Measuring Diesel Fuel Consumption to Estimate Engine Efficiency

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Prior to 2004 the cost of farm diesel for pumping, which had hovered around a dollar per gallon for years, was an accepted part of conducting irrigation business, and in may localities where ground water was shallow, was inconsequential. However, in 2004 energy prices started rising drastically and then the following summer, as it appeared that prices might be starting back down, Hurricane Katrina hit the Gulf Coast sending prices to record levels. At that time irrigators faced diesel and propane costs four times greater than they had experienced before. This increase in the cost of diesel led to renewed interest in conducting efficiency evaluations on diesel pumping plants.

Evaluating Diesel Pumping Plant Efficiency

An efficiency test for a diesel irrigation pumping plant compares the unit’s generated water horsepower (power-out) to the rate that diesel is being consumed (power-in). Equation 1 defines water horsepower (WHP).

\[
WHP = \frac{Q(PWL + H_f + [2.31 \times OP])}{3960}
\]

Eq. 1

Where:

- \( WHP \) = Water Horsepower, HP
- \( Q \) = Flow rate, GPM
- \( PWL \) = Pumping Water Level, ft
- \( H_f \) = Sum of all Friction Losses, ft
- \( OP \) = Operating Pressure, PSI

The next step in evaluating diesel irrigation pumping plant efficiency is to ascertain power-in, i.e., diesel use rate \( (D_R) \). This pamphlet describes several methods for obtaining \( D_R \).

Measuring Diesel Rate of Consumption \( (D_R) \)

The easiest way to measure the rate of fuel use \( (D_R) \) of a diesel engine occurs in the cases where the engine already has a built-in fuel use meter. These meters provide an immediate answer to the power-in question and thus afford quick solutions to the answers of economic what-if questions: What RPM should I run at to fill up my reservoir? I have four pivots in a network, and always irrigate two at one time— which ones should I pair together? See Appendix I to see how these built-in meters can easily lead to money savings.\(^1\)

When built-in diesel flow meters are not available, there are several other ways that \( D_R \) can be measured.

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\(^1\) These built-ins, subject to constant engine vibration and the elements, should periodically be double-checked for accuracy by comparing results to timed volumetric changes in the fuel tank.
Graduated Cylinder Method

Instantaneous measurement of $D_R$ can be made with easy to find items. Materials needed include:

1. Graduated cylinder (or other device to measure volume).
2. A small container (e.g., 5-gal bucket) of diesel, comparable to that running in the tested engine.
3. A small standby container partially filled with diesel used between timed measurements.
4. A stop watch device.
5. Tools (wrenches) to disconnect the fuel line.

Figure 1 shows the equipment used in a diesel pump test where a graduated cylinder is used.

Modern diesel engines use a fuel delivery system that is comprised of both a fuel supply line and a return line. In diesel engines, a fuel pump provides fuel to an injector pump which then provides fuel to injectors. This process results in fuel being delivered at high pressure to the injectors; because of this high pressure, some fuel is returned to the supply due to rapid pressure changes in the fuel system and

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2 If an accurate container with graduated markings is not available, mark a START and STOP line on a container, calculate the container volume between the two lines, and then measure the time it takes for the diesel level to drop between these two points.
to cool the fuel system components. To properly measure fuel flow from a diesel engine the fuel flow from both the supply tank and the return system must be known.

Before getting started, explain to the owner that you will be temporarily disconnecting the fuel line from the fuel tank. Normally, this procedure does not cause a problem, but the process could allow air to get into the line, stalling the engine, and thus require bleeding the lines before the engine can be started back up. Make sure you are familiar with the workings of the engine you are about to test. Most diesel engines have a procedure for properly bleeding air from the fuel system, check with the owner and ensure they know the bleed procedure before proceeding. The procedure is often located in the owner’s manual.

Clean off the area around the fuel tank where the fuel line is connected, including the end of the fuel line so that contaminants will not get into the fuel supply. Have a small container (the standby reservoir) with diesel in it. After loosening the band or hose clamp holding the fuel line in place, quickly pull it loose, quickly putting your thumb on the hose end to prevent air entry, as you submerge the hose end into the diesel of the standby reservoir. Not that the overflow line also needs to be inserted into the standby reservoir.

Fill the graduated cylinder to its top mark. Set the engine to the desired speed. Then quickly transfer the end(s) of the fuel line(s) from the standby reservoir into the graduated cylinder filled with diesel and start your stop watch. Allow the engine to operate a set time, e.g., 3 or 5 minutes, giving yourself or your partner enough time to measure water flow rate, pumping water level, and outlet pressure. When the set time is reached, pull the fuel line(s) out of the graduated cylinder and return them to the standby reservoir. Carefully read the level of the diesel fuel remaining in the graduated cylinder. Record all measurements. During all of this be mindful that the standby reservoir is not pumped dry.

Calculating $D_R$ in units of gallons of diesel per hour (a unit that farmers will be familiar with) from the graduated cylinder test can be done by using Equation 2. Example 1 shows how $D_R$ is calculated based on ml of diesel used during a set number of minutes.

$$
D_R = \frac{\left[ D_S - D_E \right]}{3785.4} \frac{T}{60}
$$

Where:

$D_R$ = diesel use rate, gallons per hour
$D_S$ = amount of diesel in graduated cylinder at start of test, ml
$D_E$ = amount of diesel in graduated cylinder at end of test, ml
$T$ = time, minutes
A gallon of #2 diesel contains 129,500 BTUs, equivalent to 50.88 HP/hour. Multiplying the hourly diesel use rate \( (D_R) \) by 50.88 HP/hr provides the fuel’s HP, and represents the equivalent horsepower per hour. Therefore, in Example 1, the equivalent horsepower is 90.32 HP/hr.

**Measuring Fuel Use in Bulk Volumes**

Another volumetric method can be used to calculate \( D_R \) by measuring gross changes in bulk volume over a longer period of time. A simple way to do this is by calculating the amount of fuel pumped during a set period. Do this by sounding the current surface level of diesel inside the tank with a clean stick; mark this level on the outside of the tank (also annotating the current hours on the engine’s cumulative hours gauge on the tank wall [fig. 2]). Return to the site in several days. Re-record the diesel level and the new hours of operation.

**EXAMPLE 2**

- Amount of diesel in graduated cylinder at start \( (D_S) = 2000 \text{ ml} \)
- Amount of diesel in graduated cylinder at end \( (D_E) = 1440 \text{ ml} \)
- Time of test = 5.00 minutes

\[
D_R = \left( \frac{D_S - D_E}{3785.4} \right) \left( \frac{T}{60} \right) = \left( \frac{2000 - 1440}{3785.4} \right) \left( \frac{5.00}{60} \right) = 1.78 \text{ gals/hr}
\]

A gallon of #2 diesel contains 129,500 BTUs, equivalent to 50.88 HP/hour. Multiplying the hourly diesel use rate \( (D_R) \) by 50.88 HP/hr provides the fuel’s HP, and represents the equivalent horsepower per hour. Therefore, in Example 1, the equivalent horsepower is 90.32 HP/hr.
Diesel tanks are often horizontal cylinders without graduated markings, so figure 3 can be used to help calculate the gallons of diesel inside the tank based on tank length, diameter, and the depth to fuel surface. The value \( a/A \) in figure 3 represents the percentage that \( a \) (the submerged cross-sectional area) is relative to \( A \) (the total cross-sectional area of the tank’s side); c.f., embedded graphic in figure 3. The value \( d/D \) in figure 3 represents the percentage that \( d \) (the actual depth of diesel in the tank) is relative to \( D \) (tank diameter). To obtain the value of \( a/A \) draw a line vertically through the point \( d/D \) to where it transects the curved line; then draw a line back horizontally to find the value of \( a/A \). For example, if the diameter of the tank \( (D) \) is 36 inches and the depth of diesel in the tank \( (d) \) is 7.2 inches then \( d/D \) is 0.20 and \( a/A \) is 0.15.\(^3\)

The quantity of diesel in gallons inside a horizontal tank at any sounding is given by equation 3.

\[
Gals = \frac{a}{A} \times 181.4 \times L \times D^2
\]

Eq. 3

Where:

\(^3\) The value of \( a/A \times 100 \) is the 5th the tank is full. Mathematically, the value of \( a/A \) is given by:

\[
\frac{a}{A} = 1.0038 \left( \frac{d}{D} \right)^3 - 1.5621 \left( \frac{d}{D} \right)^2 + 1.5366 \frac{d}{D}
\]
Gals = Volume of diesel in tank, gallons
L = Length of tank, inches
D = Diameter of tank, inches

The quantity of diesel used during the time period (∆ Gals) is then the difference in gallons as determined by equation 3 calculated at the end of the period versus what it was at the start of the period. To turn these volumetric amounts into $D_R$ merely divide the ∆ Gals by the additional clocked hours on the gauge since you first penciled down the original amount. Equation 4 calculates the diesel use rate ($D_u$) for this period.

$$D_R = \frac{181.4 L D^2 \left( \frac{[a/A]_E}{[a/A]_S} \right)}{T_E - T_S}$$

Eq. 4

Where:

[a/A]$_E$ = The value of a/A at the end.
[a/A]$_S$ = The value of a/A at the start.
$T_E$ = The hours on the gauge at the end, hrs.
$T_S$ = The hours on the gauge at the start, hrs.

Fig. 3. The relative wetted cross sectional area to the total cross sectional area based on the diameter of the tank and liquid level inside.
Note that while the bulk volume procedure above allows us to calculate the diesel use rate (power-in component), however, we are not able to make a pumping plant efficiency evaluation since the WHP (power-out) information is not available. To this end, both at the START and the END period information on Q, PWL, H_f, and OP should be collected and averaged for both dates. Ideally, the system would have its own built in water flow meter. Should this be the case, totalized gallons at START and END should also be recorded; use the information from the engine’s hours of use gauge to determine the average GPM during that period.

**EXAMPLE 2**

**Given:**
- Tank diameter (D) = 36 inches
- Length of tank (L) = 80 inches
- At the start:
  - depth from fuel surface to tank bottom (d_s) = 18.0 inches
  - Gauge hours (T_s) = 2328.0 hours
- At the end:
  - depth from fuel surface to tank bottom (d_e) = 7.2 inches
  - Gauge hours (T_e) = 2371.2 hours

**Then:**
- \([d/D]_s = 18.0 / 36.0 = 0.50 \rightarrow [a/A]_s = 0.50\) (Fig. 3)
- \([d/D]_e = 7.2 / 36.0 = 0.20 \rightarrow [a/A]_e = 0.15\) (Fig. 3)

\[
D_R = \frac{181.4 \cdot L \cdot D^2 \left( \frac{[a/A]_e}{[a/A]_s} - \frac{[a/A]_e}{[a/A]_s} \right)}{T_e - T_s} = \frac{181.4 \cdot 80 \cdot 36^2 (0.50 - 0.15)}{2371.2 - 2328.0}
\]

= 3.64 gph

**Note about the density of diesel fuel being used:** One small source of error comes from the change in specific gravity of diesel fuel with temperature changes. To adjust for the density of fuel during a test, a hydrometer can be used to measure the density of the fuel during the test. Alternatively, the temperature can be monitored during the test, and so long as the fuel temperature is the same or does not vary during the test, this source of error can be negated. Often on a cold day with a cold engine or during startup the fuel temperature can change as much as 60 degrees Fahrenheit, however, on a warm day with a warm engine the fuel temperature change can be kept to plus or minus 10 or 20 degrees Fahrenheit. This is a very small source of error, but is worth accounting for should tests be conducted where there are large changes in fuel temperature or a high degree of accuracy is sought. For most on-farm testing using the volume measurement technique, this is not worth the additional effort for the very small margin of improvement in accuracy.
Measuring Fuel Flow by Weight

Another method to measure diesel fuel flow ($D_R$) is by measuring the weight of fuel. This can be done with a load cell, a precision balance, or by weighing a fuel tank during the test (beginning and after test run). The methodology uses the same concept as the graduated cylinder, but this time the change in weight of fuel over time is measured. Load cells and balances should be calibrated. The advantage of measuring fuel flow by weight is that temperature does not impact the measurement of fuel. Bathroom scales or low quality scales should not be used because the precision is not likely to be adequate for a short term test.

As in the volumetric method, a time measurement is required. Equation 5 calculates $D_R$ using the weight method. Table 1 lists the weight of 1 US Gallon of diesel fuel with various units of mass.

\[
D_R = \left( \frac{W_S - W_E}{\text{Unit Conversion Value}} \right) \left( \frac{T}{60} \right)
\]

Eq. 5

Where:

- $D_R$ = diesel use rate, gallons per hour
- $W_S$ = weight of diesel in a container at start of test, a unit (Table 1)
- $W_E$ = weight of diesel in a container at end of test, a unit (Table 1)
- Unit Conversion Value = c.f., Table 1
- $T$ = time, minutes

<table>
<thead>
<tr>
<th>Unit of Volume</th>
<th>Unit of Weight</th>
<th>Ounces</th>
<th>Mg</th>
<th>Lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 US Gallon of Diesel</td>
<td></td>
<td>111</td>
<td>3,149</td>
<td>6.942</td>
</tr>
</tbody>
</table>

Table 1. Weight of 1 US Gallon of Diesel Fuel at 60 °Fahrenheit (15 °Celsius)
EXAMPLE 3

**Given:**
- A bucket containing diesel fuel weighs:
  - 2,555 mg at the start of the test
  - 1,722 mg at end of the test
- Test time was 6 minutes and 52 seconds (= 6.87 minutes)
- Since weighing units were mg, use 3,149 mg/gal of diesel as the unit conversion value (Table 1)

\[
D_R = \left( \frac{W_s - W_e}{\text{Unit Conversion Value}} \right) \times \left( \frac{T}{60} \right) = \left( \frac{2,555 - 1,722}{3,149 \text{ mg per gal}} \right) \times \left( \frac{5.87}{60} \right)
\]

= 2.70 gph

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Fig. 4. Diesel fuel by weight, using a load cell.
Measuring Fuel by Flow Meter

In addition to the volume and weight measurement methods, accurate flow meters are also a viable means to measure instantaneous diesel fuel flow. Diesel flow meters are portable, easily adapted to multiple diesel engines, allow for replicated intervals of testing without filling and emptying tanks, and provide a digital readout of total fuel flow or fuel flow rate. A diesel flow meter is a direct measurement device and is necessarily plumbed directly into the fuel delivery line to be effective.

Most better digital diesel fuel flow meters use a powered Hall Effect switch and a calibration setting to measure and display the fuel flow. The installation of a diesel flow meter requires the meter to be placed in the fuel line between the tank and the engine mounted fuel filter so that the fuel consumed by the engine will flow directly through the meter. This connection is commonly done using temporary rubber fuel hose and applicable threaded and barbed fittings. Diesel flow meters are directional, so it is necessary to orient the meter in relation to flow direction.

Diesel fuel flow meters usually have the option to display in a “rate” mode (gallons per hour, etc.) or the “totalizer” mode which totals the volume of fuel that has flown through the meter. In a very smooth flowing, stable system, the rate mode is useful since it displays an immediate value for fuel consumption rate. However, practice has shown that the rate mode is often inadequate in-field due to wide, varying swings in the recorded rates. The preferred method is to use the diesel flow meter in the totalizer mode for a determined period of time to absorb the swings in fuel consumption. Note that many of the engine mounted fuel flow meters will employ a wide range buffering factor to provide a steady flow rate. When performing tests with different RPMs or load settings, it is important to allow for the flow meter reading to stabilize prior to taking readings.
Modern diesel engines rely on fuel flow to cool and lubricate the fuel injection pump and, therefore, deliver much more fuel to the injection pump than necessary for engine operation. To maintain cool fuel, most on-farm diesel fuel systems “return” the excess fuel to the diesel tank to allow for maximized heat dissipation. The most successful method for managing the return flow when using a diesel fuel flow meter is to plumb a return flow loop between the diesel flow meter and the engine so that the diesel flow meter will be measuring the actual fuel that is being consumed by the engine. Experience has shown that fuel temperature will increase and stabilize during the test, presenting no adverse effects to the engine or testing procedure. The return loop flow does create somewhat of a pulse flow effect on the flow meter, so it is especially advisable to utilize a totalizer mode for the diesel flow meter over a period of five to ten minutes. It is also helpful to install the meter sufficiently far from the engine to buffer a larger portion of the return flow pulse.

The measured fuel consumption rate from a diesel flow meter can be used directly in Eq. 5 to calculate the overall efficiency of a diesel pumping plant or can be used in combination with a driveshaft torque cell to directly calculate engine efficiency.

Performing Multiple Tests

Now that the testing apparatus has been put in place on the engine, it is very easy to do additional evaluations of the pumping plant (fig. 6) to answer what-ifs: If the pump is running open discharge, what is the RPM with the cheapest water on a per acre-inch basis? If the water table drops, what will be the effect on flow rate and cost of water? The overall efficiency of diesel pumping plant entails balancing the performance of three items operating at the same time: the pump, the engine, and the drive linkage. Therefore, results can easily be obscured (especially when a dynamiter is not present to help isolate the performance of the individual components). Thus, a series of tests can help present a clearer picture of what is occurring, as was done with figure 6.

Calculating Diesel Pumping Plant Efficiency

Now that we have learned how to measure $D_R$ (power-in), the only thing left to calculate the diesel pumping plant efficiency is calculating the water horsepower ($power-out$). To read more about

Fig. 6. The average cost of an acre-inch of water from eight different diesel pumping plants being pumped open discharge at four different RPMs.

Different “virtual” drops in the water level can be simulated by applying system back pressure with a gate or butterfly valve; each PSI of additional back pressure is equivalent to 2.31 additional feet of lift.
water horsepower and pump evaluation, see the factsheets in this series entitled, \textit{Understanding Water Horsepower} and \textit{Understanding Water Horsepower}.

Data needed for an evaluation is shown in table 2, the efficiency equation for diesel units is seen in equation 5, and an example can be seen in Example 4.

\begin{table}[h]
\centering
\caption{Data required to perform a diesel pumping plant evaluation}
\begin{tabular}{|l|l|}
\hline
\textbf{Power-In} & \textbf{Power-Out} \\
\hline
Diesel Horsepower (HP) & Water-Horsepower (HP) \\
\hline
Diesel use rate (gals/hr) & Flow rate (GPM) \\
& Pumping Water Level (ft) \\
& Friction Loss (ft) \\
& Operating pressure (PSI) \\
\hline
\end{tabular}
\end{table}

The equation to calculate diesel pumping plant efficiency is shown in equation 5.

\[ Eff = \frac{WHP}{HP} \times 100 = \frac{Q \left( PWL + H_f + \left[2.31 \times OP \right]\right)}{3960} \times 100 \quad \text{Eq. 5} \]

Where:

\begin{itemize}
  \item \textbf{Eff} = Efficiency of diesel pumping plant, \% \\
  \item \textbf{WHP} = Water Horsepower, HP \\
  \item \textbf{HP} = Horsepower, HP \\
  \item \textbf{Q} = Flow rate, GPM \\
  \item \textbf{PWL} = Pumping Water Level, ft \\
  \item \textbf{H}_f = Total Friction Losses, ft \\
  \item \textbf{OP} = Operating Pressure, PSI
\end{itemize}

\begin{example}
\begin{itemize}
  \item Flow rate = 1,533 GPM \\
  \item PWL = 39 ft \\
  \item Friction Loss = 1.8 ft \\
  \item Operating Pressure = 8.0 PSI \\
  \item Diesel use rate = as in Example 1 (1.78 gph)
\end{itemize}

\[ Eff = \frac{Q \left( PWL + H_f + \left[2.31 \times OP \right]\right)}{3960} \times 100 = \frac{3960}{(50.88 \times D_R)} \times 100 = 23.7\% \]
\end{example}
What represents a good diesel pumping plant efficiency? The irrigation industry owes a debt of
grateful to the agricultural engineers of the University of Nebraska who pioneered the testing and
evaluation of irrigation pumping plants that helps us answer that question. Their program, the Nebraska
Pumping Plant Performance Criteria (NPPPC), is an offshoot of their 100-year tractor testing program.
NPPPC sets 24.5% as the touchstone value for diesel pumping plants using gearhead linkage. Therefore,
the diesel unit in Example 3 has a NPPPC value of 96.7%.

Summary

Diesel fuel consumption can be measured in many different ways. Care must be taken to
conduct the test safely. Bring the proper tools and know the air bleed procedure for the engine before
starting any test where fuel lines must be relocated. Select the method that achieves the level of
accuracy for the time and equipment that is available. Accuracy improves with time, but should be
balanced with equipment precision and the time available to conduct a pump test. Conducting the test
repeatedly over several points across the operating range of the engine allows for finding the most
efficient point to operate for the water delivered. Calculate efficiency by dividing water horsepower by
the energy available in the fuel.
Appendix I

Using Your Diesel Flow Meter to Save You Some Money

QUESTION 1 -- Filling up a Reservoir

What is the cheapest RPM to run at for filling up my reservoir? The following were the four tested RPMs, $D_R$s, fill times, and total gallons used:

<table>
<thead>
<tr>
<th>Fuel Use Rate ($D_R$)</th>
<th>Time Required</th>
<th>Gallons Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>@ 1250 RPM: 4.35 gph</td>
<td>22.4 hrs</td>
<td>97</td>
</tr>
<tr>
<td>@ 1350 RPM: 4.72 gph</td>
<td>18.5 hrs</td>
<td>87</td>
</tr>
<tr>
<td>@ 1450 RPM: 5.09 gph</td>
<td>15.6 hrs</td>
<td>79</td>
</tr>
<tr>
<td>@ 1550 RPM: 6.84 gph</td>
<td>12.7 hrs</td>
<td>87</td>
</tr>
</tbody>
</table>

Answer: Run at 1450 RPM

QUESTION 2 – Pairing Up Two Pivots to be Run at the Same Time

Assume there are four identical pivots in a network, and you always irrigate any two, two-at-a-time – which ones should you pair together? The diesel flow rates for the twelve possible general permutations are shown in the table below. However, once any two or paired up, there will remain only one other choice. Thus, in all only three options are available. Choose the option that has the average lowest flow rate.

**Possible general permutations:**

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>--</td>
<td>6.5</td>
<td>6.0</td>
<td>7.1</td>
</tr>
<tr>
<td>2</td>
<td>6.5</td>
<td>--</td>
<td>7.3</td>
<td>6.8</td>
</tr>
<tr>
<td>3</td>
<td>6.0</td>
<td>7.3</td>
<td>--</td>
<td>5.9</td>
</tr>
<tr>
<td>4</td>
<td>7.1</td>
<td>6.9</td>
<td>5.9</td>
<td>--</td>
</tr>
</tbody>
</table>

**Possible specific permutations:**

1 & 2 / 3 & 4 → 6.5 + 5.9 → Avg. 6.2 gph
1 & 3 / 2 & 4 → 6.0 + 6.8 → Avg. 6.5 gph
1 & 4 / 2 & 3 → 7.1 + 7.3 → Avg. 7.2 gph

Answer: Pair 1 & 2 together, and 3 & 4 together.