

The Non-Effect of Particulates on the ViSmart™ Sensor for Oil Condition Monitoring Applications

Customers in the oil condition monitoring industry are sensitized to the need of any sensor operating in their challenging environments without being influenced by particulates that may be present in the oil.

There are three areas of concern with regards to particles. First and foremost is the ability to survive abrasive damage. If the sensor cannot survive particulate exposure it is irrelevant as to how well it measures solutions containing particulates. ViSmart sensors have been employed in silica dispersion grinding applications to the end user's satisfaction. Abrasion due to flowing oil is not an issue due to the presence of a proprietary hard coat on the sensor surface.

A second issue relates to fouling. If the sensor becomes encased in particulates, it can no longer measure the liquid. ViSmart sensors have an antifouling coating and no issues have been observed to date. Also, there are no moving parts or substantial 3D features to coat.

The final issue is the ability to measure viscosity changed due to particulates. The ViSmart sensors are known to have a size dependent response to particulates.

This application note is intended to first discuss the three ranges of size relative to sensor response and then to present literature references that describe the particle size and distribution of soot in diesel systems. The next section then presents internal and third party data on ViSmart sensors in systems of known and unknown soot loading and other effects.

Effect of particulates:

It is first important to determine exactly what needs to be evaluated in terms of particulates. Oil particulates can be large (wear and silt particles), soot, or intermediate-sized particles. Numerous references are made to silt and wear particles as being micron scale and larger

A) Large (wear or silt) particles

Large, in the context of the ViSmart sensor, is determined by the cSt viscosity. In 10 cSt oil, the transition from small particles to large particles occurs at $\sim 1\mu$. A particle that is "large" (e.g. $>10\mu$ in 100 cSt oil) will have little effect on the resonant viscometer. These very large particles are typically silica or metal flake and are detected only using particle counters.

These particles will clog sensors with moving parts and small gaps but will have no deleterious effects on the ViSmart sensor unless they are forcibly ground into the surface.

B) Micron-scale particles

Particles ranging from $\sim 500\text{nm}$ to 10μ will influence the sensor reading in a size dependent fashion. The mechanism will vary from a purely “internal friction” model to one wherein the sensor applies rotational energy to the particles in proximity with the surface. This transition region of particle sizes will have an influence on the measured viscosity but will not clog or foul the sensor. These particulates are of limited interest in soot measurement.

C) Sub-micron particles

Particles that are much smaller than 1μ will behave as though they were a constituent of the homogeneous liquid phase, provided they do not settle from solution. In a flowing or agitated sample these particles will behave the same in a resonant sensor as they would in a high shear capillary viscometer operated at a similar shear rate. That is, they impede flow and raise the viscosity with particle load.

As stated by SWRI [1] these are the particles of interest:

“Soot particles emitted from diesel engines are chain agglomerates in the size range of 40–500 nm in diameter. These chain agglomerates consist of small particles in the size range between 10–30 nm in diameter that are generated and coagulated inside the combustion chamber of a diesel engine to form larger particles. Other particles can be either a stand-alone metallic ash, derived from the lubricating oil, fuel containing additives, or metallic ash that has joined the soot particles. As the combustion gases are expelled, the dilution process may also produce sulfuric acid particles, hydrocarbon particles or a combination of sulfuric acid nuclei coated with adsorbed layers of hydrocarbons. Sulfuric acid and hydrocarbon species may also adsorb or condense onto the soot chain agglomerates instead of forming new, stand-alone particles.

All particles emitted from diesel engines are in the respirable size range. The greatest numbers of particles tend to concentrate in the “ultrafine” range of 3–100 nm in diameter, which is 1,000 to 10,000 times smaller than the average human hair. The ultrafine range usually contains soot particles larger than 30 nm in diameter, and volatile nuclei mode particles smaller than 30 nm that form as a result of dilution and cooling of hot exhaust.

The greatest mass of particles, on the other hand, resides in the accumulation mode with a diameter from 100–300 nm. These particles are soot chain agglomerates that are generated by the combustion process. The coarse mode particles are larger than 2,500 nm in diameter, and are generated by the break-up of soot from the internal walls of the combustion chamber and the exhaust system. These coarse particles also contribute slightly to the mass.”

This is confirmed by particle size and distribution (PSD) measurements by Jung et al. [2].

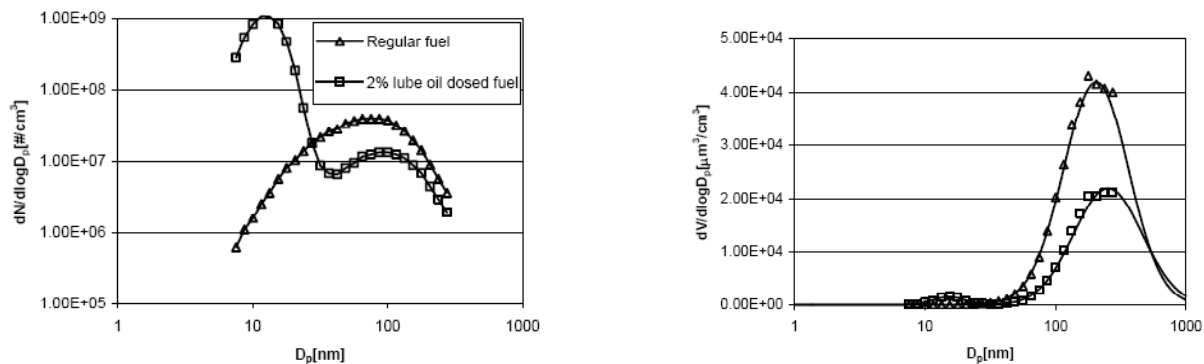


Figure 1: Size distributions at 1400 RPM, 75 % (300 N·m). (a) (Left) Number weighted size distributions of 2 % lube oil dosed Diesel particles in comparison with base fuel. (b) (Right) Volume weighted size distributions of 2 % lube oil dosed Diesel particles in comparison with base fuel.

1. <http://www.swri.org/3pubs/ttoday/Spring06/Particulars.htm>
2. “The Influence of Engine Lubricating Oil on Diesel Nanoparticle Emissions and Kinetics of Oxidation”, Heejung Jung, David B. Kittelson and Michael R. Zachariah, University of Minnesota, http://www.enme.umd.edu/~mrz/pdf_papers/2003_SPIE.pdf

Direct Evaluation of the Sensors:

Numerous studies of particle loaded (used) diesel oil and other contaminated oils have clearly indicated that the ViSmart sensor is not negatively impacted by soot and have clearly indicated that ViSmart sensor can measure soot loading effects. It should be noted that the immunity to fouling is a function of the coating on the surface and the packaging structure as other researchers have indicated soot fouling issues with poorly prepared quartz crystal sensors. These issues occur when bare crystal and metal are exposed to the soot laden fluids and electrically charged. The ViSmart sensor is electrostatically shielded from the oil and passivated both electrically and chemically with a non-stick, abrasion resistant surface. Fouling problems are historically also limited to non-planar (i.e. 3-dimensionally immersed) sensors wherein the flow is not able to continuously clean the single planar surface. This typifies both tuning fork resonators and simplistically packaged QCM sensors. The ViSmart sensor leverages advanced materials and advanced packaging to eliminate this fouling problem with proper sensor insertion into the system.

The question of ability to measure viscosity changes due to soot loading is readily answered by two sets of experimental data. One set looks at artificially loaded samples of clean oil with known addition of soot. The other examines the correlation of ViSmart data and lab data for a family of new and used samples and indicates good reproducibility of correlation across the family. For completeness, fuel dilution data is also presented.

Fuel Dilution in Oil

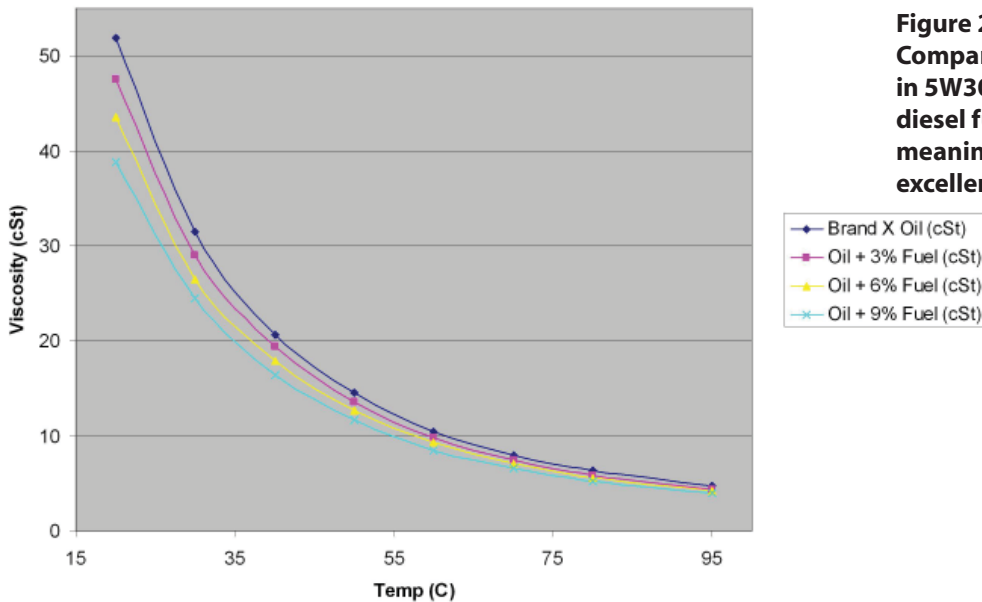


Figure 2:
Comparison of two prototype sensors in 5W30 oil with 0%, 3%, 6%, and 9% diesel fuel dilution (by volume) shows meaningful sensor dependence and excellent sensor-to-sensor tracking.

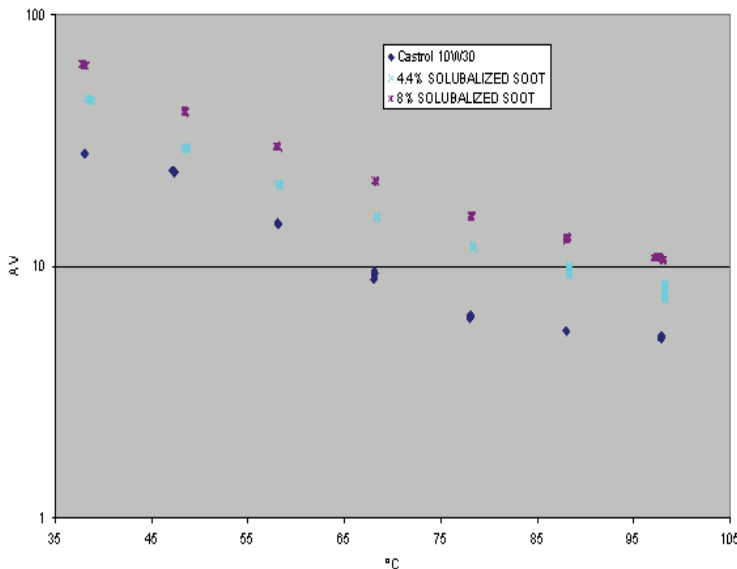


Figure 3:
Comparison of customer-provided 10W30 samples with zero, 4.4% and 8% dissolved soot measured with two ViSmart sensors.

The data above clearly indicates a reproducible measurement of artificially “spiked” oil samples with known quantities of soot. It is therefore readily apparent that the sensor offers differing responses to differing additions of soot into oil. A secondary question of how well the effect relates to the effect the soot or other contaminants would have on the laboratory measurement and how well the sensor correlates to laboratory data are also germane. These questions are addressed through third party data from a European test lab and joint data taken by Vectron and an industry partner under a double-blind correlation study.

The data is reported in acoustic viscosity units ($cP \times g/cm^3$) and does not directly demonstrate a 1:1 correlation to intrinsic viscosity (cP or mPa-s) or kinetic viscosity (cSt or mm^2/s) data. The third party (European test lab) data in Figure 4 shows that there is a linear correlation between these values. The average of the two sensor’s slopes of correlation is 1.586. Temperature differences between sensor and lab data were not corrected and were not identical for the two sensors. Temperature differences of as much as 1°C were noted.

The correlation term contains a factor of $1/\rho$ and the remaining factor is due to the relaxation time constant of the oil. The relaxation time of the oil molecules affects the resonant sensor as:

$$AV = \rho \times cP / (1 + \omega^2 \tau^2)$$

$$cP = AV \times [(1 + \omega^2 \tau^2) / \rho]$$

where $\omega = 2\pi \times 5.3 \times 10^6$ radians/second for the low shear sensor. For a density of $0.88 g/cm^3$ the time constant is estimated as ~ 19 ns.

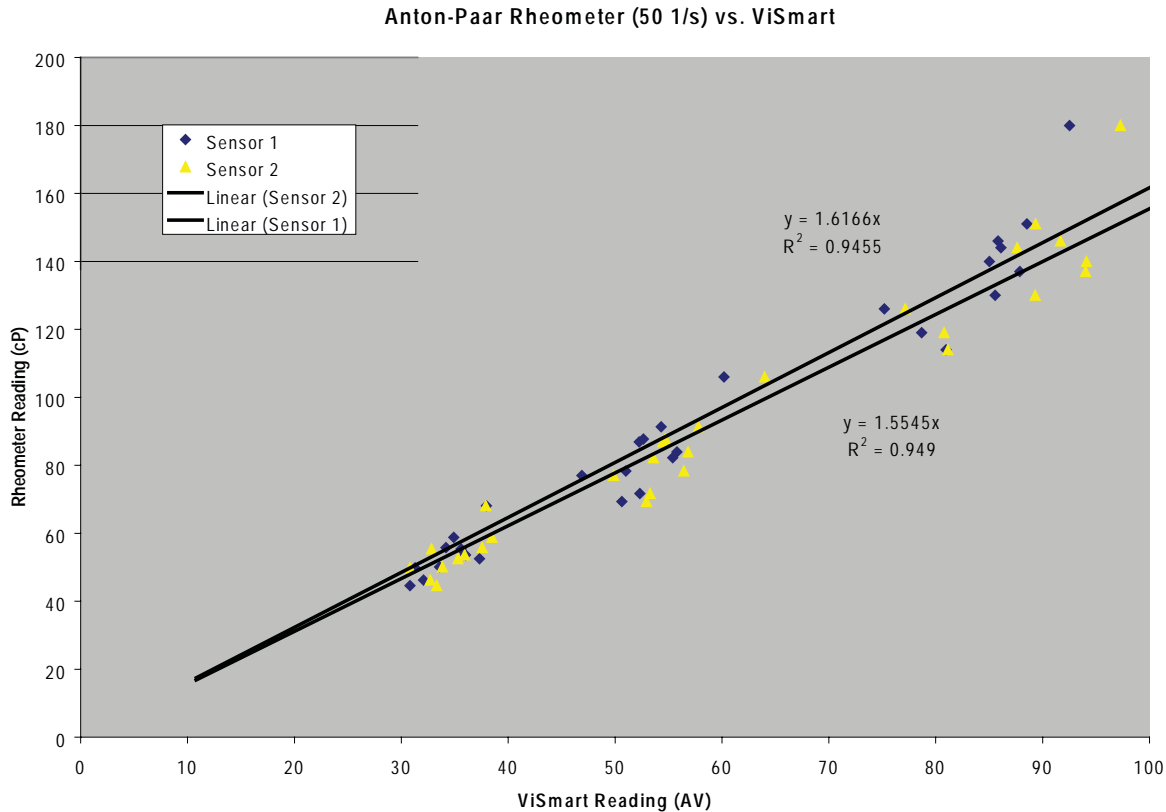


Figure 4: Correlation of cP to AV for 10 “gas engine” oils comprising a series of new and used fluids. No segregation into new and used clusters of data is observed, indicating that the contamination has correlated effect on lab and sensor data.

Additional third party data from a joint study is also available. The viscosity data for all of the oils identified as mineral oils in the sample set are plotted and curve fitted in Figure 5. There may be other mineral oils that are tested but are not labeled as mineral oil. These samples are not included. The correlation factor R-square is very close to unity for mineral oils. A similar plot is given in Figure 6 for the known synthetic oils excluding Mobil SHC 639.

**ViSmart Solid-StateSensor vs. Lab (ASTM) Viscometer
All Mineral Oils, Various Temp, Shear Rate 512**

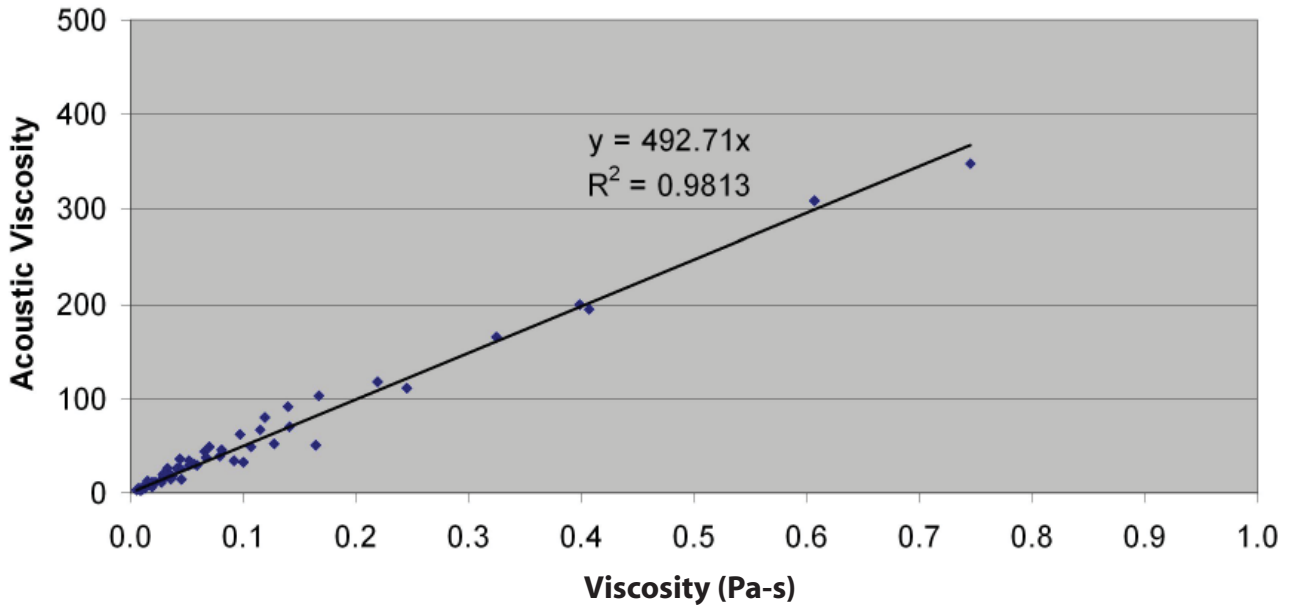


Figure 5: Correlation with All Mineral Oils in mineral oil data set. Note that cP = mPas and the correlation factor is 0.98 for this data set. The lower factor of Figure 4 (higher slope in this chart) would be more representative if only the higher temperature (lower viscosity) region were fit.

**ViSmart Solid-StateSensor vs. Lab (ASTM) Viscometer
All Synthetic but Mobil SHC 639, Various Temp, Shear Rate 512**

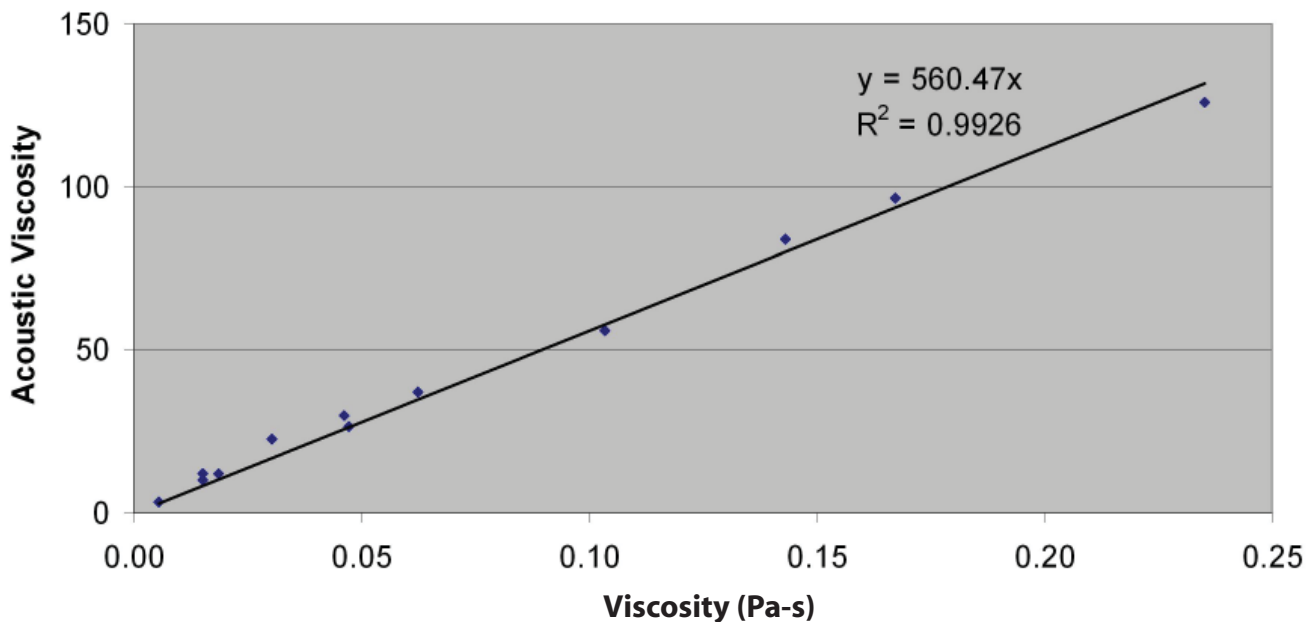


Figure 6: Correlation with Synthetic Oils w/o Mobil SHC 639 yields a correlation factor of 0.99.

A specific subset of the data related to oils aged in actual use in jet turbines in military aircraft. Oil samples #JT1-JT22 and #JT100-JT117 are two oils that went through aging up to 200 hours in jet turbines. Their viscosity data are plotted in Figures 7 and 8 respectively. Good correlation was still maintained for the aged oils, confirming that the sensor is tracking the laboratory observation of changes in oil properties through the aging process.

**ViSmart Solid-StateSensor vs. Lab (ASTM) Viscometer
Oil #JT1 -JT22, Various Temp, Shear Rate 512**

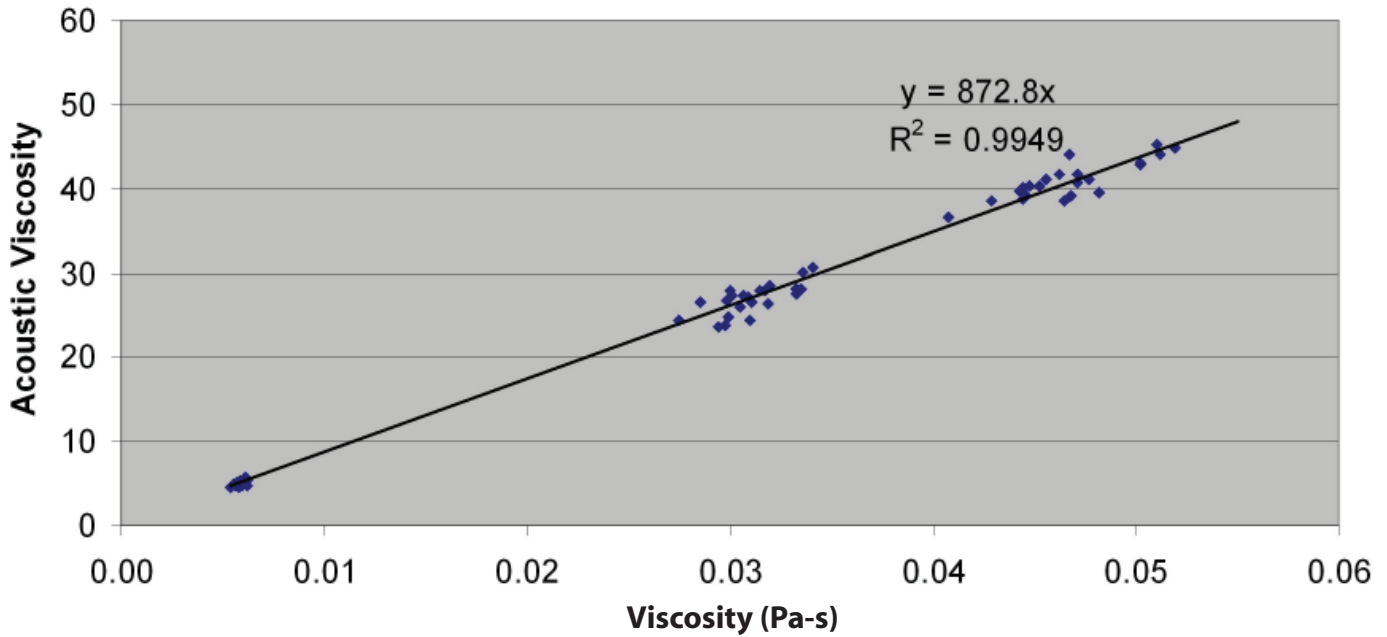


Figure 7: Correlation with Oil Samples #JT1-JT22

**ViSmart Solid-StateSensor vs. Lab (ASTM) Viscometer
Oil #JT100 -JT117, Various Temp, Shear Rate 512**

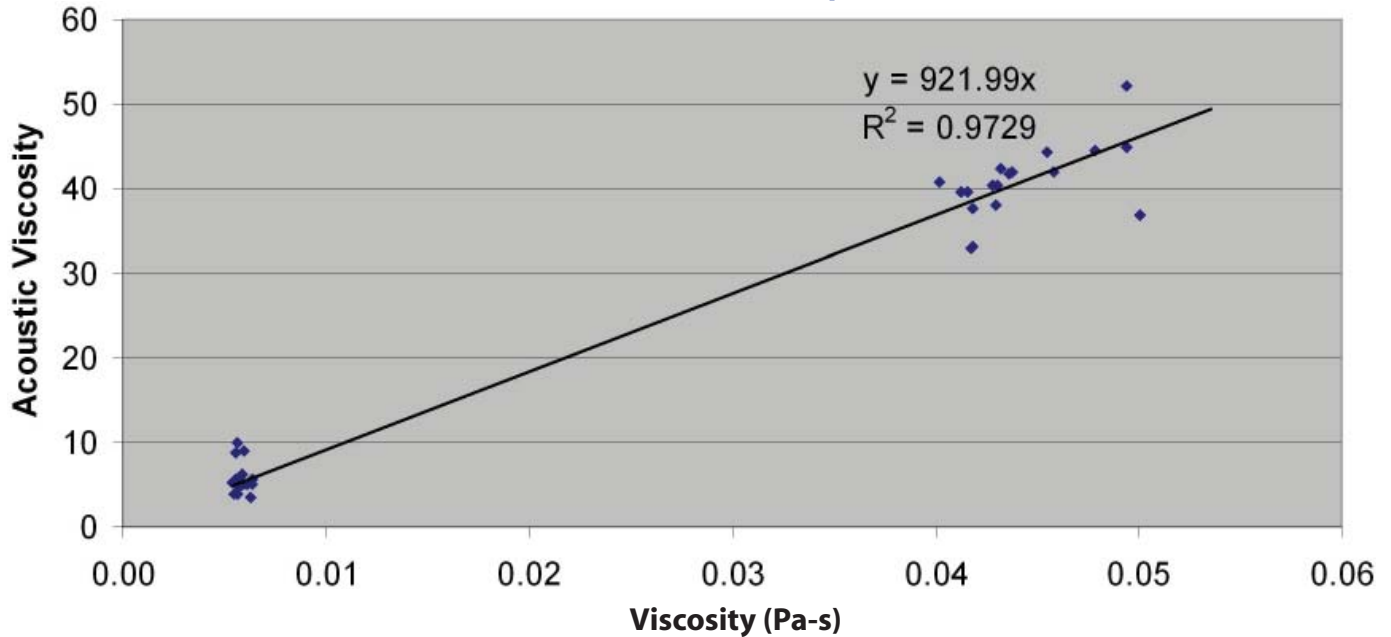


Figure 8: Correlation with Oil Samples #JT100-JT117

Conclusions:

It can only be concluded from the foregoing discussions and data that the ViSmart sensor is sufficiently robust to tolerate particulate-laden environments, does not readily foul in dirty environments, and correlates to low shear rate, non-resonant measurement methods through a meaningful range of fuel dilutions, soot loadings, variations in blend, and oxidative aging.

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