

The Effects of Diesel Fuel Additives on Water Separation Performance

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ABSTRACT

Fuel additives are being used more frequently to meet “premium diesel fuel” requirements. Although these additives improve performance, they also affect the water separation characteristics. This program was designed to determine the effects of various additives on fuel/water separation in low- and ultra-low sulfur diesel fuel. The additives studied include detergents and lubricity additives. A soy-based biofuel is also considered.

The fuel/water separation tests conducted with coalescer filter technology generally produced higher efficiencies while the addition of a detergent additive package at 175-ppm generally produced lower water separation efficiencies.

INTRODUCTION

Water in fuels is one of the major causes of diesel engine maintenance problems. The effects of water in fuel are characterized by corrosion of fuel systems parts, plugging of filters and orifices, and in some cases, failure of fuel injection equipment. The presence of water also encourages microbiological growth, which generates orifice and filter restricting residue [1].

Water is considered a key contaminant that can plug different types of filter elements, and it can come from a variety of sources. During transportation, transfer, and storage of fuel, water may become entrained in a variety

of ways [2]. Moisture enters with the air into storage tanks. Water, when dissolved in the fuel, can condense out of solution when fuel temperatures fall in underground pipelines, hydrants, or in above-ground piping and storage tanks. Water also finds its way in through leaking lines or cracked tanks. Water enters through floating roof tanks with no dome covers on refueled trucks, particularly when water downspouts are plugged with debris (leaves, ice, bugs, etc.). Residual water is also found in equipment that is gas-fed by filling with water where all the water is not subsequently drained away [3]. The mode and timing of water entry in the handling sequence before use, as well as the chemistry of the fuel itself (additives and surfactants), will determine what form the contaminant takes, either fine emulsions or large water droplets, or a combination of both.

Fuel additives are being used more frequently to provide required fuel performance. Some of the additives include cetane improvers, detergents, lubricity additives, cold flow depressants, anti-static additives and corrosion inhibitors. These additives, along with many others, are used to improve diesel fuel characteristics to meet “premium diesel fuel” requirements, and to convert Jet A to JP-8 and JP-8 to JP-8+100. More additives will also be needed as fuel lubricity decreases, due to the required sulfur reductions in future fuels. Although these products improve many fuel properties, they also affect the water separation characteristics. Additives and the subsequent combination of additives can have a significant effect on the fuel filter’s water separation ability.

OBJECTIVE

The objective of this program was to investigate water separation properties with current fuels. This program was developed with industry in an effort to determine the effects of diesel fuel additives on the water separation performance of various types of fuel/water separator products. Issues of particular interest that directly affect industry operation were:

- Do alternative fuels such as biodiesel have water-removal issues?
- How do different additives affect water-removal characteristics of conventional and alternative fuels?
- What filtration technologies best remove water in fuels with various additives and additive packages?

APPROACH

Previous efforts consisted of both field sampling and laboratory testing. The field sampling was conducted to identify typical fuel and water characteristics. Chemical laboratory testing was used to quantify these characteristics, and a fuel/water separation test stand was used to obtain fuel/water relationship data with respect to various filter media. These results are not included in this report, but were used for the design of experiment for the work presented in this paper.

This phase of the program was dedicated to determining the effects of various additives on fuel/water separation in low-sulfur diesel fuel and ultra-low sulfur diesel fuel. Testing was devoted strictly to using the fuel/water separation test stand to obtain results for various test matrices.

EXPERIMENTAL DESIGN TEST MATRIX

EXPERIMENTAL DESIGN FACTORS - Fuel/water separation efficiency may be influenced by several factors. As part of this investigation, five factors were selected to gain a better understanding of water separation. A fractional factorial experimental design was developed in which each of the five factors was tested at two levels. Table 1 lists the five design factors and their corresponding test levels.

Table 1. Experimental Design Factors and Levels

Design Factors	Levels	
	Stripper	Coalescer
Filter Technology	Stripper	Coalescer
Test Fuel	Low sulfur diesel fuel (LSD)	Ultra-low sulfur diesel fuel (ULSD)
Lubricity Additive	None	125 ppm (non-acidic)
Detergent Additive	None	175 ppm
Biodiesel Additive	None	5%

Filtration Technology - The factor that changed the most between previous test matrices and this experimental design was the decision to use commercially available test filters rather than having the test filters constructed.

Participants in this work agreed that a cellulose stripper filter and a coalescer should be used to fully understand their effects on water separation efficiency. The participants were responsible for providing the test filters required for this design of experiment (DOE).

Additives - An additive company provided the technical support for the additive selection. They acknowledged that many additive packages have generally been a multiple fatty acid chemistry. Due to acid interactions with engine components and engine oil, the industry is leaning towards additives of a monomer acid-type chemistry. Because lubricity additives are used in very high concentrations compared to other additives, fuel/water separation may always be an issue. However, since detergent additives are most familiar to fuel suppliers and engine users, we can expect to see detergent packages continually added to fuel. These detergent packages and the subsequent combination of lubricity additive packages were considered when choosing the testing additive.

This phase of testing incorporated a detergent additive package and a lubricity additive package using the recommended treatment concentration. In this testing, two additives, one acidic and one non-acidic, were utilized. The acidic detergent package can be described as a blend of long chain fatty acids derived from natural sources. The non-acidic lubricity package can be described as a polymeric fatty acid ester. These products are formulated to combine the properties of maximum lubricity with minimum impact on other fuel properties such as surfactancy (as measured on the Microseparometer test for jet fuel).

Fuel - Market fuels are consistently changing to meet lower sulfur reductions that were enforced in 2006. These changes in fuel, as well as the introduction of alternative fuels, were an important factor to consider in this work. Parts of Europe are already marketing the use of 100% biodiesel fuel. This trend to use biodiesel in America is increasing, but far from Europe's 100%. Engine manufacturers are only approving the use of 5% biodiesel. The participants decided that ultra-low sulfur diesel fuel, low-sulfur diesel fuel, and 5% soy-based biodiesel fuel would be the focus for this design.

EXPERIMENTAL DESIGN TEST MATRIX - A $2^{5/2}$ fraction of a 2^5 design was planned, which resulted in 16 unique factor-level test combinations. Additional repeat tests of selected test combinations were also planned in order to provide a good estimate of the experimental variability. This type of experimental design provides information for the statistical comparison of the average (or mean) water separation efficiency from the 'low' and 'high' levels of each factor (i.e., main effect) to determine if the factor is significant. This particular design also provides data for testing of all ten two-factor interactions among the five factors in order to identify synergistic effects. Table 2 displays the fractional factorial experimental design that all participants agreed upon.

Table 2. Experimental Design Test Matrix

Trial	Technology	Fuel	Lub Additive	Det Additive	Biodiesel
1	Stripper	LSD	None	None	None
1	Stripper	LSD	None	None	None
1	Stripper	LSD	None	None	None
17	Coalescer	LSD	None	None	None
17	Coalescer	LSD	None	None	None
17	Coalescer	LSD	None	None	None

NOTE: Check variation in repeats for "Baseline" technologies. If variation is acceptable and "Baseline" runs have >= 50% efficiency, then continue testing. Otherwise consult consortium.

8	Coalescer	LSD	125ppm	175ppm	5%
4	Stripper	LSD	None	175ppm	5%
15	Coalescer	ULSD	125ppm	175ppm	None
16	Stripper	ULSD	125ppm	175ppm	5%
6	Stripper	LSD	125ppm	None	5%
3	Coalescer	LSD	None	175ppm	None
2	Coalescer	LSD	None	None	5%
7	Stripper	LSD	125ppm	175ppm	None
16	Stripper	ULSD	125ppm	175ppm	5%
5	Coalescer	LSD	125ppm	None	None
14	Coalescer	ULSD	125ppm	None	5%
9	Coalescer	ULSD	None	None	None
12	Coalescer	ULSD	None	175ppm	5%
11	Stripper	ULSD	None	175ppm	None
13	Stripper	ULSD	125ppm	None	None
10	Stripper	ULSD	None	None	5%
3	Coalescer	LSD	None	175ppm	None
2	Coalescer	LSD	None	None	5%
14	Coalescer	ULSD	125ppm	None	5%

STATISTICAL ANALYSIS OF EXPERIMENTAL DESIGN

BASELINE TESTS - Before testing began with the fractional factorial design combinations, a few 'baseline' tests were performed to verify that the experimental setup and process were performing as expected, and the test repeatability was within acceptable levels. The baseline tests were all run with LSD fuel with no additives. Three cellulose stripper filters followed by three coalescers were run producing the water separation efficiencies noted in Table 3. This level of efficiency (near 100%) and the good repeatability among the three repeat tests provided assurance that the testing process was reliable.

Table 3. Baseline Tests – Fuel/Water Separation TWA Efficiencies

Trial No.	Filter Technology	Efficiencies, %
1	Stripper	100, 98, 100
17	Coalescer	99, 100, 100

FILTRATION EFFICIENCY RESULTS - During the testing performed from the fractional factorial design, a few changes in the run order and repeat tests were made in order to gain as much information as possible in the efficiency tests. The final data matrix contained 27 complete tests. This included the 16 original unique tests, the 2 baseline test combinations, and 9 total repeat tests on 5 different test combinations. A detailed list of the test combinations and efficiency results in the run order they were performed are included in Table 4.

Interfacial tension (IFT) measurements were performed according to ASTM D 971, as specified in SAE J1488. Microseparometer (MSEP) readings were measured according to ASTM D 3948, as suggested in SAE J1488. IFT measurements of the tested fuel were required to be

between 25 and 30 mN/m, as specified by SAE J1488. If additive was used in a particular trial run, then the fuel IFT was to be between 25 and 30 mN/m before the additive was added. IFT measurements were taken both before and after the addition of additives.

Table 4. DOE Test Matrix Results

Trial	Technology	Fuel	Lub Additive	Det Additive	Biodiesel	TWA Efficiency
3	Coalescer	LSD	None	175ppm	None	88%
9	Coalescer	ULSD	None	None	None	100%
12	Coalescer	ULSD	None	175ppm	5%	86%
15	Coalescer	ULSD	125ppm	175ppm	None	100%
Misc.	Stripper	LSD	125 ppm	175 ppm	5%	13% *
8	Coalescer	LSD	125ppm	175ppm	5%	83%
4	Stripper	LSD	None	175ppm	5%	10% *
15R	Coalescer	ULSD	125ppm	175ppm	None	100%
16	Stripper	ULSD	125ppm	175ppm	5%	16% *
6	Stripper	LSD	125ppm	None	5%	95%
2	Coalescer	LSD	None	None	5%	100%
7	Stripper	LSD	125ppm	175ppm	None	13% *
5	Coalescer	LSD	125ppm	None	None	100%
14	Coalescer	ULSD	125ppm	None	5%	99%
11	Stripper	ULSD	None	175ppm	None	10% *
13	Stripper	ULSD	125ppm	None	None	100%
10	Stripper	ULSD	None	None	5%	100%
6R	Stripper	LSD	125ppm	None	5%	23% *
3R	Coalescer	LSD	None	175ppm	None	90%
12R	Coalescer	ULSD	None	175 ppm	5%	8% **
6R	Stripper	LSD	125ppm	None	5%	62%
6R	Stripper	LSD	125ppm	None	5%	100%

* Test terminated early, but efficiency calculation assumed zero efficiency for the rest of the test time.

** Data point not used in DOE analysis.

ANALYSIS OF VARIANCE RESULTS - After completion of the baseline and the fractional factorial design tests, an analysis of variance (ANOVA) statistical technique was used to investigate the factor effects and the two-factor interactions on the average water separation efficiency. The ANOVA identified which factors were statistically significant with respect to the average efficiency. For example, the ANOVA tested whether the average efficiency of the stripper filter technology was significantly different from the coalescer filter technology. Additionally, the ANOVA was used to assess the efficiency data to determine if there were significant interaction effects among the five main factors. Was there a joint or synergistic effect wherein the effect of one factor on the average efficiency was dependent on the level of another factor? All statistical comparison tests were made at the 5% significance level. This is the probability of stating that there is a difference in the average efficiency when, in fact, there are no differences.

The final test matrix resulted in an unbalanced design. This means that there was an unequal number of test runs made at each factor-level combination. Because the design was unbalanced, the efficiency was compared using adjusted means instead of arithmetic means. The adjusted means were estimated using a least-squares means technique for each factor level [4] and are provided in Tables A-1 and A-2 in the Appendix.

Table 5 lists the results of the ANOVA for the five main effects and the ten two-way interactions. Each comparison of the adjusted means resulted in a probability value (p-value). If the p-value for a particular factor (or interaction) was greater than the significance level (0.05), it indicates there was not sufficient evidence to conclude that significant differences exist among the