

Possible Influences on Fuel Consumption Calculations while using the Hydrogen-Balance Method

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ABSTRACT

The Hydrogen-Balance equation makes it possible to calculate the fuel economy or fuel consumption of hydrogen powered vehicles simply by analyzing exhaust emissions. While the benefits of such a method are apparent, it is important to discuss possible influencing factors that may decrease Hydrogen-Balance accuracy. Measuring vehicle exhaust emissions is done with a CVS (Constant Volume Sampling) system. While the CVS system has proven itself both robust and precise over the years, utilizing it for hydrogen applications requires extra caution to retain measurement accuracy. Consideration should be given to all testing equipment, as well as the vehicle being tested. Certain environmental factors may also play a role not just in Hydrogen-Balance accuracy, but as also in other low emission testing accuracy.

INTRODUCTION

The Hydrogen-Balance equation was introduced in SAE 2008-01-1036, and is used to calculate fuel consumption or fuel economy of hydrogen fueled vehicles. The equation uses conservation of mass to determine the amount of fuel consumed by measuring the exhaust emissions. Hydrogen is chemically combined with oxygen from the air creating energy and water as an exhaust byproduct. By measuring the exhaust for water content, the fuel consumption can be calculated. In addition to water, small amounts of unburned or uncombined hydrogen may be present. This must also be taken into account for fuel consumption even though, in most cases, the concentrations are extremely low.

BMW has developed and built hydrogen ICE (Internal Combustion Engine) vehicles since the 1970's. Technology has progressed over the years resulting in the most current version of the vehicle named the BMW Hydrogen7 [1]. Based on the 7series, the Hydrogen7 uses gaseous hydrogen supplied by a cryogenic liquid fuel tank. This system stores large amounts of hydrogen as a liquid and also supplies the engine with gaseous hydrogen. The cryogenic system, however, makes an external fuel supply for fuel consumption testing all but impossible [2]. A simplified testing method that left the stock fuel supply system intact was needed for

Hydrogen7 testing. The Hydrogen-Balance equation and procedures were borne out of this necessity and now promise fuel consumption measurements on any type of hydrogen powered vehicle without modifications.

Hydrogen-Balance is more than just a solution to a BMW specific problem. It is a method that has the accuracy and repeatability to be the preferred industry wide method for fuel consumption testing. For the equation and procedures to be accepted, however, the topic must be explored further. This report presents possible influences on fuel consumption when using the CVS system on a roller-type chassis dynamometer, it also addresses issues present when measuring "almost zero" emissions. The testing environment creates possible measurement errors because of water content present in the test cell and dilution air. In some cases the motor and exhaust system can affect test repeatability and accuracy. The CVS system must also be closely examined to be sure that no water content in the exhaust is lost or affected along the way to be tested. In addition some analyzers have been known to exhibit some cross-sensitivity to water in the exhaust.

VEHICLE SIDE INFLUENCES

EXHAUST SYSTEM

The vehicle exhaust system presents a possible problem during cold starts. It is during this time that the cold metal exhaust system creates condensation that results in water loss. The water is not really lost; however, as it will be turned back into steam when the exhaust heats up and any errors will therefore be corrected. This assumption can be checked with exhaust temperature measurements. When the tailpipe exhaust temperature is greater than 100°C, then it can be assumed that the temperature in the exhaust system can only be higher, and only water vapor can exist in the system. The measurements are therefore not dependant on the initial water content of the exhaust.

A NiCr-Ni temperature sensor was used to measure the exhaust temperature at the tailpipe of the Hydrogen7. The temperature measurements for an EU tests can be seen in figure 1.

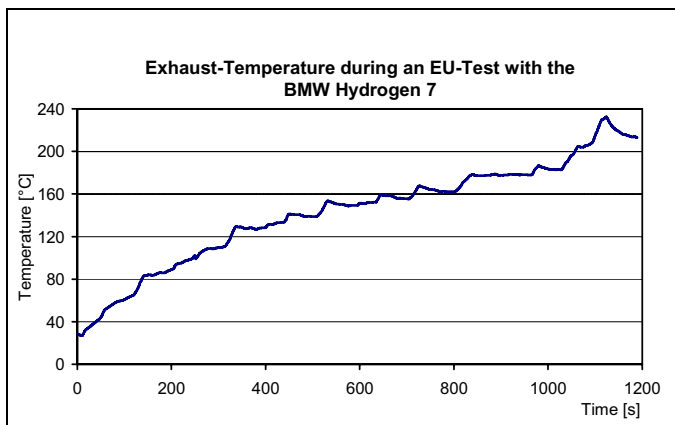


Figure 1: Exhaust temperature during EU emission test

The temperature during the test starts at around 30°C. At $t = 270\text{sec}$, the exhaust temperature reaches 100°C. Before $t = 270\text{sec}$ it is possible that there is still water condensation inside the exhaust. At the end of the test, the exhaust reaches a maximum of 225°C at $t = 1140\text{sec}$. The measurements show that any water condensation initially present in the exhaust system was turned into steam after $t = 270\text{sec}$. With this, it is safe to say any error coming from initial condensation in the exhaust system is adequately corrected later in the test and it can also be assumed that this conclusion is valid for all other test cycles and procedures. Additionally, second-by-second data validates the conservation of mass, as it can be seen in the developing of values on an UDDS cold and hot start in comparison, figure 2. This is most obvious looking at the second hill of UDDS where water peaks with the UDDS cycle speed.

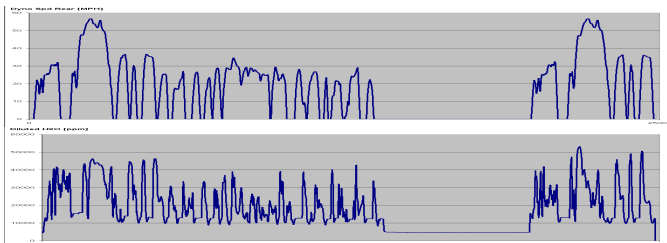


Figure 2: Second-by-second dilute water during UDDS emission test



Figure 3: Heated connection tailpipe to CVS

To avoid any other undefined water loss BMW uses flexible heated ($>90^\circ\text{C}$) lines from the tailpipe to the CVS

and the heated inner mixing T. Figure 3 shows two lines, one for each exhaust tip if necessary.

It is necessary to note that the dew point for a Lambda 1 mixture is 79°C . This means that water content at the tailpipe is 35 Vol-% (see also appendix 1).

CRANKCASE VENTILATION

Crankcase ventilation occurs when gas from the crankcase is pumped into the engine air intake. This happens when sufficient pressure in the crankcase opens a valve allowing the exit of gasses to the motor intake. This gas from the crankcase contains water vapor from the cylinders that made it past the cylinder rings. The crankcase gas is not measured since it does not pass through the exhaust, but rather bypasses all measuring devices and goes directly into the air intake. Blow-by measurements found that at $\text{Lambda} < 2$, the gas in the crankcase was around 6-7% water by volume.

The actual concentration of water in the crankcase will be smaller than this, however, since the engine runs predominantly at a $\text{lambda} > 2$. In the end, the influence from Crankcase ventilation can be neglected. Measurements on an engine dynamometer under stationary conditions determined the exhaust water concentration content dwarfed the amount of water lost to, or coming from the crankcase [3].

Figure 4 displays the exhaust track and measurement system. Every component of the system must be explored for possible measurement error.

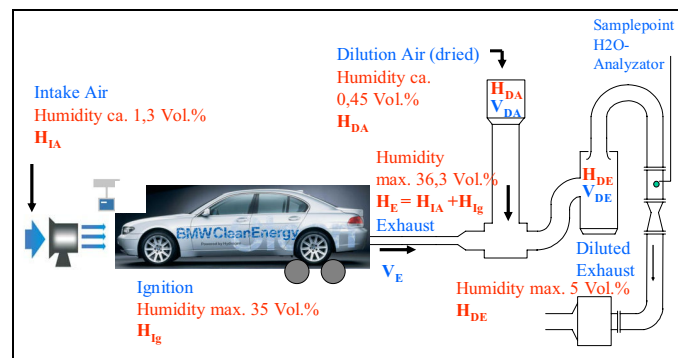


Figure 4: Principal of CVS-water-mass-balance

TEST CELL INFLUENCES

Since water is the most important factor in fuel consumption calculations, the amount of humidity in the test cell can have an influence on measurement accuracy. The test cell air is not usually conditioned for water content, and whether dry or humid, all of the water taken into the motor will exit as exhaust. Dried dilution air with its own humidity, is then mixed into the exhaust. To accurately calculate fuel consumption, water content of the intake air and dilution air must be measured and should stay constant over the test time.

THE DRYER

The dryer delivers dried dilution air to the system and therefore may influence the measured fuel consumption. This was explored during a hydrogen vehicle test on one of BMW's test stands. The water content in the air was sampled before and after going through the dryer. The preconditioned air was measured in a few spots in order to test the humidity. Figure 5 shows the dryer with intake and exit pipes as well as the placement of measurement devices.

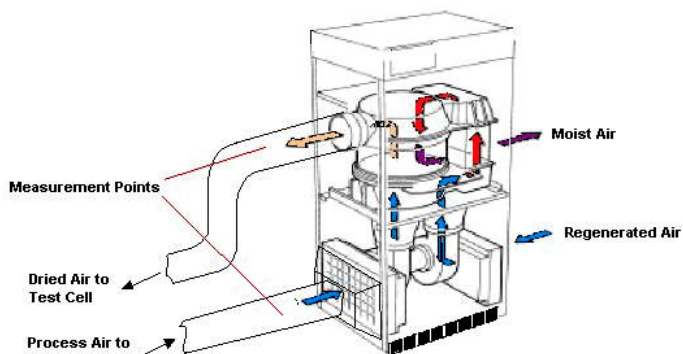


Figure 5: Dryer with piping and measurement points

Essentially, the dryer takes air from the test cell, dries it, and then returns the air to the dilution system at a higher temperature. The dryer uses test cell air because it is conditioned and assumed to be reasonably stable. The dryer is capable drying minimum 1100 cubic meters of air in an hour. If the air in the test cell has an initial specific humidity of 8 g/kg, when dried, it will be less than 2.5 g/kg. This means the dilution air humidity is dependant on the initial humidity and temperature of the test cell air. The following figure 6 shows an example of how the air at the induction point is related to the exit air at maximum delivery rate.

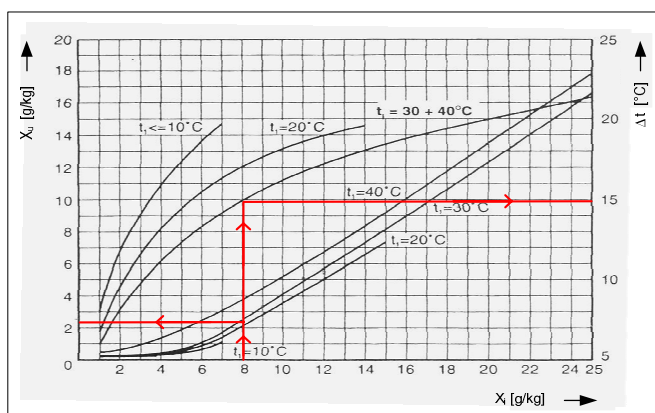


Figure 6: Calculating the maximum humidity of the dryer air

When drawing a line on figure 6 from the humidity in the test cell, 8 g/kg, to the curve corresponding to the cell temperature of 28°C, then the dried air is shown to be 2.5 g/kg. With this information, the line drawn from 8 g/kg starting humidity can be extended to the $t_w = 30+40^\circ\text{C}$ curve. This point of intersection corresponds to

a change in temperature of 15°C. Drying results in an air temperature of around 43-45°C. This is the amount of change that will be seen in the dryer air exit temperature, initially 28°C.

TEST AND MEASUREMENT RESULTS

The tests were completed with two capacity humidity sensors with integrated temperature sensors. The temperature was measured with NiCr-Ni thermo elements. The humidity sensors were connected to a data logger in a laptop that uses an "AMR-Control" program. The accuracy of the humidity sensors was within $\pm 2\%\text{RH}$, while the temperature was within $\pm 0.1^\circ\text{C}$. The measurements started about 15 minutes before the test and continued 10 minutes after. Figure 7 shows the entrance and exit temperatures for the dryer. The test cell and dryer intake air was at a temperature of 26.5°C before the test and held steady until the start of the test. After the start of the test, the temperature rose to an initial high of 27.5°C and at the very end climbed to a value of 31°C. This temperature data looks somewhat similar to the EU test cycle, the speed climbs ever higher at the end, much like the temperature in this example.

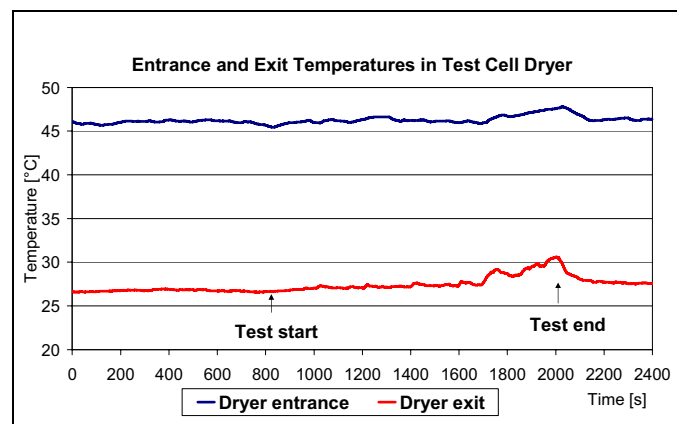


Figure 7: Dryer entrance and exit temperature during an EU test

The exit temperature of the dryer was initially 46°C, which fits well with the estimated range of 43-45°C seen earlier in figure 6. There was not much temperature change in the dryer air over the course of the test, rising to a maximum of 48°C at the end of the test. The time delay between maximum temperatures of the dryer inlet and outlet was 24 seconds.

During the course of the test, the incoming air had a humidity of between 8 and 9 g/kg, figure 8. In most cases the humidity stays constant during the test, however at the end of the test the water content fell from 8.8 g/kg to 8 g/kg.

The dried air coming from the dryer cycled from a specific humidity of 3 g/kg to 4.2 g/kg. The resulting data curve has a sinusoidal trend with maximum and minimum values coming in 300-second intervals. The highest value comes at $t \approx 2000$ sec. with a value of 4.2 g/kg. During the EU-tests the dryer delivered air with a humidity of between 3.1 g/kg and 4.2 g/kg. This is a deviation of 35% which is a result of the dryer having only so much drying capacity along with changing