

Correlation of solid-state viscosity sensor to lab methods for oil condition monitoring for fixed and mobile equipment

Introduction:

There exists a critical need in the mobile and fixed asset market to empower field units to determine oil quality on demand and provide complementary oil condition information that has been traditionally obtained from oil analysis labs. The current methodology of testing in off-site labs is non-optimal and costly due to the logistical challenges of shipping samples and the time delay in getting information back to personnel to be able to make quick and informed decisions. Determining oil quality in real-time with embedded and portable oil assessment devices operated by mechanic personnel provides the operational flexibility and rapid means of screening oil quality that is key to establishing a program to provide real-time condition based monitoring products for the care of all assets.

Measuring the viscosity of oil is a rapid method of determining oil condition, and is considered an important parameter in assessing asset readiness. The viscosity sensor which can compliment IR spectroscopy and other bulk property sensors can provide instantaneous on-line viscosity and temperature data, has no moving parts with an extremely wide operating range and offers universal plug-n-play connectivity for integration with and into other handheld products. The SenGenuity viscosity sensors have been tested in actual commercial specified oils in order for a correlation function to be established between the ASTM methods acquired dataset and the sensor generated viscosity values; these correlation functions can be stored on any handheld for automatic conversion. The SenGenuity viscosity sensor is currently installed in commercial markets such as machine tool oil monitoring and coating applications in rigorous environments where ROI benefits have been realized, and are now being evaluated for mobile and fixed assets where oil condition monitoring is of paramount importance.

Contaminants in oil (water, solvents and fuel) are known to degrade viscosity and cause damage to internal components of diesel assets, whether they are trucks or construction equipment or military vehicles. High water contamination levels in diesel fuel have been shown to be the reason for corrosion and pitting leading to increased metal wear particle counts. The presence of residual cleaning solvents and fuel contamination has caused seals to swell and create less than ideal engine operating situations. Knowledge of viscosity in real time provides a significant benefit to measure aging of oil, ingress of contaminants during commercial operations and prevent incipient mechanical failure due to loss of oil lubrication properties.

Conventional mechanical and electro-mechanical viscometers designed primarily for laboratory measurements are difficult to integrate into the control and monitoring environment. As a consequence, many companies rely on decisions based on intermittent "snapshot" data acquired from periodic sampling where conventional instrumentation can be affected by temperature, shear rate and other variables.

Acoustic wave (AW) sensors offer a number of advantages over conventional mechanical and electromechanical viscometers as they are small solid-state devices that can be completely immersed in the oil providing an instantaneous viscosity data stream for embedded OEM or end-user spot-check applications. The sensors are unaffected by shock or vibration or by flow conditions so they can be used in harsh operating conditions to measure viscosity with a temperature range of -25°C to 125°C with a high degree of accuracy. At the same time, sensor measurements are not affected by particulates.

SenGenuity's low shear viscosity sensor that is packaged as a bolt is targeted at embedded integration to fixed and mobile diesel assets and provides a real-time, in-line instantaneous monitoring of viscosity. A customer has tested the low shear viscosity sensor on 600 samples of new and used oil ranging from hydraulic to turbine to gear to diesel engine oils. The data has been correlated to lab measurements by this and other customers thereby resulting in viscosity data which bridges the traditional dataset to the new methods of measurement.

Technology:

SenGenuity, a designer and manufacturer of AW based sensor products, has developed a unique method to offer a viscosity sensor with a wide dynamic range in a single sensor (Figure 1).

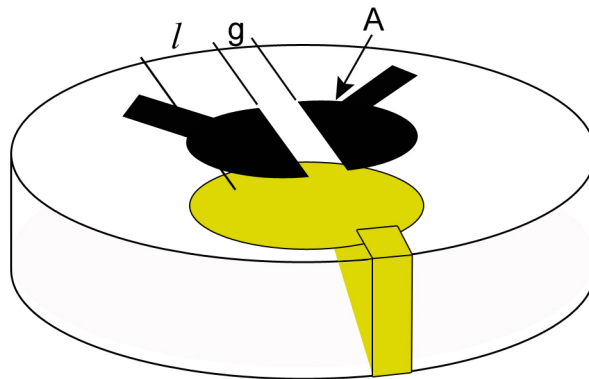


Figure 1. The Mono-Crystal Filter (MCF) design based Viscosity Sensor

The SenGenuity ViSmart™ is a commercially available, robust, reliable and cost-effective surface acoustic wave solid-state threaded-bolt viscometer for integration into in-line, real-time monitoring and process control systems for scalable applications

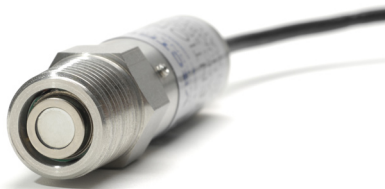


Figure 2. SenGenuity solid-state ViSmart™ sensor

The sensor has no moving parts (other than the atomic scale vibration of the surface) and, due to the high frequency of the vibration, several millions of vibrations per second, is independent of flow conditions of the liquid and immune to vibration effects of the environment. High temperature electronics are utilized that allow a very wide operating temperature range for the sensor.

The importance of these acoustic sensors lies in the distinctly different measurement principle. Whereas one class of mechanical devices measures kinematic (flow) viscosity and the other class measures intrinsic (friction) viscosity, the acoustic wave (AW) sensors measure acoustic impedance, $(\omega\eta)^{1/2}$, where ω is the radian frequency ($2\pi F$), ρ is the density and η is the intrinsic viscosity.

The viscosity measurement is made by placing the quartz crystal wave resonator in contact with liquid. The liquid's viscosity determines the thickness of the fluid hydro-dynamically coupled to the surface of the sensor. The sensor surface is in uniform motion at frequency, $\omega = 2\pi F$, with amplitude, U . The frequency is known by design and amplitude is determined by the power level of the electrical signal applied to the sensor. As the shear wave penetrates into the adjacent fluid to a depth, d , determined by the frequency, viscosity and density of the liquid as $d=(2\eta/\omega\rho)^{1/2}$, as depicted in Figure 3.

Acoustic viscosity is calculated using power loss from the quartz resonator into the fluid. The unit of measure is acoustic viscosity (AV) and is equal to $\rho\eta$, ($\text{g}/\text{cm}^3 \cdot \text{cP}$).

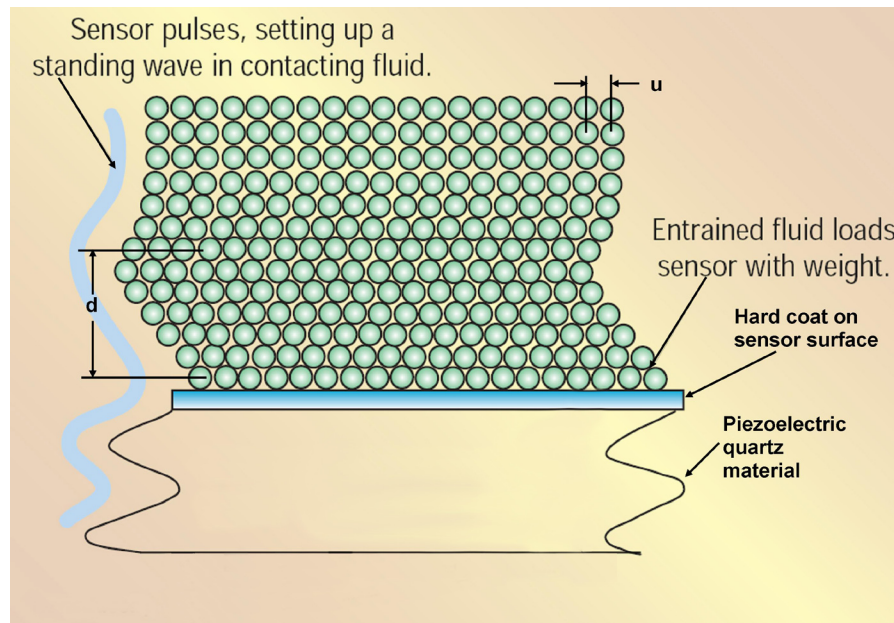


Figure 3. Cross section of the sensor showing transducers on the lower surface and liquid molecules on the upper surface.

Acoustic viscosity is calculated using power loss from the quartz resonator into the fluid. The unit of measure is acoustic viscosity (AV) and is equal to $\rho\eta$, ($\text{g}/\text{cm}^3 \cdot \text{cP}$) density times dynamic viscosity.

The acoustic wave resonator supports a standing wave through its thickness. The wave pattern interacts with electrodes on the lower surface (hermetically sealed from the liquid) and interacts with the fluid on the upper surface. The bulk of the liquid is unaffected by the acoustic signal and a thin layer (on the order of microns or micro inches) is moved by the vibrating surface. Also present is a proprietary hard coat surface that is scratch proof and abrasion resistant which allows the sensor to be operable in extreme environments and enabling AW sensor to be a suitable candidate for oil condition based monitoring applications in mobile and fixed asset markets.

Testing for the Evaluation of the Oils

Significant testing has been accomplished by the oil condition based community in order to ascertain the performance for the solid-state viscometer. The tested oils fall in two categories: clean and contaminated. The viscosity values for the oils are measured at ASTM approved rheometer equipment (at 512 1/s shear rate) and with the solid-state sensor at the following temperatures of 30°C, 40°C, 60°C, 100°C. Based on this data, functions are generated to interpolate the viscosity for intermediate temperatures.

The SenGenuity low shear solid-state viscosity sensor measures the acoustic viscosity (AV), which is the product of dynamic viscosity and mass density. Dynamic or kinematic viscosity is more commonly used in industry. The goal by customers is to establish correlation between acoustic viscosity and dynamic viscosity.

Correlation with All Oil Samples

The viscosity data of all oil (hydraulic, gear, engine, turbine, et al) samples at different temperatures are plotted and curve fitted, as shown in figure 4. We can see that most data points fall in the same trend except for a few points. The correlation factor R-square is 0.9107, which means an accuracy of 91%. The outliers are from extremely thick synthetic oil (1,000 and 3,000 cP) that almost reaches the limit of the viscosity sensor measurement range. If these outliers are taken out, the curve become steeper and correlation factor is slightly improved, as shown in figure 5.

The equation in figure 5 can be used as a default correlation equation when oil type is unknown or when the oil type is not covered by correlation study and represents 92 percent accuracy for the SenGenuity solid-state viscosity sensor.

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

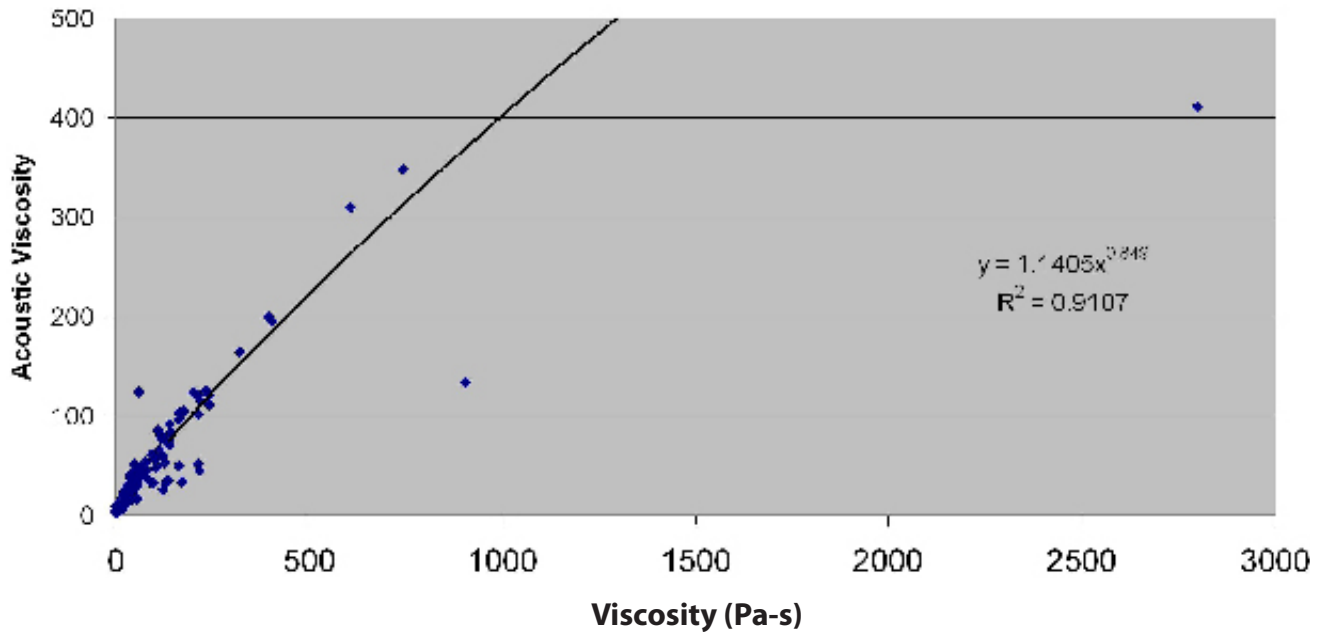


Fig. 4 Correlation with All Oil Samples

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

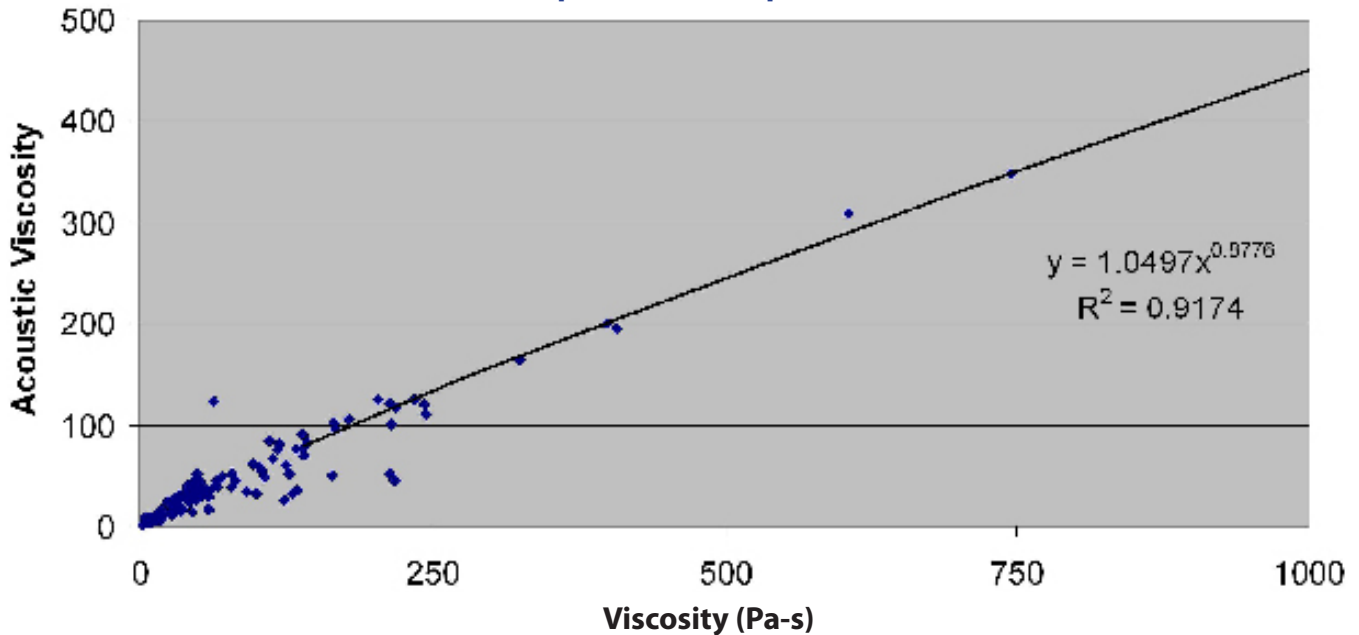


Fig. 5 Correlation with All Oil Samples w/o Outliers

The viscosity data for all known mineral oils in our sample inventory are plotted and curve fitted in figure 6. These oils are mostly Mobil or Exxon mineral oils and are inclusive of other manufacturers.

The correlation factor R-square is very close to unity for mineral oils for the SenGenuity solid-state viscosity sensor.

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

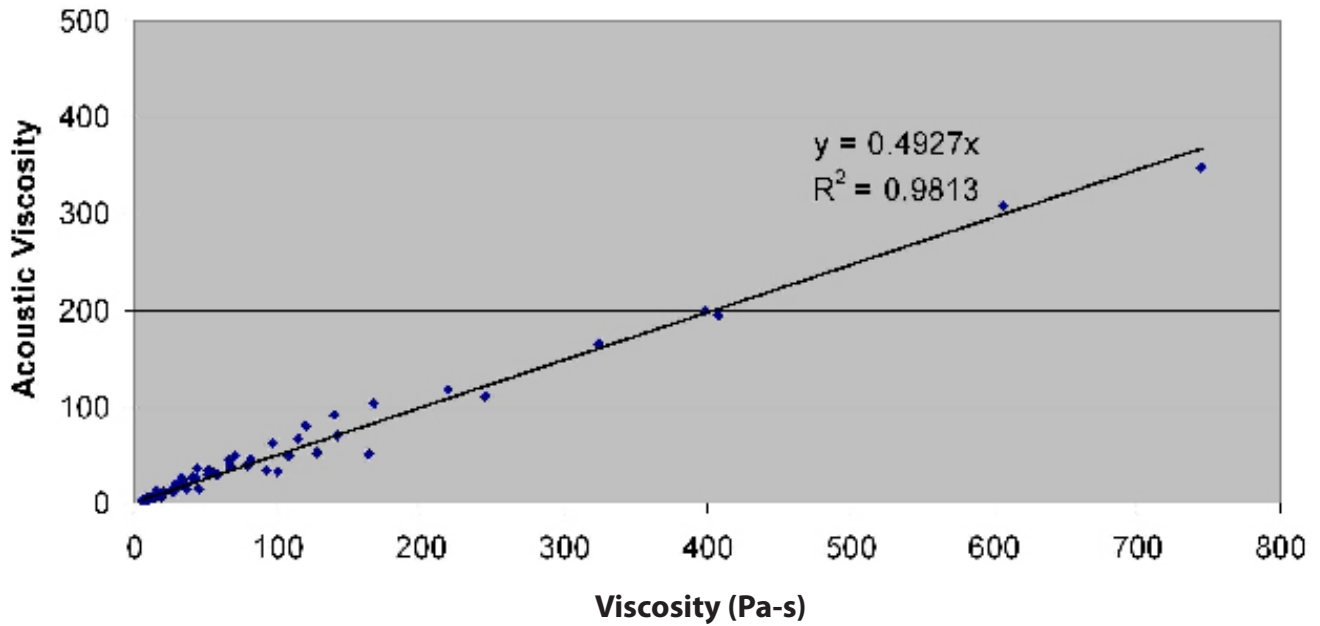


Fig. 6 Correlation with All Mineral Oils

The viscosity data for synthetic oils within our sample inventory are plotted and curve fitted in figure 7. If one curve is used to fit all the synthetic oils, the correlation factor is 0.9249.

It is important to note that figure 8 denotes the correlation function to a single oil (Mobil SHC 639, ISO 1000 grade); observe the 99 percent accuracy for the SenGenuity solid-state viscosity sensor.

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

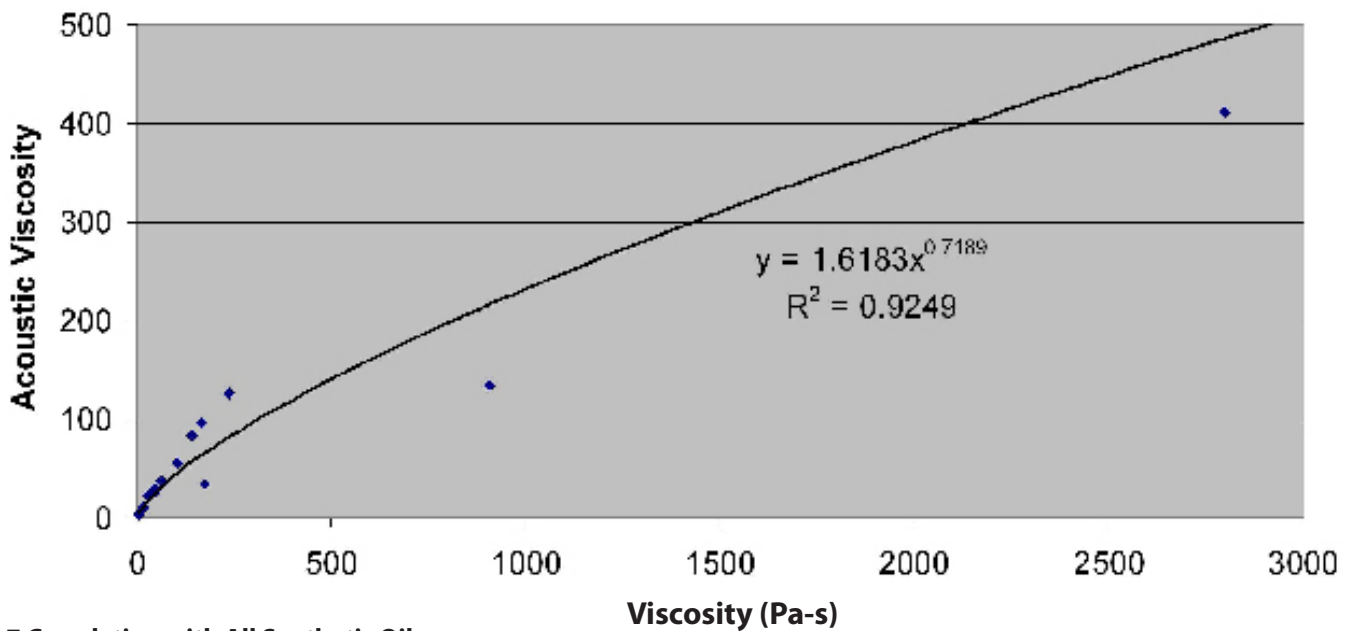


Fig. 7 Correlation with All Synthetic Oils

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

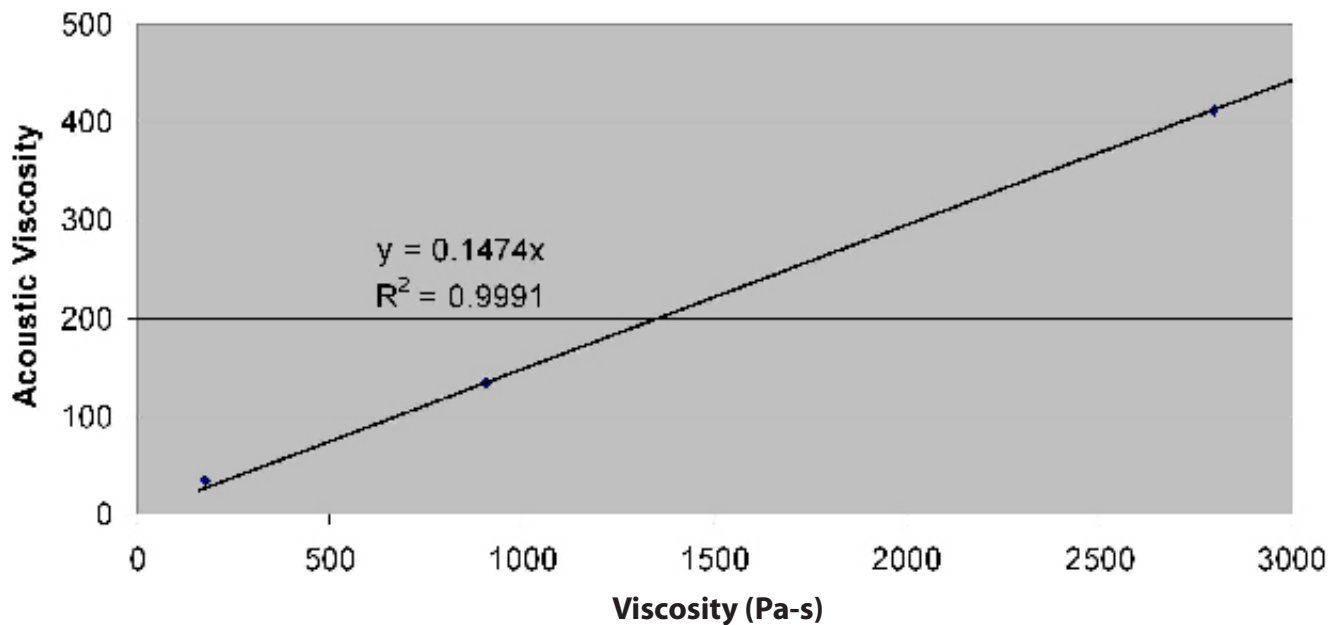


Fig. 8 Correlation with Synthetic Oil Mobil SHC 639

All the correlation equations are in the form of:

$$X = AY^B$$

Where, X is the acoustic viscosity and Y the dynamic viscosity. A and B are parameters that depend on oil types.

If SenGenuity does not have any information about oil type, standard equations can be used with the correlation factor is 0.9107. If SenGenuity determines the oil type, the correlation can be further improved (determination either with a quick test, or look up in the database).

Conclusions

The conclusions that can be drawn from the data above and the customer testing are:

1. There is correlation between lab method and Vectron viscosity sensor for each oil (or group of oil), and that a library of "fresh oil" correlations is practical.
2. The SenGenuity ViSmart™ viscosity sensors operate at repeatable shear rates that are relevant to the assets being lubricated under normal operating conditions.
3. The ViSmart™ sensors offer acceptable correlation to lab measurements at these shear rates.
4. The correlation changes with aging and contamination of the oil, since aging and contamination change the oil and the shear rate at which the oil is measured.
5. Deviations of the oil from a predefined interpolation function at any temperature is a significant means of screening oil quality and is more accurate than "compensating" to 40°C.
6. Evaluating deviations in "acoustic viscosity" is of comparable value to using kinematic viscosity. That is, independent and accurate knowledge of density is only important for correlation between on-site sensor testing and lab data.

Benefits

The commercially available SenGenuity viscosity sensor can be readily applied in field operations or installed at on-equipment for continuous monitoring of viscosity to enable the mechanic personnel to test the oil in minutes. It would be complementary to lab oil analysis test burden by providing real-time viscosity data and would enable streamlining of logistic costs. And given no calibration is required for the rugged vibration and shock proof sensor that is already in use in harsh industrial environments, maintenance costs are extremely low.

The SenGenuity viscosity sensors are currently used in 24/7 applications in the commercial sector, with real-time data transfer for decision making abilities. The real-time in-line thread bolt sensor can be fully immersed in the oil or simply used for spot-checking. Providing real time viscosity data and using the sensor continuously would provide the necessary information to personnel to make critical decisions in actual field applications leading to extension of machine life and maintenance schedules while complimenting the other oil quality parameter data stream obtained from the labs.



Figure 9. SenGenuity solid-state ViSmart™ sensor

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