

# Impact of Ice Formation in Diesel Fuel on Tier 4 Off-Road Engine Performance with High Efficiency Fuel Filtration

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## ABSTRACT

The winter of 2013-2014 provided an opportunity to operate off-road vehicles in cold weather for extended time as part of a vehicle/tier 4 diesel engine validation program. An unexpected area of study was the performance of high efficiency, on engine, fuel filters during continuous vehicle operation in cold weather. During the program we observed unexpected premature fuel filter plugging as indicated by an increase in pressure drop across the filter while in service. Field and laboratory testing was completed at John Deere and Donaldson to understand the cause of filter plugging.

Although conditions were found where winter fuel additives could cause plugging of high efficiency filters, premature filter plugging occurred even when testing with #1 diesel fuel. This fuel contained no additives and was used at temperatures well above its cloud point. In some cases, laboratory testing of returned plugged filters did not reveal a high pressure drop across the filter and visual examination did not provide additional insight.

This paper discusses the vehicle/tier 4 engine and filter testing activity that lead us to conclude that ice crystals, formed when initially dissolved water in diesel fuel is exposed to sub-freezing temperatures, can cause temporary plugging of high efficiency fuel filters. Included is information on filter testing, laboratory testing methods, and results along with information about fuel, temperatures, and dissolved water content.

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## INTRODUCTION

Off-road vehicle applications using engines designed to meet final tier 4 emissions regulations have started to reach end users. Part of the design strategy to meet emissions regulations includes using tight tolerance high pressure fuel injectors and common rail components to control fuel injection during the engine combustion process.

Protection of the high pressure common rail components has driven on-engine fuel filtration requirements to levels of filtration efficiency that were not required in previous generations of engines. For example, where previous engine designs used filters that could remove 99% of particles in the 10 micron range, new engine designs require filters to remove 99% of particles that are less than 4 microns in size.

This increased filter performance for on engine tier 4 applications has produced interesting findings in terms of how normal fuel additives and water can affect vehicle operation. This paper

describes the experimental work done to show that ice crystals, formed in diesel fuel as it drops and stays below freezing temperatures, will be captured by high efficiency filters similar to traditional hard particle contaminants.

## LABORATORY TESTING OF FUEL FILTRATION SYSTEM IN COLD CONDITIONS

During FT4 engine/vehicle development in late 2013 and early 2014, unexpected premature filter plugging was observed as a gradual decrease in pressure to the inlet of the high pressure common rail pump. A rudimentary component test was set up in an engine cold room to see what effects temperature and fuel had on this phenomenon. A closed system, using a 300 gallon tote with 200 gallons of #1 diesel, was built as shown in Figure 1.

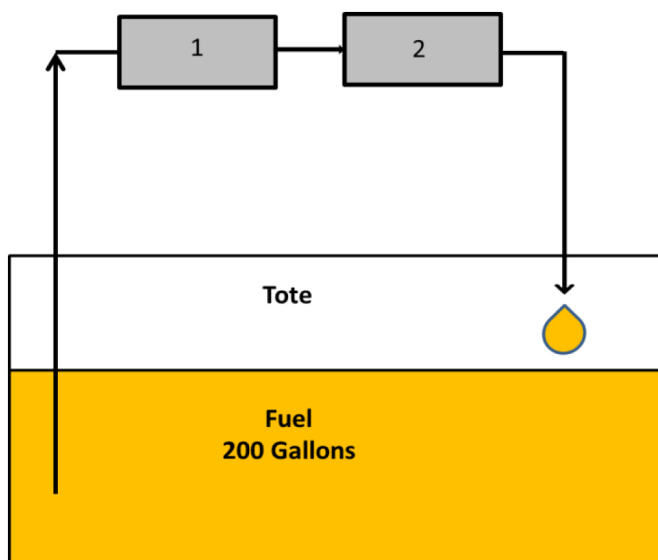


Figure 1. Experimental filtration apparatus as described in the text. The fuel is drawn from a tote through primary filter (10um) with electric lift pump / header (1). Fuel is pushed through secondary filter (2um) / header (2) and returned to tote.

#1 diesel, meeting ASTM D975, with a cloud point of  $-43^{\circ}\text{C}$  was used. The test was conducted in a cold room at  $-30^{\circ}\text{C}$  in which the entire filtration apparatus was cold soaked for three days. The electric lift pump was then run to circulate the fuel and after 17 hours of continuous running a pressure drop of 20kPa (3PSI) was observed from the start of test. The flow rate was approximately 40 gal/hr.

John Deere tested combinations of filters and filter designs and observed that pressure drop would occur in the high efficiency secondary filter. Pressure drop would increase across the filter, reach a certain value and then level off. The secondary filter was replaced with an unused filter and the test continued with no pressure drop increase occurring thereafter, indicating that the source of pressure drop had been removed.

Filters tested by John Deere were sent to Donaldson to determine the root cause of the observed pressure drop. These filters had not been kept cold during transport and had no evidence of contaminant in them when analyzed. Typical analytical chemistry methods combined with visual inspection using electron microscopy showed filter media contained essentially no capture contaminant. From this analysis it was concluded that the most likely sources of the observed pressure drop was either ice crystals or waxes formed in the fuel. In order to determine the possible relative contribution from each contaminant, a series of laboratory experiments were performed.

## EXPERIMENTAL METHODS AND RESULTS TO DETERMINE CAUSE OF FILTER PRESSURE DROP USING COLD FUEL

### Experimental Methods

Diesel fuel (#1 and #2) meeting ASTM D975 was obtained from a local source and filtered through a  $0.45\ \mu\text{m}$  Supor-450 membrane from Pall Life Sciences before use. The amount of dissolved water in

fuel was controlled by passing a controlled relative humidity (R.H) stream of  $\text{N}_2$  through the fuel at room temperature. Water activity/relative humidity in the fuel was measured using a Vaisala MM70 and calibrated using Karl Fischer titration with a Metrohm 756 KF Coulometer. The calibration of the water content in both fuels produced a room temperature saturated water content of 95 PPM for #1 ULSD and 167 PPM for #2 ULSD. The cloud point of the fuels used in this study was  $-45^{\circ}\text{C}$  (#1) and  $-17^{\circ}\text{C}$  (#2), as tested per ASTM D2500.

The filtration apparatus used throughout the study is shown in Figure 2. Fuel is drawn from a sump using a Tuthill DGS.38 gear pump at a rate of 195 ml/min and pushed through the remaining equipment. The fuel first passes through an Optek-Danulat TF-16 turbidity meter and then a Labjack EI1034 temperature probe. Fuel is then sent downward through a 47mm patch of filter media ( $13.8\ \text{cm}^2$  exposed area) and the pressure differential across the media is measured with an Omega PX2300-DI transducer. This entire apparatus is placed in a CSZ Z32 controlled environment chamber.

Ice particles in fuel were imaged by placing fuel samples in a sealed vessel and imaging with a 50X objective on an optical microscope. Samples were cooled at  $1^{\circ}\text{C}/\text{min}$  from room temperature to  $-28^{\circ}\text{C}$  using a Peltier cooled microscope stage. We found the highest quality images were obtained using transmitted polarized light to illuminate the sample.

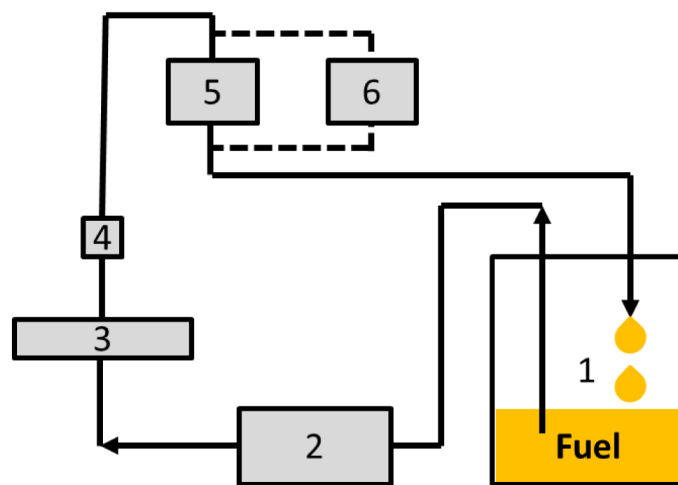


Figure 2. Experimental filtration apparatus as described in the text. The fuel is drawn from a sump (1) using a gear pump (2). Fuel is first fed through a turbidity meter (3) and temperature probe (4). Fuel is then passed through a filter (5) and the pressure differential is measured (6) and recirculated back into the sump.

Filter media sample were characterized using capillary flow porometry with a PMI APP 1200 AEXSC instrument. Samples were wet with Silwick (surface tension =  $20.1\ \text{mN/m}$ ) and tested to a maximum pressure of 26 PSI. A tortuosity correction factor of 0.715 was used to calculate all pore size distributions. Further structural analysis of filtration media was performed using bubble point testing with Isopropyl Alcohol (IPA) according to ASTM F316. Standard testing against dust was performed for all filter grades according

standard multipass testing protocols. Half of the media samples we tested for both efficiency and capacity per ISO 19438 and half were tested for capacity per SAE J905 and efficiency per SAE J1985.

## Results and Discussion

The filtration of ice particles in diesel fuel was tested using four different filtration media. These media are referred to as A-D and span a variety of efficiencies and constructions. Structural parameters and standardized testing results of the media are given in Table 1. Media A and D are of similar composition, but have drastically different performance. Both of these media are layered structures with a top layer of synthetic and glass fibers supported by a cellulose layer. The efficiency and capacity differences are due to the amount and exact type of fibers used in the recipe. Media B is a two layer composite with melt-blown synthetic fibers on a cellulose support layer and is between the efficiency of media A and C. Finally, media C is a single layer of cellulose and glass construction with standardized efficiency close to media D, the most efficient of all the media tested.

Table 1. Physical parameters and standards test dust filtration performance of media used in this study. Bubble point testing was performed according to ASTM F316 using isopropyl alcohol (IPA). Superscript labels denote the standard test procedure used (a) Multipass test per ISO 19438 (b) Capacity per SAE J905 and efficiency per SAE J1985.

| Media | IPA Bubble Point (°H <sub>2</sub> O) | Mean Flow Pore Size (μm) | Beta=200 Particle Size (μm) | Dirt Holding Capacity (g/ft <sup>2</sup> ) | Construction                     |
|-------|--------------------------------------|--------------------------|-----------------------------|--------------------------------------------|----------------------------------|
| A     | 4.4                                  | 35.6                     | 30 <sup>a</sup>             | 24 <sup>a</sup>                            | Glass/Synthetic on Cellulose     |
| B     | 11.3                                 | 9.4                      | 10 <sup>b</sup>             | 23 <sup>b</sup>                            | Meltblown Synthetic on Cellulose |
| C     | 14.6                                 | 3.6                      | 5 <sup>b</sup>              | 2.5 <sup>b</sup>                           | Glass/Cellulose                  |
| D     | 18.3                                 | 2.5                      | <4 <sup>a</sup>             | 21 <sup>a</sup>                            | Glass/Synthetic on Cellulose     |

Each of these media was tested for filtration of ice particles from diesel fuel through the following procedure. First, a 1 liter sample of fuel is brought to a specific dissolved water content by bubbling a room temperature stream of either humid or dry air through the fuel. Relative humidity (also called water activity) of the fuel is defined as the percent of dissolved water content relative to the maximum saturated water content for a specific temperature. After the desired water content was achieved, the sample was placed into the filtration apparatus in an environmental chamber and cooled to -28 °C in approximately 1 hour. The R.H. of the air in the environmental chamber was held at 1-2% to avoid condensation onto the apparatus electronics. Once the fuel temperature was lowered to -28°C, it was cold soaked for 2 hours before starting filtration.

When the temperature of the fuel decreases, the amount of dissolved water that the fuel can hold also decreases. If the water content of the fuel is higher than the solubility at any given temperature, there will

be precipitation of free (undissolved) water into the fuel.

Furthermore, if precipitation occurs below 0°C, the precipitated water will be in the form of ice.

One measure of how filters perform is to compare both the pressure differential across the filter as it loads with ice particles captured from the fuel. Figure 3 shows how the pressure across the filter changes for each media when exposed to #1 USLD with an initial water content of ~90% R.H. The turbidity (cloudiness) of the fuel is also measured to provide a relative concentration of ice particles. In our experiment the turbidity signal is measured as the ratio of light scattered at 11° to the intensity of light that passes through the sample. The signal was calibrated by the manufacturer as PPM of diatomaceous earth in water. Our turbidity meters are scaled to accurately measure low turbidity signals by setting the signal saturation to a value of 25. In the first 5 minutes of most experiments we observe a sharp increase in turbidity as the ice particles are mixed and achieve a uniform contamination level throughout the apparatus.

Figure 3 shows that within 2 hours of loading neither filters A nor B build significant pressure due to ice particle loading. Filters A and B also showed no decrease in turbidity over the experimental timeframe. As the filter efficiency is increased, we observed that both media C and D build pressure across the filter as ice particles are captured. The decrease in the concentration of ice particles is accompanied by a decrease in the turbidity over time. Of the two media that were observed to load with ice, media D was found to have the higher efficiency for ice particle removal as it lowered the turbidity faster than media C. For both media C and D we observed the rate of pressure differential increase decays as the turbidity decreases. This is due to the multipass nature of the experiment in which the concentration of ice particle being fed into the filter decreases over time.

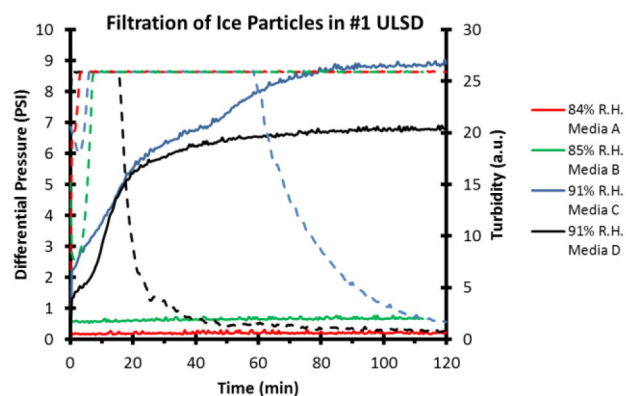


Figure 3. Differential pressure (solid lines, left axis) and turbidity (dashed lines, right axis) for filtration of ice particles in #1 USLD at -28 °C. Filtration performance is shown for media A-D as red, green, blue, and black, respectively.

The effect of varying water/ice content was tested on media D and shown in Figure 4. In this experiment the initial relative humidity in the fuel was varied from 93% to 9%. This is equivalent of starting water content in the fuel ranging from 88 to 9 PPM, respectively. We observed the differential pressure achieved after two hours of filtration is proportional to the initial water content in the fuel. This