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A better understanding of molecular forces enhances free water separator selection

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Molecular forces, such as interfacial tension, viscosity, relative density and temperature, control suspended water removal from fuel/water mixtures. A better understanding of these physical properties will assist engineers investigating separation techniques. Equations and case histories review several free water removal methodologies such as salt driers, liquid/liquid coalescers, etc., and their effectiveness on emulsion and surfactant-containing streams.

A big problem. Today, water contamination in refinery fuels can be a bigger problem than solids contamination. Water in fuel can corrode and plug engine parts and is a significant contributor to tank bottom corrosion and bacterial growth. In addition, water may contain corrosive materials like chlorides that will cause equipment damage. Unfortunately, it doesn't take much water to cause a problem. Water concentrations as low as 100 ppm can cause a product to be off-specification due to haze, color or overall water concentration. Detergents and additives that are surfactants make water removal more difficult because they lower the interfacial tension between water and the fuel.

Field tests conducted at two refineries show how a stacked coalescer/separator configuration with polymeric medium outperforms salt driers in terms of total water removal from diesel fuel and do not disarm (lose efficiency to coalesce) when exposed to surfactants like conventional glass fiber coalescers.

Difficult to remove. Two forms of water can be present in fuels: dissolved or suspended as tiny droplets that range in size between $0.1\mu m$ to $10\mu m$ in diameter. This size is so small that it cannot be visually detected except when a highly concentrated haze is formed. The free water is suspended as an emulsion. The more stable the emulsion, the more difficult it is to remove the water. Factors that affect water removal from a water/fuel mix-

ture include interfacial tension (IFT), viscosity, relative density and temperature.

Interfacial tension. The ability to remove water improves as the IFT between the two phases increases. The IFT (σ) between two liquids is a measure of the attraction force between each phase for its own species. At a two-liquid interface, a natural surface tension is created as each phase is repelled by the other phase. A ring-pull method is commonly used to measure IFT. This method measures the force required to pull a platinum-iridium ring of known circumference from one discontinuous phase into the next. The typical units of IFT are dyne/cm. The IFT is a critical factor when considering liquid/liquid coalescence because the largest possible stable droplet size that will form by the coalescence process will be dictated by IFT. A system with a high IFT (i.e., $\sigma > 20$ dyne/cm) can sustain a larger stable coalesced droplet size, which can be easily separated. Systems with a low IFT (i.e., water in fuels with additives: $\sigma < 20$ dyne/cm) form smaller stable coalesced droplets and require high efficiency separators. Besides IFT, the coalesced droplet size will also depend on the system dynamics including the relative droplet velocity, density and viscosity.

One method for correlating drop size to flow conditions has been developed by Hu and Kintner.[1] The drag coefficient (C_d) of different organic drops in water is related
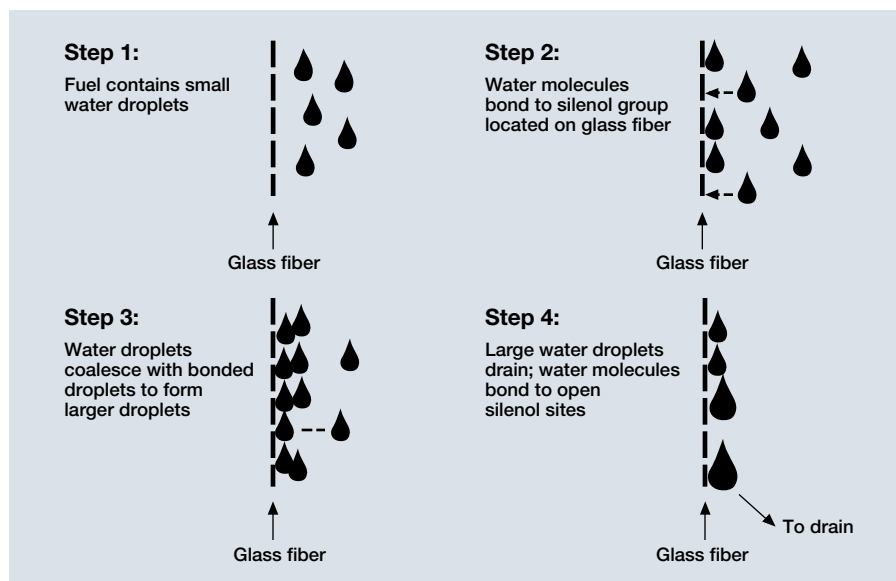

Step 1: Fuel contains small water droplets

Glass fiber

Step 2: Water molecules bond to silenol group located on glass fiber

Glass fiber

Step 3: Water droplets coalesce with bonded droplets to form larger droplets

Glass fiber

Step 4: Large water droplets drain; water molecules bond to open silenol sites

To drain

Glass fiber

Fig. 1. Simplified mechanism for effective coalescing.

by a physical property group (P) and the Weber number (We) over a range of Reynolds numbers (Re). A unique curve is produced when $C_d * We * P^{0.15}$ is plotted against $Re/P^{0.15}$.

where
C_d = Drag coefficient = $4gd\,\Delta\rho/3\rho_0 V^2$
P = Physical property group = $\rho_0^2\,\sigma^3/g\mu_{''}^4\,\Delta\rho$
We = Weber number = $V^2 d\rho_0/\sigma$
Re = Reynolds number = $\rho_0 Vd/\mu_0$
V = Terminal velocity
d = Droplet diameter
g = Acceleration due to gravity
ρ_0 = Density of continuous phase
$\mu_{''}$ = Viscosity of continuous phase
$\Delta\rho$ = Density difference between droplet and continuous phase
σ = Interfacial tension

Conventional coalescers can work effectively on mixtures with an IFT no lower than 20 dyne/cm. Other factors that reduce IFT, and make coalescing more difficult, include using surfactant-containing inhibitors, detergents and additives with the fuel. In addition, solid contaminants also lower the IFT. Refined fuels that contain detergents may have an IFT of 10 dyne/cm or lower.[2]

Viscosity. Liquid media viscosity has a significant impact on the coalescence process. The two droplets must first travel through the liquid and collide. The next step is fusion of the two droplets, which requires the breakdown of the liquid/liquid interface between the droplets. Both steps in the coalescence mechanism are impeded by increased viscosity. The droplets must overcome a higher drag force to reach one another. The breakdown of the liquid/liquid interfaces to create larger fused droplets is made more difficult by a higher viscosity fluid. Therefore, more residence time is required to accomplish the same coalescence level compared to a lower viscosity fluid. This can be done by either lowering the flowrate or increasing the coalescer medium's area.

The ΔP across the coalescer will also be affected by viscosity:

$\Delta P = K\mu Q$

where
Q = Flowrate
μ = Viscosity
K = Medium constant (coalescer).

Relative density. The relative density between the two phases to be separated (e.g., water from gasoline) can have an important effect on coalescer performance. As the density of the coalesced liquid to be removed approaches the bulk liquid's density, separation becomes more difficult.

Temperature. The fuel/water mixture's temperature can also affect separation efficiency. As temperature increases the IFT decreases, lowering the water droplets' size. In addition, fuels saturated with water at high temperatures can contain a high concentration of dissolved water, which cannot be removed by liquid/liquid coalescers. As the temperature decreases, the water falls out of solution into a suspended state and can then be removed by a liquid/liquid coalescer.

Surfactants—double trouble. Not only do surfactants reduce coalescer efficiency by lowering the IFT, they also *disarm* the conventional glass filter coalescer, which is one of the biggest operational problems. When a liquid/liquid coalescer is performing efficiently, water molecules bond with the silenol functional group (Si-O-Si) of the glass fiber. The water molecules that collect on the glass fiber coalesce with incoming water molecules to form larger droplets that eventually become heavy enough to drain from the coalescer. In an efficiently operating coalescer, once a droplet has fallen from the silenol functional group, the coalescing process repeats (Fig. 1).

Disarming occurs when surfactants bond with the silenol functional group. The silenol group has a greater affinity for surfactant molecules than for water. As the surfactant bonds to the glass fibers, the water molecules pass quickly through the glass fiber medium (Fig. 2). This process greatly reduces water removal efficiency, increasing the probability of water breakthrough and shortening the coalescer's service life. **Result:** frequent changeouts and increased disposal cost of coalescer cartridges.

Other water removal technologies. Conventional technologies used to remove water from fuel include:
 • Tank settling, which may be unreliable and take several days, an unacceptable amount of time to remove the water effectively
 • Sand filters, which have high capital costs and may not always be efficient
 • Salt driers, which experience temperature sensitive operational problems and can add corrosive chlorides to the fuel.

Table 1. Estimated operating costs of stacked coalescer/separator system for different refinery fuels*

Fuel	Viscosity, centistokes 100°F	Operating costs, ¢/gal
Gasoline	0.7	0.015
Jet A	1.6	0.023
Jet B	2.3	0.024
Diesel (2-D)	3.5	0.032
No. 2 Fuel oil	3.6	0.033
No. 4 Fuel oil	8.5	0.067

*Assumes a 20,000-bpd flowrate.
Includes both filter and coalescer/separator stack replacement costs.
Does not include initial capital and installation costs.
Filters sized at 0.5 gpm/ft² and changed out eight times/year.

Table 2. Summary of test coalescer test results at refinery A

Fluid: #2 Diesel
Viscosity: 3.5 cSt at 100°F
Fluid temp.: 97°F

Flow, gpm	Stack pressure drop, psid	Coalescer Haze test* coalescer inlet	inlet free water, ppmv	Coalescer outlet free water, ppmv	Haze test* coalescer outlet
1	2	6	120	11	1
1.5	2	6	120	10	1–2
2	4	6	120	9	1
3.5	11	6	120	6	2–3

*based on Colonial Pipeline Co. "Line Chart" system.
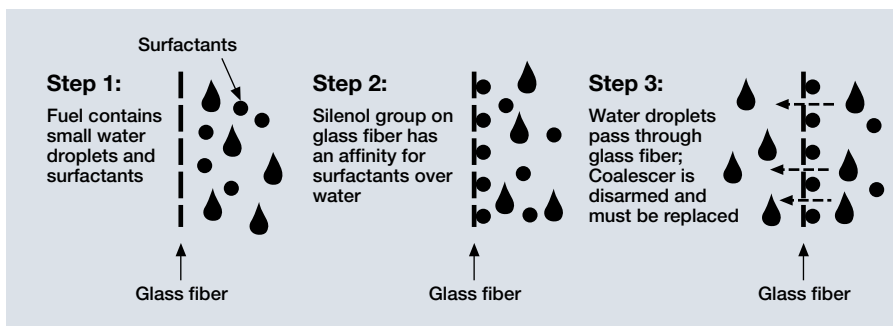
Fig. 2. Mechanism for disarming.

Step 1:
Fuel contains small water droplets and surfactants

Surfactants

Glass fiber

Step 2:
Silenol group on glass fiber has an affinity for surfactants over water

Glass fiber

Step 3:
Water droplets pass through glass fiber; Coalescer is disarmed and must be replaced

Glass fiber

Fig. 3. Stacked coalescer/separator.

Water inlet

Contaminated fuel inlet

Purified fuel outlet

1 Isolation valves
2 Particulate filters
3 Sample ports
4 Water flowmeter
5 Water metering valve
6 Fuel globe valve
7 Pressure gauges
8 Liquid/liquid coalescer unit
9 Water outlet
10 Flow regulator
11 Flow totalizer

Table 3. Comparison of operating costs between salt drier and stacked coalescer/separator system at refinery A

Item	Incremental annual costs of operating coalescer
Filter usage	($24,000)
Coalescer usage	($36,000)
Salt (includes maintenance, material and disposal)	$240,000
Total	$180,000*

*Does not include benefits resulting from reducing amount of off-test product, which is currently 4% of the diesel run through this drier.

Table 4. Summary of test coalescer test results at refinery B

Fluid:	#2 Diesel
Viscosity:	4.0 cSt at 100°F
Fluid temp.:	98°F

Flow, gpm	Stack pressure drop, psid	Coalescer inlet free water, ppmv	Coalescer outlet free water, ppmv	Haze clear-up temp., °F Coalescer	Drier
0.5	1	150	*	*	95
1	2	150	4	81**	95
1.5	3	150	6	68**	95
2	4	150	6	68**	95

*Not measured for this run.
**Visual test was "*bright and clear.*"

A fuel stream may go through one or more of these methods to meet a refinery's haze or moisture specification.

Some problems experienced with salt driers include bridging, which results in poor overall usage (at times under 50%)[4] of the salt and channeling, which is large hole formation throughout the length of the drier.[5] Channeling is caused by high flowrates and poor distribution through the drier. Maintenance problems such as plugging can occur at lower temperatures.[6] In addition, any water that remains in the fuels after it flows through the salt drier will contain chlorides, which can result in corrosion problems downstream in tanks, piping and equipment. Salt drier efficiency is best when operated within a relatively low temperature range and at a steady flowrate. Also, salt driers can remove dissolved water where coalescers may only remove free or suspended water.

However, liquid/liquid coalescers should have the advantage of removing free water from hydrocarbon on a *continuous* and *reliable* basis. They should not add any potentially corrosive materials to the fuel, have very high removal efficiencies and relatively low capital and operating costs. Liquid/liquid coalescer can operate efficiently at fluctuating flowrates and temperatures.

Better stream preparation improves downstream coalescing. A newer design uses a filter stage to remove particulates and has a stacked coalescer/separator configuration with polymeric medium to improve flow distribution and overcome disarming (Fig. 3). This design results in improved reliability and lower operating costs (Table 1).

Laboratory test. Tests conducted at an independent laboratory on unleaded gasoline used a stacked coalescer/separator. The test protocol closely followed API 1581 Jet Fuel Separator qualification and specifications.[7] The IFT range of the unleaded gas mixtures charged to the test unit was 3 dyne/cm to 7 dyne/cm. A finely divided water emulsion in gasoline was used to challenge the coalescer. Free water concentration in the inlet mixture was set from 100 ppm to 3% (30,000 ppm) by volume. In all test cases, the effluent concentration of free water after passing through the coalescer was less than 15 ppm by volume.

Testing also demonstrated the limitations. The coalescer stage size is limited by ΔP and by the viscosity on the coalescing mechanism. Design flow through the coalescer is inversely proportional to the viscosity of the fluid in cSt. Results showed that a 20-in. long coalescer (3¾ in. diameter) can handle a flowrate of 30 gpm of gasoline (viscosity = 0.7 cSt) for a clean ΔP of 5 psid. The same sized coalescer can handle 6 gpm of a diesel stream (viscosity = 3.5 cSt) when sized for equivalent pressure drop and water removal efficiency.

The separator is velocity limited and not adversely affected by increasing viscosity. Water breakthrough occurs within the separator once a maximum velocity or flowrate is reached. The design velocity for the commercially available 20-in. separator is 30 gpm regardless of viscosity.

These stage limitations indicate that a larger coalescer stage with the same sized separator can handle higher flowrates for more viscous fluids. A 40-in. coalescer/20-in. separator, for example, can handle twice the flow of diesel as compared to a 20-in. coalescer/20-in. separator. Because lower viscosity fluids like gasoline are limited by the separator, a larger coalescer *does not* improve the flowrate per coalesce/separator stack.
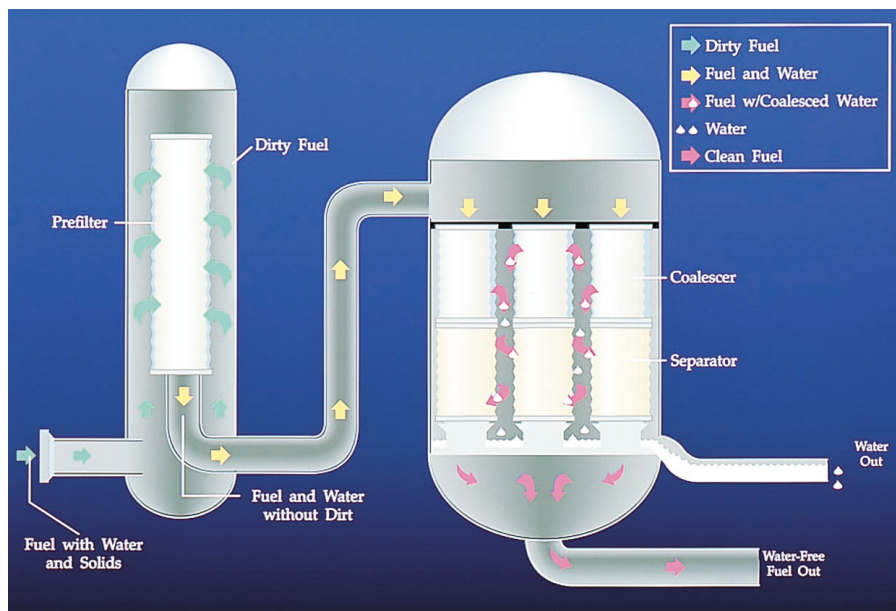

Fig. 4. Liquid/liquid coalescer sidestream test stand.

Field results. Field tests were conducted at two refineries on diesel streams. The water source in diesel can be traced to a steam stripper at the back end of a diesel hydrotreater. When the diesel exits the steam stripper bottom most of the water is dissolved. As the diesel cools water drops out of solution into suspension. Because a coalescer can only remove suspended water, it is important to locate the coalescer in the *coolest* possible location.

Fig. 4 is a schematic diagram of the side-stream coalescer field test apparatus. It consists of a 3 μm particulate prefilter, a coalescer/separator stack enclosed in a glass filter housing, and associated valves and gauges for pressure and temperature measurements. An inline flowmeter measured the stream's flowrate. The test coalescer consisted of a 6-in. coalescer stacked on top of a 6-in. separator. Fuel samples were collected upstream and downstream of the coalescer for water content measurements.

Refinery A. At a major U.S. refinery, conventional diesel is prefiltered by 10 μm absolute filters, flowed to coalescers and a salt ($CaCl_2$) tower for water and haze removal. In terms of haze, the salt drier at Refinery A was found to have minimal efficiency in haze removal when fluid temperatures exceeded 100°F. Haze temperature improvement increased to approximately 10°F at temperatures around 75°F. After flowing through the salt drier, diesel is then filtered by 10 μm absolute filters to remove salt particles and other solids. Salt tower operation has been expensive, requiring extensive maintenance due to salt pluggage and disposal. In addition, approximately 4% of the diesel that is processed through the drier is off-specification due to temperature-related haze.

Table 2 summarizes the test results. The diesel entering the test stand typically contained over 120 ppm of free water with an average haze rating of 6. Downstream of the stack, the free water contents were between 6 ppm and 11 ppm. The filtrate samples for 1 gpm, 1.5 gpm and 2 gpm were bright and clear with an average haze rating

of 1. At a flowrate of 3.5 gpm, a coalescer limitation was reached due to high differential pressure and the average haze rating increased to between 2 and 3.

The total water content of the samples collected at flowrates from 1 gpm to 2 gpm compared favorably to that of samples taken downstream of the salt drier (110 ppm collected at ~100°F). Operating costs analysis by Refinery A indicates a significant difference between the salt drier and the stacked coalescer (Table 3). High maintenance, materials and disposal costs of the drier more than offset the incremental costs required for additional filters and coalescer stacks. Use of the coalescer either in place of, or in conjunction with, a salt drier is being considered in a refinery expansion.

Refinery B. A medium-sized U.S. refinery removes water from diesel with a horizontal separator and an NaCl salt drier. During the warm weather months (May to

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September), the diesel has occasional haze problems requiring additional drying. Refinery B's quality check is called the haze clear-up temperature, which involves cooling the diesel until a stable haze appears and then slowly reheating it until the haze disappears. The temperature at which the sample starts to clear is recorded as the haze clear-up temperature. The lower the haze clear-up temperature, the drier the sample.

Test results are summarized in Table 4. The diesel entering the test stand typically contained over 150 ppm of free water and was rated as hazy and cloudy. Effluent samples of the coalescer were bright and clear with free water concentrations ranging from 4 ppm to 6 ppm. The effluent samples' haze clear-up temperatures, as measured by Refinery B, ranged from 68°F to 81°F. Typical haze clear-up temperatures of salt-dried diesels are between 90°F to 100°F, well above the specification of the Colonial Haze test of 70°F.

Field test results indicate that the water removal performance of the newer liquid/liquid coalescer is favorable compared to a salt drier and may be used in place of, or in conjunction with, a salt drier to get efficient water removal from refinery fuels, as well as reduce maintenance and operating costs.

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