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• *Title:* Technology Showcase: Integrated Monitoring, Diagnostics and Failure Prevention.

Proceedings of a Joint Conference, Mobile, Alabama, April 22-26, 1996.

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A NEW ELECTRONIC VISCOMETER BASED ON RAYLEIGH WAVE MECHANICS

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Abstract: The operation of a new viscometer is shown to be based on Rayleigh wave mechanics, where a thin walled tube of 5 mm diameter is immersed to a fixed depth of 60 mm in a fluid and is caused to undergo axial vibrations due to a vibrating piezoelectric plate which supports the tube. The motion of the tube is damped by the fluid, and the piezoelectric crystal feedback circuit gives a voltage inversely proportional to the square root of the viscosityxdensity product. The design and performance characteristics of the viscometer are described. The device is under patent application.

The instrument is portable and gives a measurement of viscosityxdensity within 1 minute over a wide range, and can be modified to permit continuous measurements as a function of time. The results are accurate for a Newtonian fluid and give an apparent viscosityxdensity for other fluids. A probe measures the fluid temperature during the test. Only a small amount of fluid is necessary for measurement. The Rayleigh theory is shown to be obeyed by the instrument.

The electronic circuit uses a phase-locked loop to drive the thin walled tube at resonance, about 1.5 kHz. The processed feedback signal is large, varying from 2 volts down to about 0.5 volts DC when measuring SAE 10 to 60 weight motor oils. There is an onboard computer to process the data. The computer gives a prediction of viscosity at 40 °C, or can be modified to predict viscosity at any reference temperature, for a paraffinic lubricating oil. For a particular fluid it is possible to build in data reduction in the computer. For example, equations for density as a function of temperature can be stored in the computer to reduce the viscosityxdensity product to viscosity and to density.

Key Words: Viscometer; Rayleigh Wave Mechanics; Electronic Phase-Locked Loops.

Background: The viscosity of a fluid is the most important property when considering lubricated bearings. It is the viscosity which makes it possible for the rotating shaft to drag the lubricant into the narrowing gap of the journal bearing. As the gap becomes narrower the pressure must increase, and this effect is used to support the rotating journal of the journal bearing to carry the load without metal to metal contact. In 1687 Sir Isaac Newton formalized the concept of viscosity. His postulate can be described mathematically, as the

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resistance to shear stress (τ) of a fluid is proportional to the velocity gradient (du/dy; also called shear rate since it has dimensions of sec^{-1}), thus

$$\tau = \eta \; \frac{du}{dy} \qquad (1)$$

Fluids for which the coefficient of viscosity, η (N-s/m^2), is essentially independent of the shear rate are called <u>newtonian fluids</u>, but since the coefficient of viscosity is a truly thermodynamic property of a fluid, it is a function of the pressure and temperature. For many hydrodynamic bearings the pressure does not change the coefficient of viscosity (usually just called the viscosity) much, but changes in temperature have a large effect on the viscosity. For mineral oils, at atmospheric pressure, the viscosity changes by an order of magnitude for a change in temperature of 40 °C around room temperature. Although mineral oils are essentially newtonian fluids, greases, paints, and vegetable oils may have limited ranges of shear rate where they act newtonian.

There are a great number of viscometers on the market (see Van Wazer, et.al. [1]), but most of them can be classified by operation into a few categories. One of the earliest devices was a <u>Falling Ball Viscometer</u>. This device predicts the viscosity by measuring the terminal velocity of the ball in the fluid, where the gravitational force is balanced by buoyant force (Archimedes 285-212 B.C.) and viscous drag force (Stokes 1901).

The <u>Saybolt Viscometer</u> is another very simple device. The flow of the sample fluid through an orifice at the bottom of a cup is established under gravity, and the time to collect 60 ml of fluid is called Saybolt seconds. Saybolt seconds can be converted to kinematic viscosity (absolute viscosity divided by density) using an empirical equation. The original design was by H. G. Saybolt, Standard Oil Co., and the first published description was given by W. H. Herschel in 1918. This method is no longer supported by ASTM Standards, and a glass capillary viscometer has succeeded in its place.

The <u>Capillary Tube Viscometer</u> is supported by ASTM Standards D445 and D446. This system operates by measuring the time a known quantity of fluid passes through a capillary tube, and the result can be related to kinematic viscosity. A scientific understanding of the flow in a capillary was first presented by Hagen in 1839.

The <u>Rotating Drum Viscometer</u> gives the absolute viscosity of a fluid by measuring the drag of the fluid on the drum. This is based on Couette's viscometer devised in 1890.

All of these devices usually operate at or near atmospheric pressure, and measure or control the temperature of the test fluid.

In 1947 a new class of viscometer was constructed based on Rayleigh wave mechanics. Mason [2] has shown that a high-frequency torsionally oscillating crystal in a test fluid will generate viscous waves. Both a reactive and resistive loading occurs in the crystal which lowers the frequency and raises the resistance at resonance. The viscosity times density

product of a fluid can be determined by measuring the changes in the properties of the crystal with respect to an essentially inviscid fluid (air). Since the shear rate varies during the cyclic oscillation, correct values of viscosity are only obtained for newtonian fluids. An apparent viscosity results for non-newtonian fluids. Apparent viscosity is especially useful to follow chemical changes in a fluid, such as a polymerization process.

Woodward [3] introduced a vibrating plate viscometer in 1953, where a thin plate immersed in a fluid is vibrated in its plane. Shear waves are set up in the liquid, and the liquid exerts a retarding force on the plate consisting of a resistive and reactive component. The retarding force is inversely proportional to the square root of the absolute viscosity times density product of the fluid and is measured in comparison to an essentially inviscid fluid (air).

The subject of this paper is a new device to measure viscosity times density operating on the same principle ～ the Woodward device, but using an axially vibrating thin wall tube immersed in the fluid.

Piezoelectric Viscometer: A stainless steel piezoelectric audio bender is used to vibrate a thin wall tube immersed in a test fluid, and it is found that the viscosityxdensity product is inversely proportional to the square of the velocity amplitude of the tube in the fluid. A brief introduction to piezoelectric elements is given by Singmin [4].

Figure 1 is a drawing of the viscometer sensor. The viscosity probe is a thin wall stainless steel tube which is inserted in a sample of fluid to be measured. The end of the tube is sharpened so as not to present a blunt edge which can act as an apparent additional mass when vibrated, in accordance with the theory of Lamb [5]. The tube is immersed in the test fluid to the center of the hole through the tube wall, which also allows the test fluid to rise up inside the tube to the same height as on the outside. The sensitivity of the probe (see governing equations section) is inversely proportional to the surface area of the tube in the fluid, and at the depth of 60 mm it is on the order of 10 mV per mm. The viscosity probe is attached to the piezo ceramic audio transducer stainless steel plate. The piezo ceramic is sintered to the top side of the plate and has sections which are used for the application of a drive signal and for feedback signal monitoring. The piezo ceramic is driven by a square wave using a phase-locked loop to maintain axial mode resonance of the viscosity probe. The feedback circuit generates a voltage in proportion to the deflection of the ceramic which is used to determine the effect of the test fluid on the viscosity probe. The design of the mechanical spring (transducer), mass (viscosity probe), base support, and isolation neoprene spring is such that the sensor operates only at its axial resonance mode. The housing is isolated from the vibrating probe-transducer system so that forces on the housing do not affect the measurement. The base-and-pins support is designed to minimize forces being transmitted to the housing and to avoid radial forces on the transducer due to differential thermal expansion. The Neoprene isolation spring is very soft to minimize force transmission to the housing. An integrated circuit is used to measure the fluid temperature with a resolution of 0.1 °C. The sensor head is connected to the electronics by a shielded cable.
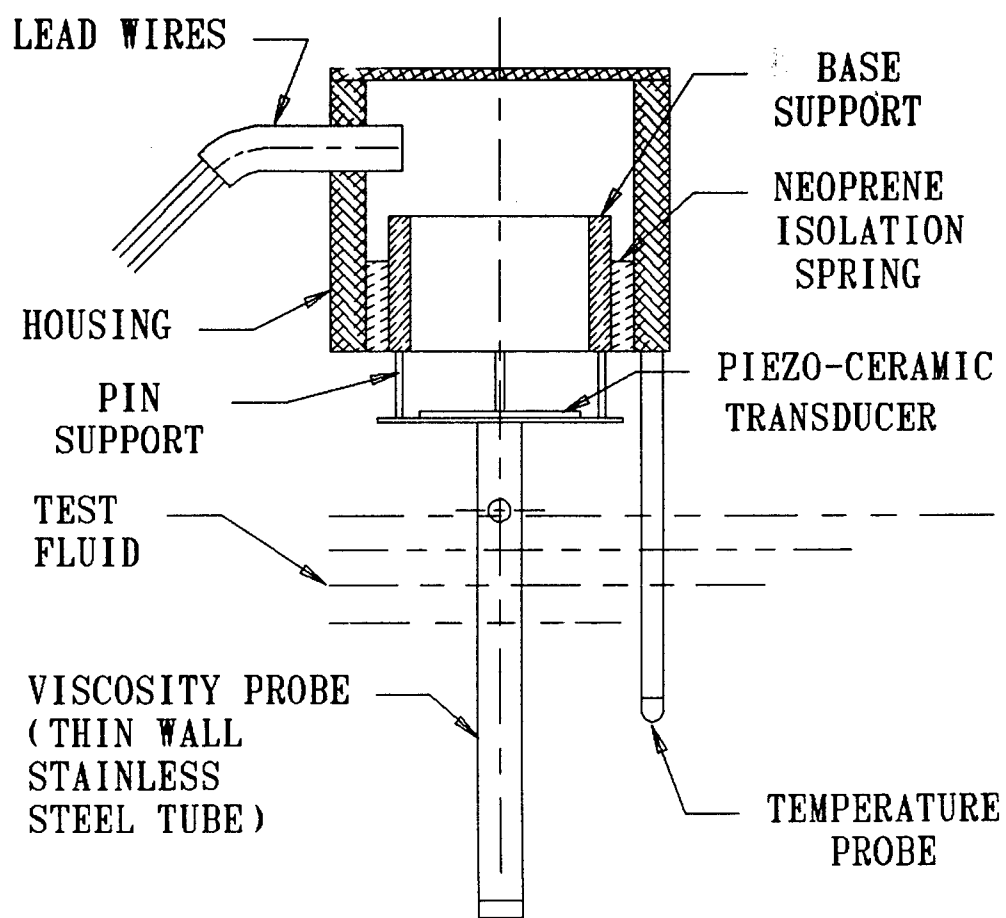
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LEAD WIRES

BASE SUPPORT

NEOPRENE ISOLATION SPRING

HOUSING

PIN SUPPORT

PIEZO-CERAMIC TRANSDUCER

TEST FLUID

VISCOSITY PROBE (THIN WALL STAINLESS STEEL TUBE)

TEMPERATURE PROBE

Fig. 1 PIEZOELECTRIC VISCOMETER SENSOR

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Theory: The theory for a vibrating plate immersed in a fluid is based on Rayleigh wave mechanics, and was initially given by Woodward [3]. More recently, the theory of Woodward was reexamined by Oka [6], and the results of his work will be presented here. In the Oka derivation, it is assumed that the system is operated at resonance and the driving force remains constant. The resulting equation is

$$\eta\rho = \left(\frac{R_o^2}{2A^2}\sqrt{\frac{m}{k}}\right)\left[\frac{V_{oa}}{V_o} - 1\right]^2 \qquad (2)$$

Where R_o is internal friction, A is wetted area of tubular probe, m is probe mass, k is spring rate of transducer, v_{oa} is <u>velocity amplitude</u> of probe in air, and v_o is <u>velocity amplitude</u> of probe in test fluid.

Since the velocity amplitude can be replaced with the frequency times displacement amplitude, and the displacement amplitude is proportional to the piezo ceramic feedback voltage amplitude, Eq.(2) can be modified for application to the piezo ceramic transducer as follows.

$$\eta\rho = \left(\frac{R_o^2}{2A^2}\sqrt{\frac{m}{k}}\right)\left[\frac{f_a V_{oa}}{f V_o} - 1\right]^2 \qquad (3)$$

Where V_{oa} is the ceramic feedback <u>voltage amplitude</u> with the probe in air, and V_o is the ceramic feedback <u>voltage amplitude</u> with the probe in the test fluid. It is usual to assume the frequency ratio, f_a/f, is equal to unity.

In Eq.(3) the terms in parenthesis are constant for an instrument, as well as the feedback voltage amplitude in air in the bracketed term; requiring two measurements for calibration. The device can be calibrated in air and in a calibration fluid, or by using two different calibration fluids. The latter method of calibration is the method that has been found to be most useful.

Electronics: The microcontroller-based piezoelectric viscometer has been designed as a battery powered portable unit with an onboard computer. The electronics are built on a printed circuit board in a separate housing from the sensor, and connected by cable to the sensor head. Figure 2 shows the block diagram of the electronic circuit.

As currently implemented, the viscometer's phase-locked loop, shown in Fig. 2, has a running frequency of 1467 Hz. It will acquire and track the resonant frequency for measuring heads that resonate within a range of approximately +/- 300 Hz. This frequency range is free of nonaxial mode vibration, therefore only the axial mode vibration of the tubular probe is activated. Also, there is a small increase in resonance frequency of the measuring head with more viscous oils, and this range accommodates this effect well.

12 button Keypad

Keypad Interface Circuitry

8 Bit Microcontroller

Parallel I/O

8 Bit Processor

12 K ROM

512 Byte RAM

512 Byte EEPROM

Serial I/O

RS-232C Interface

Serial Communications

LCD Display

Piezo Drive Control

16 Bit A/D Converter

Power Supply and Battery Monitor Circuit

Phase Locked Loop Keying Circuit

Analog Phase Locked Loop and Piezo Drive Circuitry

Piezo Feedback Signal

Feedback Signal Conditioning

Piezoelectric Transducer with Feedback Electrode

Fluid Temperature Sensor and Interface Circuitry

Piezo Temperature Sensor and Interface Circuitry
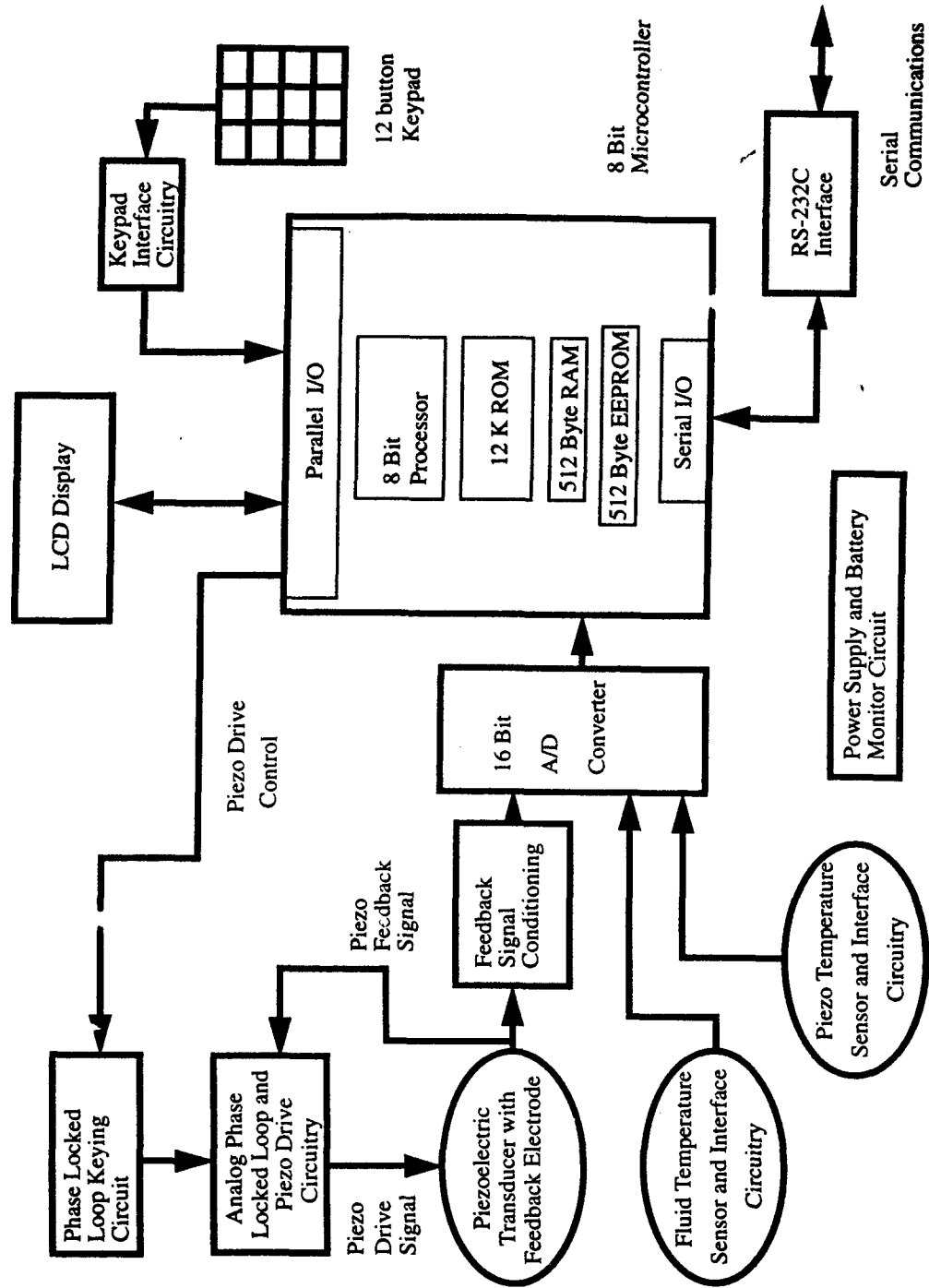
Piezo Drive Signal

Fig. 2 Block Diagram of Microprocessor Controlled Piezoelectric Viscometer

A 14.4 volt nickel cadmium battery is used to power the device, but both positive and negative 12 volts as well as 5 volts are required for operation. A switching power invertor circuit was used to develop the +/- 12 volt sources. These circuits generate electrical noise, and special shielding was designed to eliminate this problem.

The battery life tests show that the battery lasts 8 hours between recharge cycles. A recharge time of 1.5 hours is required during which time the viscometer may be operated from an external power supply (wall cube).

The Motorola MC68HC711E9 microcontroller used by the device has 12 kbytes of onboard read only memory, which limits the software to fit within these constraints. It has been necessary to restrict the use of floating point real numbers to a few inputs in favor of integer input from the keypad.

The viscometer will measure, calculate, and display the viscosityxdensity product and the temperature of the test fluid. In the case of a specific type of oil, such as a paraffin based minera oil with viscosity index near 100, the software contains curvefit data wi ch relates the viscosityxdensity product to the ISO number for the oil at the temperature of measurement. Thus, for a paraffinic oil the computer can reduce and present the following data: 1. test temperature, 2. viscosityxdensity at test temperature, 3. ISO Number, 4. viscosity at test temperature, 5. density at test temperature, and 6. viscosity or density at any other reference temperature. The viscometer can display the results of the measurements through the RS-232C interface to a personal computer equipped with communications software, such as Pro-Comm Plus, or the simple TERMINAL program provided with the Microsoft Windows package. The link operates at 9600 bits per second with one stop bit, eight data bits, no parity bit, and no flow control.

Experimental Results: Test results using Cannon Instrument Co. reference oils are shown on Figure 3. According to the theory given by Eq. (3), a log log plot of $[V_{oa}/V_o - 1]$ versus viscosityxdensity should give a straight line with a slope of 1/2. The data is in agreement with the theory line as shcwn on Fig. 3. Test re ults using mineral oils give a range of application from 10 to 2000 cPoise (a higher range is possible but was not tested) with an accuracy of +/- 1.5% of full scale viscosity, but typically within +/- 5% absolute error. The operating temperature range is +/- 5 °C around room temperature, with a repeatability of 2%. There are 3 factory adjustments required per unit. The chemical resistance of the stainless steel sensor probe is satisfactory for many fluids, and the tube material could be modified for special case fluids such as acids.

Conclusions: The piezoelectronic viscometer is a useful instrument for measuring viscosityxdensity at the test temperature of a newtonian fluid where the viscosity is greater than 10 cP. The viscosity can be calculated by making a separate measurement of density at temperature. High pressure measurements can be made by inserting the measuring head into a high pressure chamber, but the test fluid must have a free surface for proper immersion by the tubular probe. For a specific fluid where density versus temperature data is known, the computer software can include a calculation to reduce the data automatically during a measurement. In the case of a non-newtonian fluid the device will give a value
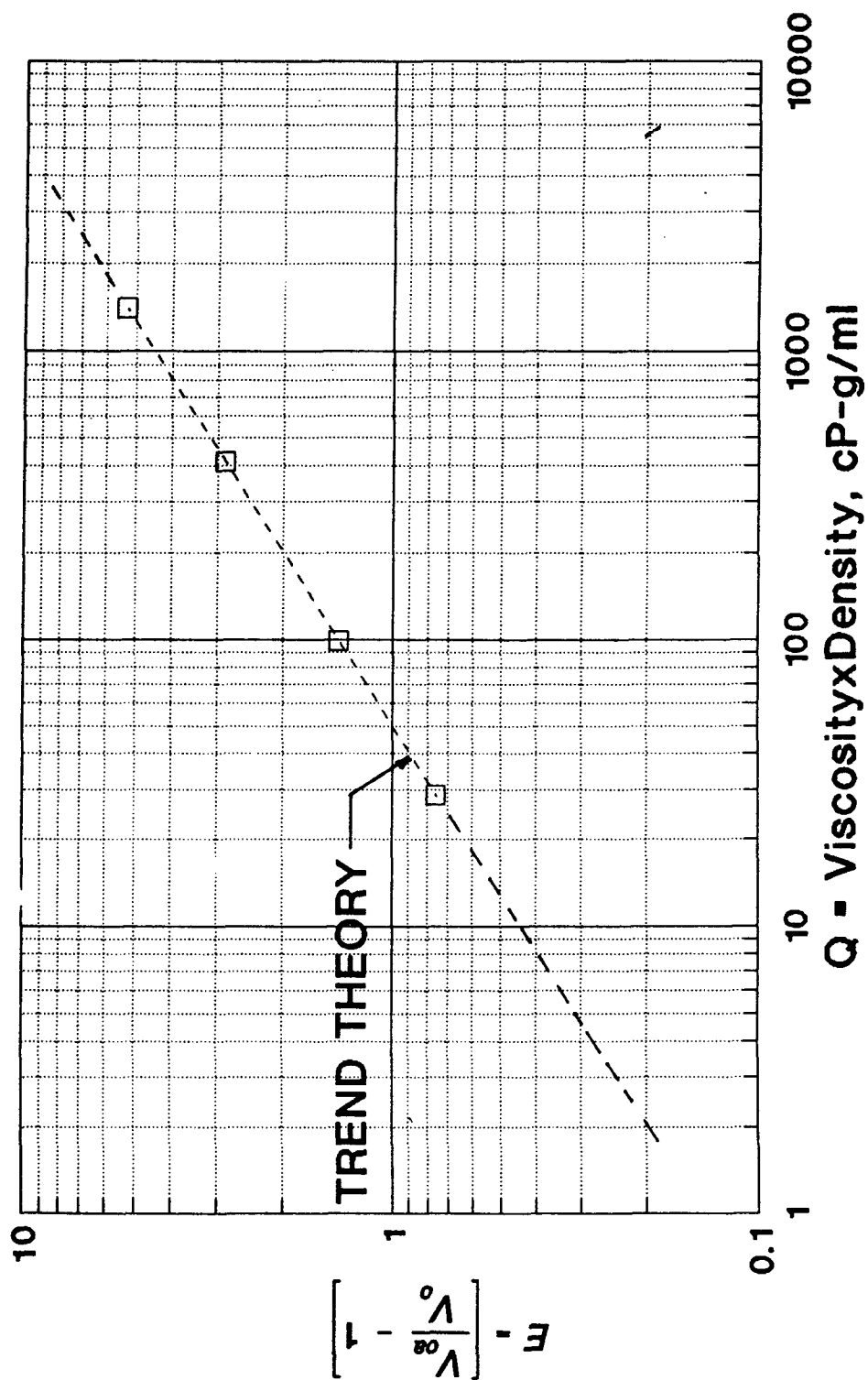
Fig 3 VISCOMETER TEST DATA

$$E = \left[\frac{V_{08}}{V_o} - 1\right]$$

Q - ViscosityxDensity, cP-g/ml

TREND THEORY

of the apparent viscosityxdensity product, but this can be related to an operational requirement of the fluid such as a mixing criteria, for example.

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