VALIDATING THE USE OF A VIBRATING VISCOMETER AT RESONANCE FREQUENCY FOR FUEL CHARACTERIZATION

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ABSTRACT

Historically, instrument developers strive for additional sensitivity to provide advanced measurement solutions, and viscosity is one of the most sensitive and essential characteristics that determines a fluid’s quality.
Today’s industry specialists widely consider vibrating viscometer technology the most reliable in-process measurement. The technology (vibrating at resonance frequency) provides reliable and repeatable measurement for large viscosity ranges, commonly from 0.1 to 1,000,000 mPa.s.
Described below are resonant vibrating technology and the sensor’s detailed design. Following a simple experimental design, the capabilities of said viscometer on fluids characterized by a low viscosity (<10 mPa.s.), i.e. fuel combustibles, will be evaluated.
In order to address manufacturers’ common and difficult process environments, various temperature conditions are integrated in the discussion.
Finally, the study results are revealed and potential adaptations to other application fields are discussed.

INTRODUCTION

Vibrating technology at resonance frequency usually provides reliable and repeatable measurement for large viscosity ranges, commonly from 0.1 to 1,000,000 mPa.s. Several manufacturers use this technology for viscosity measurement and control in industrial processes. However, some processes work at very low viscosity and, for this reason, require additional sensitivity. This is the case for many fuel manufacturers and refineries, where high-value products require verified repeatability of measurement and control.

Described below are a viscometer’s resonant vibrating technology and specific design research that achieves optimal sensitivity. Following an experimental design, the capabilities of the resonant vibrating viscometer on fluids characterized by a low viscosity (<10 mPa.s.), i.e. fuel combustibles, are evaluated following a simple experimental design.

1- VIBRATING VISCOMETER AT RESONANCE FREQUENCY

Today's industry specialists widely consider vibrating viscometer technology the most reliable in-line measurement. Common technologies offered are piezoelectric (or tuning fork) which provides oscillation at resonance frequency with a mechanical wave correlated to viscosity. Another technology consists of a torsional or plane vibration, with vibration amplitude correlated to viscosity. Later discussed is plane vibration applied to a sensor in order to reach the highest sensitivity measurement possible.

1.1. VIBRATING VISCOMETER SOLUTION

Each sensor has a dedicated electronic device. The two parts are inseparable. The main part of the sensor is composed of a vibrating rod held in oscillation at resonance frequency by drive magnets. When the rod is immersed into a viscous material, the amplitude of the vibration is dampened. The vibration amplitude varies according to the product viscosity in which the rod is immersed.

The sensor has a receiving coil which detects the response. The electronic device acquires the coil's amplitudes and generates various signals. The signals are changed into a measurable property that is to a specific value, like viscosity. In addition, the electronic device powers the whole system and provides process information (viscosity or temperature) through various outputs (current outputs, serial port, or LCD screen).

1.2 VIBRATING SENSOR THEORY

According to Badiane [1], viscosity sensors using piezoelectric material and magnetostrictive material require a high-frequency system. Cantilever structures are used increasingly in applications involving viscosity sensing. The oscillator's vibration is due to an electric current through a coil which is under a static magnetic field. When the mechanical oscillator is immersed into a viscous fluid, vibration amplitude decreases because of energy dissipation.

The sensor is composed of a mechanical oscillator, permanent magnets and two coils. A drive alternative current at fixed frequency is applied through the first coil and serves as the vibration source for the oscillator. This vibration generates induced current in the second coil. It is proportional to the vibration amplitude and, therefore, to fluid viscosity.

1.3 INCREASED SENSITIVITY RESEARCH

In regards to sensitivity increase, keeping in mind that the viscous friction force is more important than the drag force. As a consequence, the cylindrical model of the vibrating viscometer does not address these conditions, thus requiring new sensor geometry. According to fluid-structure interaction theories by Tuck [2] and Stokes [3], the hydrodynamic force is a function of the vibration amplitude.

From here, several sensor geometries are considered. It has been necessary to find a solution increasing the viscous friction force at a maximum level while decreasing the drag force. A design integrating these two conditions in one sensor includes a large surface in a plane parallel to the movement of the rod and a small surface in a plane that moves perpendicular to the rod. This plane design has been deeply studied and patented by Sofraser. [4]

Enhanced patented product includes a design allowing the determination of fluids physical characteristics, and improving sensitivity results of viscosity measurement.

1.4 DESIGN DESCRIPTION

The sensor's design consists of an oscillating element that is substantially rigid, including an axis coupled with a distal part that is considerably flat and stiff. This design provides a large contact surface with the product in a first direction, and an almost negligible contact surface with the product in a second, perpendicular direction. In order to determine the viscosity of a product with high sensitivity, the oscillating element is set in motion in a direction parallel to the sensor plane. Thus, the element oscillates in a direction which is at the same time perpendicular to the axis of the oscillating element and in the plane formed by the sensor.

In Figure 1, a cross-section illustrates a perpendicular view of the plane formed by the sensor.

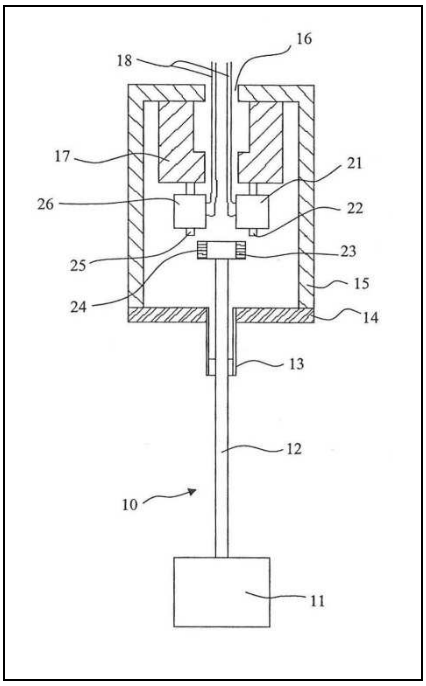

FIGURE 1. PERPENDICULAR VIEW OF PLANE FORMED BY THE SENSOR

When the oscillating element is immersed in the product and set in oscillation at resonance frequency, the different forces that apply on the sensor are:

- the drag force, opposing the sensor movement, expressed as:

$$F_{drag} = C_T . \rho . S . \frac{v^2}{2} \quad (1)$$

Where C_T = drag coefficient depending of the geometric shape of the plane
ρ = fluid density
S = edge surface, perpendicular to the vibration direction
v = plate velocity in the fluid

- and the viscous friction force, expressed as:

$$F_{vis} = \mu . S_a . grad(v) \quad (2)$$

Where µ = dynamic fluid viscosity
S_a = friction surface parallel to viscous force

Oscillation of the oscillating element is realized by minimizing the drag force on the sensor in relation to the viscous friction force, which is maximized by large contact surface of the sensor with the product, parallel to the oscillation direction.

In the oscillation mode illustrated in Figure 2, the oscillating element is set in oscillation following the direction A1. In other words, the oscillating element oscillates in a parallel way to the plane represented by the sensor (11) and substantially perpendicular to the axis (12). In this oscillating mode, the surface Sp of the plate, perpendicular to the vibration direction, becomes negligible. The drag force F_{drag} also becomes negligible.

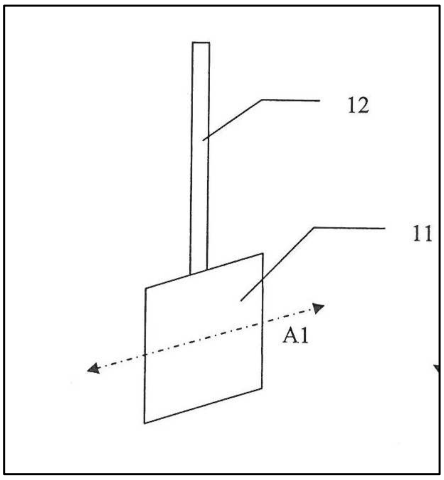

FIGURE 2. THE OSCILLATION MODE OF THE OSCILLATING ELEMENT

Calculations allow that as a function of the vibration amplitude, it is possible to determine the product's viscosity. In a practical way, the correlation is obtained by interpolation at references values.

2- CAPABILITIES OF THE RESONANT VIBRATING VISCOMETER ON FLUIDS CHARACTERIZED BY A LOW VISCOSITY

Described here are methodology and results of a simple experimental design using the resonant vibrating viscometer on low viscosity product. One goal of this experiment is to determine the repeatability and the sensitivity of the sensor, while illustrating sensor capabilities on fluids used by fuel manufacturers and refineries. This simple experimental design is a first step of a larger design of experiment that would include additional parameters such as pressure, density, etc.

2.1 EXPERIMENTAL SET-UP

In normal process conditions, the influence of temperature on viscosity is measured by using a temperature compensation mathematical calculation when required. The influence of temperature on the sensor body is taken into account with thermal drift correction.

In this experimental design context, it is important to isolate each parameter, in order to observe in an independent way each of them (viscosity and temperature). To do so, the sensor body as well as the sensor's vibrating rod, are isolated by two double jackets. The double jackets bring complete isotherms to the measurement and are shown in the 3D drawing in Figure 3. Using this method, both the measured fluid and the sensor body will reach the same isothermal temperature. Reinforcement of the vibration isolation spotlights the sensor repeatability in identical measurement conditions.

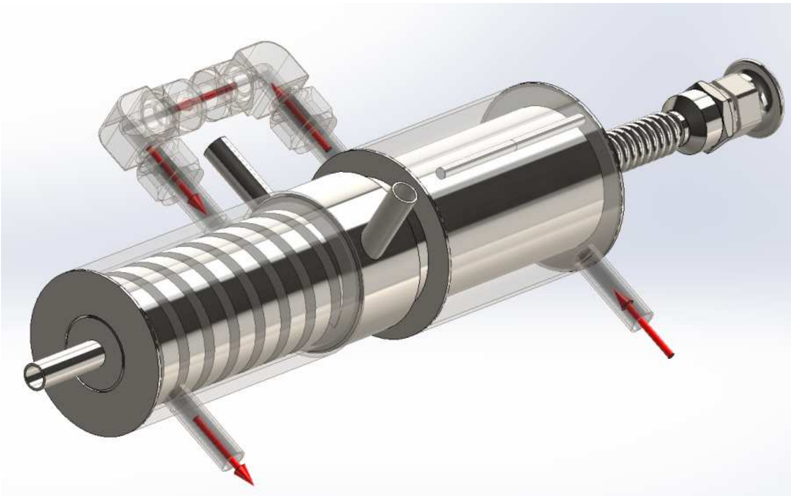

FIGURE 3. EXPERIMENT SENSOR DESIGN, ENTIRE VIEW

2.2 EXPERIMENTAL DESIGN

The experimental design consists of three steps. The first step, which is performed on every sensor that leaves the factory, involves correlating the sensor's response on certified mineral oils. The second step is verifying results of various low viscosity solvents in which viscosity behavior at temperature is known. The last step is testing the sensor on different fuels sourced from different suppliers that are located near the factory. The goal is to demonstrate the discriminate character of the sensor, to indicate viscosity variations according to temperature, and to determine if there are viscosity discrepancies for the identical fuel samples coming from different sources.

2.2.1 CORRELATION ON CERTIFIED MINERAL OILS

The viscosity information provided by the sensor is relative. In same fluid and same environmental conditions, the information is the same. But for two rheological different fluids, the response can be different, but perfectly repeatable. As the sensor provides a relative measurement, it is necessary to make a correlation of the signal given by the sensor electronic on certified calibrated mineral oils (Cannon). The factory calibration is performed with these oils or solvents.

The sensor range defined for the experiment is 0 - 5 mPa.s. In this low viscosity range, four sample oils based on solvents generate calibration points, thus verifying the sensor oscillating rod amplitude with viscosity while maintaining a high sensitivity at 0.1 cP.

The results of calibration and correlation are shown in Table I and Figure 4.

TABLE I. CALIBRATION RESULTS ON CERTIFIED MINERAL OILS

CERTIFIED OIL (CANNON)	OIL TEMPERATURE (°C)/°F	AMPLITUDE (mV)	EXPECTED VISCOSITY (mPa.s.)
AIR	-	9002	0,0000
N4	62,1°C / 144°F	8564	0,2317
N4	22,7 / 73°F	8493	0,3215
N1.0	50,8 / 123°F	8322	0,6034
N1.0	21,9 / 71°F	8189	0,8875
S3	38,9 / 102°F	7688	2,5209
S3	22,5 / 73°F	7425	3,7469

The sensor’s response is modeled and allows the drawing of a precise calibration curve, based on seven experimental points.

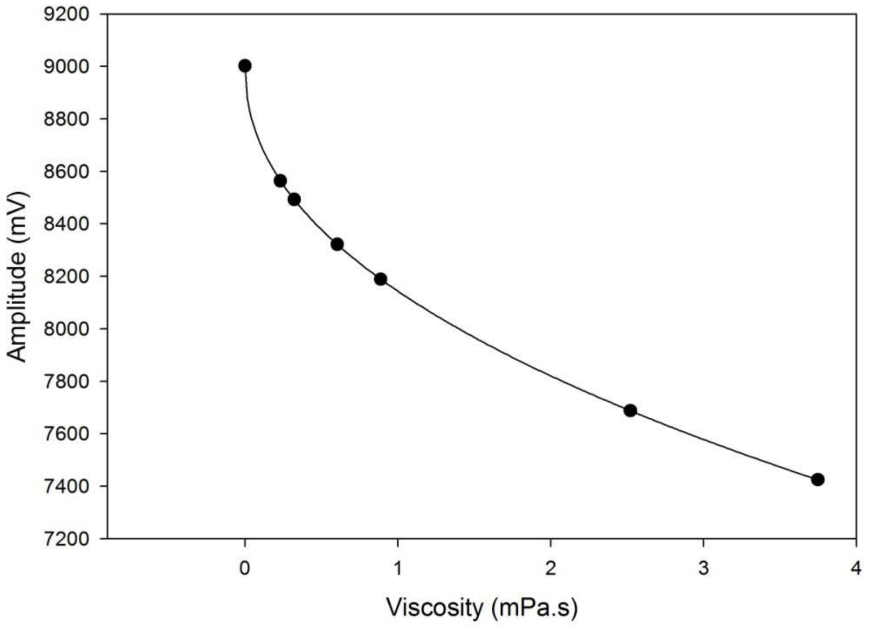

FIGURE 4. VISCOSITY CORRELATION RESULTS ON CERTIFIED MINERAL OIL

The Table II illustrates the sensitivity precision (mPa.s. / mV) for each given low viscosity.

TABLE II. SENSITIVITY ACCORDING TO VISCOSITY

VISCOSITY (mPa.s.)	SENSITIVITY (mPa.s. / mV)
0,1	0,0007
0,2	0,0011
0,5	0,0017
1,0	0,0025
2,0	0,0037

The acquisition chain and accumulation of errors due to noise and resolution gives a precision of ± 0.5 mV.

2.2.2 VERIFICATION STEP: VISCOSITY MEASUREMENT ON SOLVENTS

Once the correlation on certified oils and the linearization of the response is realized, the results are verified on known solvents, and their behavior is observed at different temperatures.

A performance validation test for a major automotive injector manufacturer is realized with a series of measurements on Heptane. Figure 5 shows a Heptane viscosity table and viscometer results, and Table III demonstrates the standard deviation of 0.005 mPa.s.

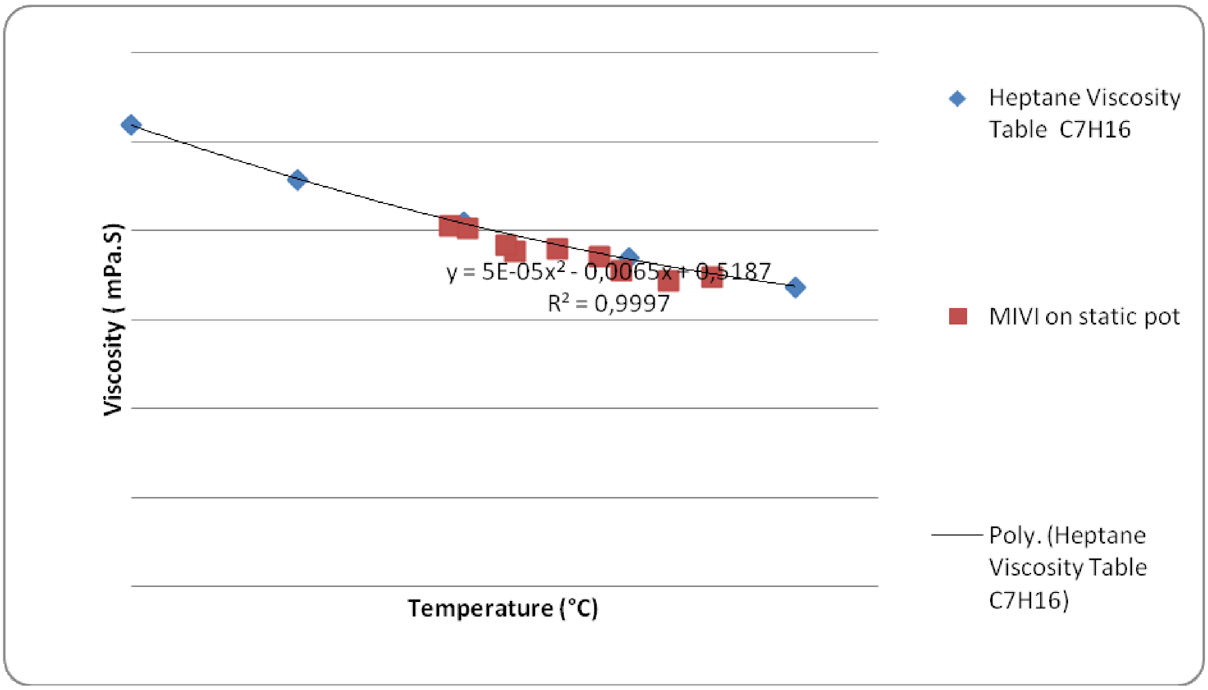

FIGURE 5. MEASUREMENT TEST WITH HEPTANE

TABLE III. MEASUREMENT TEST WITH HEPTANE AND STANDARD DEVIATION

TEMPERATURE	EXPECTED VALUE (mPa.s.)	AVERAGE VISCOMETER VALUE (mPa.s.)	STANDARD DEVIATION
20°C / 68°F	0.404	0.393	0.005
25°C / 77°F	0.385	0.374	0.005
30°C / 86°F	0.363	0.351	0.005

After comparing the sensor's response and expected results, if necessary, a standard deviation can be realized and applied to the electronic signal's calculation.

2.2.3 FINAL EXPERIMENT FOR FUEL CHARACTERIZATION

In order to know the optimum conditions for combustion, as a function of the fuel, it is important to precisely monitor the viscosity of a fuel. This is very important at the injection step, which is a complete in-line process. The experiment is still being realized and some results will be given. These are of interest for motorists and fuel manufacturers using motors sample benches.

The purpose of this experiment is to determine if the same fuels of different origins have the same behavior. The discriminate use of the previously verified sensor will allow that question to be answered with precision.

CONCLUSIONS

In addition to being able to easily characterize the product, the sensor precisely monitors the stability of a process; both attributes are useful in refineries and fuel manufacturers.

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