SPECTROVISC Q3000 SERIES VISCOMETER – A PORTABLE KINEMATIC OIL ANALYSIS SOLUTION FOR FIELD-BASED USERS

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Synopsis

This paper describes how using the handheld, solvent-free SpectroVisc Q3000 Series device in the field provides immediate and accurate kinematic viscosity measurements, even when compared to traditional laboratory viscometers. The SpectroVisc Q3000 Series uses new solvent-free technology to accurately perform kinematic viscosity measurements requiring no calibration, no density verification, and no temperature measurement.

The focus of this paper is to first provide details on the SpectroVisc Q3000 Series' design and then describe how that design performs compared to traditional laboratory viscometers. Finally, a case study compares the measurement results between the SpectroVisc Q3000 Series portable, kinematic viscometer and the SpectroVisc capillary (Modified Zeitfuchs) tube viscometer used in many commercial oil analysis labs.

1. Traditional Viscometer Theory and Design

Current viscosity measurement techniques rely heavily on the use of capillary, cone and plate, and concentric cylinder viscometers. These devices are mainly limited to the laboratory setting and contain obstacles to portability. While the capillary viscometer suffers from difficult and lengthy procedures for calibration, cleaning, and temperature control, the rotational viscometer is hindered by its rotating parts and delicacy. Higher sensitivity viscometers have since been developed based on differential or light scattering methods, but these are expensive and laboratory based [1-4].

Some commercial instruments have been developed to address a need for portable viscosity measurement, especially where it is essential to determine the status of critical fluids in real-time. Such viscometers include attempts at miniaturization of the differential [2] and rotational viscometers [5-7]. Although these devices reduce sample volume, certain components remain complicated and costly, posing a challenge for their widespread adoption.

Other devices and methods have recently developed based on MEMS technology, including membrane oscillation frequency measurement [8-10], acoustic wave measurement [11], the piezoelectric actuated cantilever [12] and the shear resonator [13]. Despite requiring reduced sample volumes, many of these devices lack temperature control and are not kinematic in nature, so may not yield comparable results.

2. SpectroVisc Q3000 Series Viscometer Theory and Design

The SpectroVisc Q3000 Series viscometer design includes an upper sample-loading well, microchannel, and temperature control electronics to measure fluids at a constant temperature of 40°C. Two models are available: the Q3000 which measures viscosity over the range 10-350 cSt and the Q3050 viscometer with a range of 1-700 cSt. The SpectroVisc Q3050 also calculates oil viscosity at 100°C from the 40°C measurement with the input of the Viscosity Index for the fluid.

Operation of the device is simple; after loading ~60µl oil into the upper well of the chip, gravitational force causes the fluid sample to flow down the microchannel where a combination of emitters and detectors in the IR range detects its rate of progression. It requires no user calibration, temperature measurement, or density analysis. This viscometer operates as a Hele-Shaw cell, where Stokes flow is present between two parallel plates. The distance between plates is necessarily small relative to the width and height of the plates. As depicted in the schematic diagram of Figure 1, the presence of only two parallel plates causes the microfluidic device to be unbounded, meaning that the fluid is exposed to air on two sides.
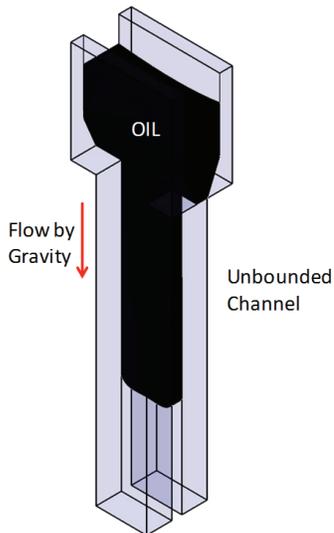

Figure 1: Micro Fluidic Kinematic Viscometer - Schematic

The unbounded microchannel is very advantageous for cleaning; you just wipe the microchannel surfaces after separating the two parallel plates to clean the device. The optical detection method, where LEDs positioned on the one side of the microchannel and respective photodiodes on the other side are not obstructed by side walls, is also advantageous.

Although overflow of the microchannel might have been a problem based on the absence of side walls, surface tension generates a concave meniscus between oil and air, as seen in Figure 2. To have a positive pressure that forms this concave meniscus requires an oleophilic material.
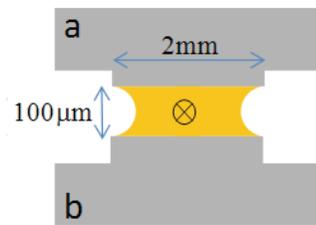

Figure 2: Concave Meniscus – Top View

The laminar flow condition dictated by the small gap between plates ensures the flow can be modeled as existing only in the vertical direction. At steady state under laminar flow conditions, viscous and gravitational forces are balanced such that

$$\mu \frac{d^2 u}{dy^2} + \rho g = 0$$

(Equation 1)

where µ is dynamic viscosity, u is velocity, r is fluid density and g is gravitational acceleration. From that, the kinematic viscosity of the fluid can be determined using the average velocity,

$$\nu = \frac{g d^2}{12 U}$$

(Equation 2)

where U is the average velocity, g is the gravitational acceleration, and d is the channel depth.

Here the $\frac{d^2u}{dx^2}$ term is neglected because the geometry of the microchannel is straight and the fluid is moving due to only gravitational force. Near the funnel region this one dimensional equation is not valid due to transient effects of viscous forces balancing gravitational force.

Regardless, these effects are avoided with placement of the optics sufficiently down the microchannel.

To successfully operate the device as a Hele-Shaw cell depends on the aspect ratio of the microchannel being large enough. However, hydrostatic considerations must be considered due to the unbounded design. If the hydrostatic pressure by the oil exceeds the opposing pressure due to surface tension, the fluid will overflow through the unbounded sides. To maximize surface tension, aluminum acts as a microchannel material because it can be easily machined and forms a small contact angle with the investigated oils. For example, the contact angle between engine oil and aluminum surface is 2.73 degrees and engine oil surface tension is approximately 31mN/m. The surface tension induced pressure value at the unbound surface is

$$\Delta P = \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \sim 620\,Pa$$

where R1 is radius of meniscus (half of microchannel depth; 50µm) and R2 is infinite (the plate width in relative terms is very large).

It reasons that 620Pa is the maximum hydrostatic pressure that the surface tension can hold when two aluminum plates are 100µm apart. Therefore, the maximum length of the microchannel is

$$\Delta H = \frac{\Delta P}{\rho g} \sim 76\,mm$$ based on the previous calculation, as well as the variety in surface tension and contact angle among oils, the microchannel length used in the Q3000 series viscometers is 42mm.

Figure 3a and 3b shows the two aluminum plates that were created by an ultra precision computer machining system and how they attach to a hinge that allows easy opening and closing.
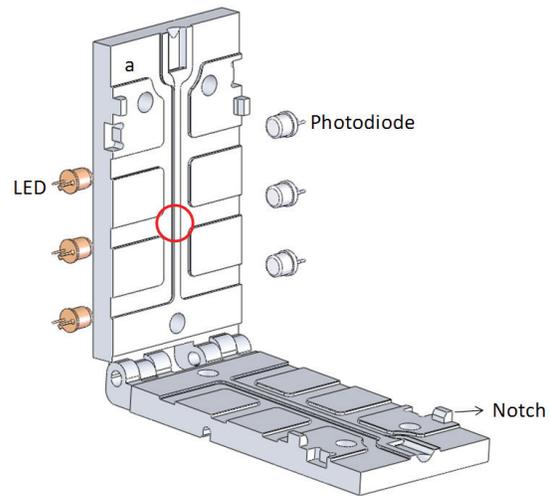

Figure 3b: LEDs and Photodiode Positions

The fluid passing between an LED and a photodiode causes a drop in the photodiode voltage. Using the time points that mark these voltage drops, the average velocity of the oil calculates from the elapsed time between photodiode 1 and 2 as well as photodiode 2 and 3. The average velocity is then used in Equation 2 to generate a kinematic viscosity for the measured sample. Two resistance temperature detectors (RTDs) embedded within the aluminum plates enable a custom designed proportional-integral-derivative (PID) controller attached to a heating element to effectively maintain the temperature at 40°C.

3. Case Study – SpectroVisc Q3000 versus SpectroVisc Q300

Knowing the viscosity of a lubricant is critical for condition monitoring. As a result, fieldbased users need portable viscometers to immediately assess critical equipment while working on-site. Other portable viscometer options currently available as commercial products require solvents, density and temperature measurements to arrive at results. They do not correlate with laboratory viscometers, meaning that the collected data is not cotrended. In-use oils, in particular, make precise viscosity measurements by any technique a challenge given their particulates, water and combustion by-products.

Figure 3a: Aluminum Plates with Hinge

The process of comparing results from one instrument to another involves factors, such as:

- Wide variability in the performance of in-use oils

- Variability in the performance of the viscometers

- Variability in application requirements

Rather than use a single benchmark to compare portable and laboratory viscometers, the following case study provides a method for determining whether a portable viscometer will "do the job" given particular requirements.

For this comparison, a SpectroVisc Q3000 serves as a portable viscometer and a SpectroVisc Q300 as a laboratory viscometer. The SpectroVisc Q3000 is a portable, solvent-free kinematic viscometer developed for applications where immediate results are required. The SpectroVisc Q300 is a capillary (Modified Zeitfuchs) tube viscometer designed for laboratory analysis.

Both instruments measured the viscosity of a number of samples, and the measurements were compared from instrument to field viscometer. Two series of comparisons were made. The first set of samples consisted entirely of NIST-certified standards and the second sample set consisted of used oils.

Each sample was run three times, each on the SpectroVisc Q3000 and the SpectroVisc Q300 with kinematic viscosity readings taken at 40°C. Results from both sets were averaged and compared.

The application of NIST standards allows the accuracy of both approaches to be compared and also to see how closely the portable Q3000 reproduces results consistent with those of the laboratory. The used oil measurements, on the other hand, are for real-world, immediate results. Here the actual viscosities are unknown, making absolute accuracy comparisons impossible. The goal is to determine how the portable tool compares to the laboratory instrument across a spectrum of widely varying samples. If the results from the two approaches are "close enough" for the user, the portable tool can be substituted for the analytical instrument.

Figure 4 shows the performance of the Q3000 compared to the SpectroVisc Q300 over a range of certified viscosity standards. The Q3000 performs consistently across the calibrated range, with a relative standard deviation less than 2%.
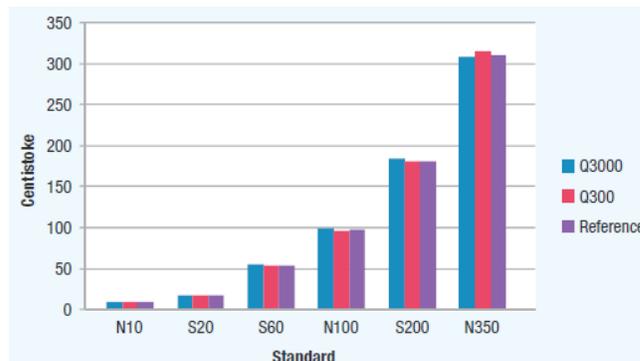

Figure 4: Q3000 vs. Q300 Performance Using a Range of Certified Viscosity Standards

4. Results

The following data was obtained using a range of certified viscosity standards:

- Table 1 compares the Q3000 against the NIST references

- Table 2 compares the Q300 against the NIST references

- Table 3 compares results from the two solutions directly

- Table 4 compares used engine oils

TABLE 1		
Q3000	Ref	% Diff
10.13	10.03	1.00
17.93	18.04	0.61
54.86	54.08	1.44
99.26	97.15	2.17
185.00	180.80	2.32
308.67	310.90	0.72
Portable Viscometer Q3000		

TABLE 2		
Q300	Ref	% Diff
10.02	10.03	0.11
18.06	18.04	0.09
53.79	54.08	0.54
96.64	97.15	0.52
180.93	180.80	0.07
314.90	310.90	1.29
Lab Viscometer Q300		

TABLE 3		
Q3000	Q300	% Diff
10.13	10.02	1.11
17.93	18.06	0.70
54.86	53.79	2.00
99.26	96.64	2.71
185.00	180.93	2.25
308.67	314.90	1.98
Portable Q3000 vs. Lab Q300		

TABLE 4			
Sample	Q3000	Q300	% Diff
Used Engine Oil	54.56	55.24	1.22
Used Engine Oil	108.67	111.63	2.66
Used Engine Oil	132.00	128.80	2.48
Used Process Oil	158.33	161.80	0.98
Gear Oil	237.00	230.30	1.03

Not surprisingly, the Q300 laboratory viscometer yielded results that are in line with referenced ASTM norms (0.44%) for variation. The portable Q3000 reported results were within its expected 3% specification, and the results from the Q3000 and the lab-based viscometer were also within 3% (Table 3). In the used oil comparison, Table 4 shows that results from the portable Q3000 were consistently within 3% of the bench top Q300.

5. Conclusion

The key question is whether 3% is adequate in the context of the user's specifications. As mentioned earlier, used oil can present significant challenges for repeatability measurements, especially with oil, water, fuel and particle contamination — any of which can drive repeatability above 5% between tests of the same sample. OEM engine and rotating equipment providers and users consider viscosity variations greater than 10% (from nominal values) to be the first evidence of potential problems. A portable viscometer can detect such issues immediately, allowing improved decision making and more efficient preventive maintenance.

Undoubtedly, the advent of new solvent-free technology for field-based viscosity monitoring offers the performance necessary to detect variations of in-use oil to signal an impending problem at the equipment site. In addition, case study results show agreement within 3% of all samples between traditional laboratory viscometers and the portable viscometers. This indicates that the SpectroVisc Q3000 Series device can deliver accurate results in a portable setting, using a fraction of the sample volumes required by commercial laboratory viscometers.

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