While a hydrogen flame is almost invisible, an HHO flame is brightly luminous. The difference is not easily explained by conventional factors such as contamination due to sodium or potassium electrolyte.

The presentation of the flame is subjective. However, it can be converted to data by means of a spectroscopic measurement which is a plot of light intensity as a function of its wavelength. It is generally obtained using an electronic spectrophotometer instrument. At this time, an HHO spectrograph is not available. Fig. 3 [15] shows a spectrograhic signature of a butane flame. This illustrates how various free radicals that form momentarily during combustion produces emission peaks at characteristic wavelengths. In the case of hydrocarbon combustion, the C_2 radical is particularly abundant.

The effect of HHO could be caused by radicals that are produced momentarily when HHO burns. The

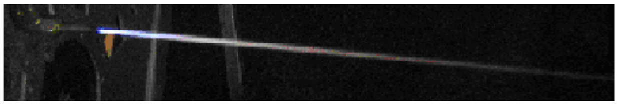

Figure 1: HHO flame

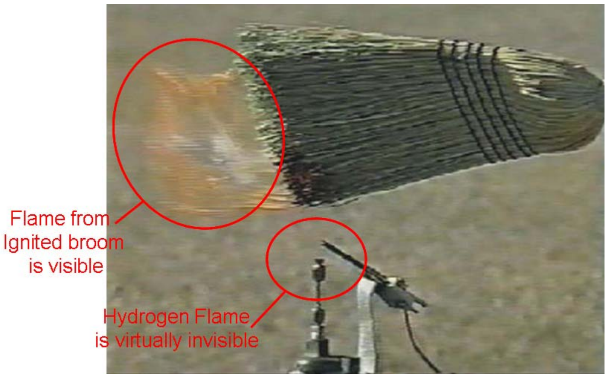

Figure 2: Conventional hydrogen flame

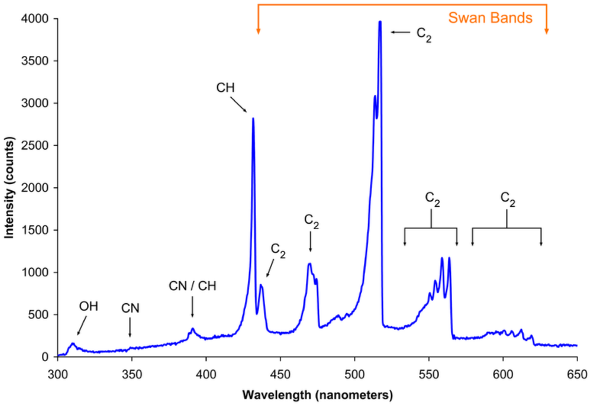

Figure 3: Flame spectrograph of a butane flame

concentration of these radicals could be measured by analyzing flame spectroscopic data. This might enable calculation of a baseline independent of engine performance that could be used to predict the strength of the effect of HHO on engine efficiency.

Conclusion.

This sort of analysis highlights the state of uncertainty regarding laboratory evaluation of the idea of HHO. To resolve these issues, engine lab evaluations of HHO might follow these guidelines:

- An investigation should be a diligent attempt to replicate the best results that have been obtained.
- There is a wide variety of configurations of reactors that are purported to produce HHO. If the effect of HHO on engine efficiency is the result of some product of the combustion of HHO, it is possible that this factor can be identified and quantified by means of flame spectroscopy. Then all of the variability associated with reactor operation can be reduced down to a few variables or perhaps one variable. It would also be important that this factor remains constant for each series of tests.
- Mass flow rate of HHO should be measured. The issue of the average molecular weight of HHO should also be investigated further. For most types of mass flow measurement of gas, average molecular weight is a relevant variable.
- Test conditions include load and speed. Load on the engine should be regulated by means of a feed back control loop. Effective compression ratio should also be included among test conditions. Most Diesels for vehicles are turbocharged. By carefully offsetting the turbocharger waste gate actuator, effective compression ratio can be adjusted.
- By means of combustion pressure analysis, engineers can essentially see what is going on inside

the cylinder through the course of the compression/power stroke. Almost none of this sort of work has been done with HHO but it could be very helpful in developing a mathematical model of the effect of HHO on the Diesel engine cycle. This could be helpful in improving the performance and flexibility of HHO technology.

References

[1] Dempsey, P.; *Troubleshooting and Repairing Diesel Engines.* Pg. 18, ISBN: 978-0-07-149371-0.

[2] Yilmaz, A.C.; Uludamar, E.; Aydin, K.; *Effect of hydroxy (HHO) gas addition on performance and exhaust emissions in compression ignition engines.* International Journal of Hydrogen Energy, Vol. 35, Issue 20, Oct. 2010, Pgs. 11366-11372. See files: yilmaz_fig3_4.xls, yilmaz_fig3.png, yilmaz_fig4.png.

[3] Milen, M; Kiril, B; *Investigation of the effects of hydrogen addition on performance and exhaust emissions of diesel engine*, FISITA 2004, World Automotive Congress. See files: milen_fig7_8.xls, milen_fig7.png, milen_fig8.png.

[4] Purdue University evaluation. See file: purdue.xls

[5] Fox Valley Technical College evaluation. See file: fvtc1.xls

[6] Univ. of Northwest Ohio evaluation. See files: unoh.xls and unoh.png

[7] Bari, S.; Esmaeil, M.; *Effect of H2/O2 addition in increasing thermal efficiency of Diesel engine.* Fuel, vol. 89, pgs. 378-383. See files: bari_fig4.xls, bari_fig4.png.

[8] Wang H-K.; et. al., *Effect of regulated harmful matters from a heavy-duty Diesel engine by H2/O2 addition to the combustion chamber.* Fuel (2012), Vol. 93 pgs. 524-527. See files: wang_fig3.xls, wang_fig3.png.

[9] Birtas, A.; et. al., *Effects of Air-Hydrogen Induction on Performance and Combustion of a Diesel Engine.* SAE Paper 2011-24-0094.

[10] Yilmaz, A. C.; *Design and Applications of Hydroxy (HHO) Systems*

[11] Santilli, R. M.; *A new gaseous and combustible form of water.* Hydrogen Energy, Vol. 31, (2006) Pgs. 1113-1128.

[12] Ware, C.; *Optimized HHO injection for Class 8 Diesel Vehicles.* wp14.pdf

[13] Prisecaru, T., et. al.; *Experimental validation of an HHO gas cutting flame CFD model.* 9th International Conference on Quantitative InfraRed Thermography. Politehnica University of Bucharest, Romania

[14] Simon, J. M., et. al.; *Guidelines for use of hydrogen fuel in commercial vehicles.* Pg.23 *Dept. of Transportation document*

[15] wikipedia image. Spectrum_of_blue_flame.png

[16] Petchers, N., *Combined Heating, Cooling & Power Handbook: Technologies & Applications*, Fairmont Press, ISBN 0-88173-433-0, pg. 350, Table 17-2.

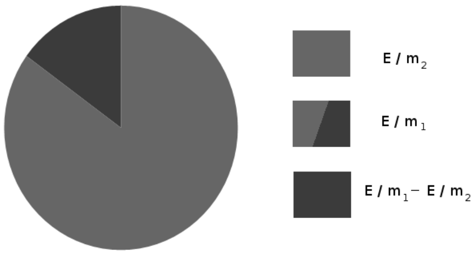

Figure A.1: Yield energy

Appendix A

Total energy is given as power multiplied by time, in this case, the time interval of the test run. With or without gas injection, the total amount of energy produced is the same since load and speed should be the same for both tests. The additional energy produced is actually the amount produced by a quantity of fuel. That is defined by the equation:

$$\frac{E}{m_1} - \frac{E}{m_2} \tag{A.1}$$

where E is the amount of energy produced within the time interval, m_1 is the mass of fuel used with HHO injection and m_2 is the mass of fuel used without HHO injection. The relationship can be visualized in Figure A1. The total area of the circle is proportional to $\frac{E}{m_1}$. The area of the lighter gray is proportional to $\frac{E}{m_2}$. Therefore, the area of the darker wedge would be proportional to the difference $\frac{E}{m_1} - \frac{E}{m_2}$ which is the additional amount of energy produced.

The fraction of the total area that the darker wedge occupies is necessarily the area of the difference divided by the total area of the circle. This fraction would be:

$$\frac{\frac{E}{m_1} - \frac{E}{m_2}}{\frac{E}{m_1}} \tag{A.2}$$

The E term cancels out of Eqn. A2. Also, the two terms in the numerator when multiplied by m_1 give:

$$1 - \frac{m_1}{m_2} \tag{A.3}$$

The total amount of energy produced per gram of hydrogen would be $\frac{E}{m_g}$ where m_g is grams of hydrogen gas injected during the time interval. The additional amount of energy produced would be this quantity times the proportion given by Eqn. A3 thus giving Eqn. 2:

$$\frac{E}{m_g}\left[1 - \frac{m_1}{m_2}\right] = \textit{energy yield} \tag{A.4}$$

In the case where the amount of energy produced with and without HHO is slightly different, such that $E_1$is the amount of energy produced with HHO and $E_2$is the amount of energy produced without HHO, the values $m_1$and $m_2$should be adjusted to what they would be if total energy produced is E_{avg} which equals $(E_1{+}E_2)$ / 2. Assume that the mass of fuel used is proportional to the energy produced within the interval between $E_1$and E_2. To set the m value to what it would be if the E value was equal to E_{avg}, we would have to increase m if $E < E_{avg}$ and decrease m if $E > E_{avg}$. The adjustment would have to be inversely proportional to E so it would be $\frac{E_{avg}}{E}$. The adjustment for $\frac{m_1}{m_2}$ would be $\frac{E_{avg}}{E_1}$ / $\frac{E_{avg}}{E_2}$ which factors out as $\frac{E_2}{E_1}$ or the correction factor k given in Eqn. 3.

Appendix B.

Various reasons are commonly given as to why HHO increases Diesel engine efficiency. In this discussion, an increase in combustion efficiency shall be discounted because this explanation is not consistent with laboratory data.

Combustion efficiency is sometimes confused with fuel conversion efficiency so the first task will be to define these terms. Combustion efficiency is the fraction of energy latent in the fuel that is released by combustion. For Diesel engines, combustion efficiency is generally better than 98% as will be calculated below based on typical emissions data.

Fuel conversion efficiency is the fraction of energy latent in the fuel that is converted to useful mechanical output of the engine. It is typically about 35%. Much of the heat released by combustion is lost by conduction to the engine block or through the exhaust gas. Fuel conversion efficiency is a subset of combustion efficiency.

Table B1 [16] gives values needed to determine combustion efficiency. The three emissions components found in Diesel exhaust that contain carbon are particulate carbon (soot), carbon monoxide, and hydrocarbon (principally methane).

On this table, MJ per MJ of input from fuel is obtained by multiplying the heat of combustion of the emissions component (MJ/gram) by grams per MJ input. These quantities for each component are summed to obtain the E_c , the amount of energy contained in emissions components per MJ of fuel energy. Combustion efficiency is given by:

$$\eta_c = 1 - E_c \tag{B.1}$$

where η_c is combustion efficiency. This value is approximately 0.98 or 98%. HHO injection reduces emissions by about 10% [6]. Even if it reduced them to nothing, the fuel conversion efficiency could be increased by no more than 0.6% (2% increase in combustion efficiency x 0.3 fuel conversion efficiency). The file unoh.xls indicates an average increase in fuel conversion efficiency of 11% which could not be accounted for by an increase in combustion efficiency.

It may be possible to arrive at an explanation for the HHO effect by means of combustion pressure analysis. Almost no combustion pressure analysis has been done with HHO. Milen and Kiril [3] obtained a single plot of pressure versus volume with and without HHO at 1500 RPM.

Emissions component	**MJ/g**	**per MJ of input**	
		grams	**MJ**
Carbon (soot)	0.032808	0.09	0.00295272
carbon monoxide	0.010112	0.05	0.0005056
Hydrocarbon (methane)	0.050009	0.16	0.00800144
total MJ per MJ input (E_c)			0.01145976

Table B.1: Diesel emissions components