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DESIGN OF A VISCOMETER USING MAGNETOSTRICTION OF FERROMAGNETIC PROBES

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ABSTRACT

On-line measurement of viscosity of process liquids at process temperature is difficult though industrially very important. A viscometer is designed which can do this up to about 300 °C almost on-line within about 1-8% accuracy except for very viscous liquids like glucose. It uses a ferromagnetic probe designed to mechanically vibrate in the ultrasonic frequency range. An excitation coil sends repeated excitation current pulses to induce mechanical vibration in the probe tip. When placed in a process fluid, the vibration amplitude is damped due to the viscosity of the fluid, and the damped vibration is sensed by Faraday's principle by a sensing coil. The number of pulses per second needed to keep the probe vibrating above a threshold level is directly proportional to the viscosity of the fluid. Necessary calibration was done and the performance tested using several pure liquids as references with known viscosities in the range 0.1 - 2,000 cp at temperatures between −80 and +300 °C.

INTRODUCTION

On-line quality control of process fluids is needed industrially which can be achieved if on-line viscosities of these can be measured at process temperatures without stopping the production (Willard *et al.*, 1985).

Ultrasonic probes may be a better alternative to the conventional static viscosity measurements like using the falling ball or capillary rise methods. In this work, the rate of damping of a vibrating metal tip by the viscous fluid is used to arrive (in about a minute or less) at the viscosity values of the process fluids (Sarkar, 1978). The damped vibration of the ferromagnetic tip is generated by the magnetostriction or piezomagnetic principle (Bozorth, 1951). Therefore, such a viscometer can sample process fluids at temperatures less than the Curie temperature of the ferromagnetic tip.

When a ferromagnet is mechanically stressed, a voltage is generated by magnetostriction principle (Craik *et al.*, 1966). Similarly, when a voltage is applied to a ferromagnet, its dimensions change by the inverse magnetostriction principle. In this study, a current pulse in the exciting coil around the magnetic tip induced a voltage in the tip by Faraday's principle. This voltage caused the probe tip to mechanically change its shape due to the inverse magnetostriction principle mentioned above. Depending on the geometry of the probe, the mechanical stress drove it to vibrate at its fundamental or one of the harmonic frequencies. The vibrating tip eventually got damped due to the viscous drag from the test process fluid. A sensing coil wired around the magnetic tip sensed the amplitude of the damped vibration by Faraday's principle again. Using a level detection circuit in conjunction with a pulse generator, excitation pulses were sent to reexcite the probe tip when its vibration amplitude fell below a preset level. More viscous a fluid was, faster was the damping of the ferromagnetic tip. Pure liquids with known viscosities were used to calibrate the damping rate and convert these to viscosity readings. Unknown viscosities were then read directly by interpolation of these calibration curves corresponding to the damping rates of the tip in those fluids. The consistency with other methods was within 3% at room temperature for almost all the test samples but was off by 12% at 100 °C for glucose.

MATERIALS AND METHODS

The transducer probe consisted of a ferromagnetic strip, two surrounding coils one for converting the mechanical energy to voltage pulses and the other for driving the tip, and a preamplifier stage all encased in steel casing with the tip protruding out for probing the process fluid directly.

Various geometries of the magnetic strip were tested to arrive at the best one offering maximum dimension change with applied voltages for highest sensitivity in the temperature range used. The best geometry with optimum magnetostriction coefficients in transverse direction was an ellipsoidal one with low aspect ratio (Craik *et al.*, 1966). Considering the difficulty and cost involved for such a probe, a moderate substitute for the ellipsoidal geometry, viz., rectangular strips were used. The mechanical vibration with the center of the strip held fixed is at the first harmonic frequency with antinodes at the edges providing the greatest excursion of the probe tip. Typically for 8 cm x 0.2 cm x 0.05 cm strips, this frequency is in the ultrasonic range. The fundamental or the higher harmonic vibrations were avoided since maximum tip displacements give maximum sensitivity. Figure 1 displays a block diagram of the circuitry.

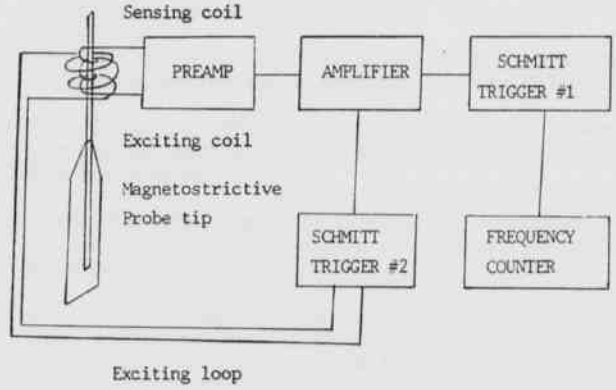

Figure 1. Block diagram showing the viscometer probe and the electronic circuitry for detection of the frequency of damped vibration of the ferromagnetic tip.

The bandwidth of a sharp mechanical disturbance (like a touch on the strip) is infinitely wide and it excites the chosen geometry at its first harmonic frequency f_1 which generates electrical pulses at the same frequency. These pulses are microvolt intensities and at megahertz frequencies. It is better to preamplify these to about one tenth of a volt

in the probe itself to avoid amplification of noise. This was done with 741 operational amplifiers with minimum possible external components housed inside the steel casing.

When the vibrating magnetic strip comes in contact with a viscous medium, the tip vibration is mechanically damped and generates damped microvolt pulses at the same ultrasonic frequency. After amplifying these pulses to about 10 V maximum, they are detected by a pair of Schmitt triggers. The first one detects only the onset of the oscillations and sends a square pulse to a digital counter. The second one detects the tail of the damped oscillations at a preset voltage level and sends the square wave output to the exciting coil around the probe tip. Thus the viscous nature of the process fluid is measured by frequency (damping rate per second) which is linearly proportional to the viscosity of the fluid.

Pure liquids with known viscosities in the range 0.1 cp – 2000 cp were used to calibrate the digital counter readings (Table 1). Eleven calibrating liquids were used in 3 ranges of viscosity values — first with viscosities less than 1, second with viscosities between 1 and 100, and finally liquids with viscosities more than 100. All 3 calibration curves were linear with different slopes. Unknown viscosities were then directly read by interpolating the calibration curves at the frequency meter readings. Most of the viscosities obtained in this way were within about 1-3% of the standard viscosity values (Weast, 1986) except for glucose which was 12% off from its accepted viscosity value. The frequency meter readings took typically a few seconds (at the lower ranges of viscosities) to at most a minute (for glycerin and glucose) to stabilize and hence can be claimed to be on-line or instantaneous. At temperatures between the room temperature and the Curie point, the voltage pulse amplitudes decreased because the net magnetization decreased with increasing temperature (Kittel, 1986) though the frequency remained unaltered. By manually resetting the Schmitt trigger levels, the viscosity measurements up to about 300 °C was possible within 1-12% accuracy using 99.98% nickel probe tips.

Table 1. Pure liquids used to calibrate viscometer at 20 °C

Reference Liquids	Viscosity (cp)	Counter Reading
Acetaldehyde	0.22	33
Ethyl Acetate	0.46	69
Benzene	0.65	98
Chloroform	0.58	87
Ethyl Alcohol	1.20	228
Aniline	4.40	827
m-Cresol	20.8	4002
Cyclohexanol	68	12650
Olive Oil	84	16017
Rapeseed Oil	163	35403
Glycerin	1490	323005

RESULTS AND DISCUSSION

Table 2 shows viscosity values obtained for 8 test liquids at 20 °C. Note that the disagreements with other methods are less than 3% in the wide range of viscosities covering over three orders of magnitude.

Table 3 reports measurements done using this meter at various temperatures. In the wide temperature range from – 80 to 300 °C deviation from the viscosity data obtained by other methods is about 1 to 8%. For glucose it is 12% at 100 °C. Note here that the data at both low and high temperatures were collected fast to avoid averaging of temperature through possible nonuniformity of heating and increased convection at higher temperatures could not be avoided. All of these might have contributed to the observed deviation. Finally, manual adjustment of the Schmitt trigger levels at higher temperatures was difficult and was the prime source of human error. Currently there exists no theory for thermal correction of magnetostriction amplitudes particularly for the ferromagnetic alloys of cobalt, nickel and iron and hence one needs to use empirical corrections for extreme temperatures which has not been done in this study.

For large industrial process operations, stirring is unavoidable. Since mechanical loading will interfere with the vibration frequency, viscosity testing has to be done with an outlet keeping on-line condition but avoiding disturbances from stirring and mixing in the process chamber.

Table 2. Test Results of Viscosity Measurements at 20 °C Using Calibration Curves for Ultrasonic Viscometer

Test Liquids	Viscosity Data at 20°C	Measured Viscosity at 20°C (cp)	Difference %
Antimony Disulfide	0.36	0.37	+2.8
Allyl Alcohol	1.36	1.35	-0.7
CCl_4	0.97	0.98	+1.0
Cyclohexene	0.66	0.65	-1.5
Ethylene Glycol	19.9	20.1	+1.0
Sulfuric Acid	25.4	24.8	-3.1
Cottonseed Oil	70.4	72.1	+2.4
Castor Oil	986	976.2	-1.0

Table 3. Viscosity Measurements at Extreme Temperatures

Test Liquids	Operating Temperature	Viscosity at Op. Temp (cp)	Measured Viscosity (cp)	Difference %
Acetone	-80	1.49	1.51	+0.7
	-42.5	0.69	0.68	-1.4
	0	0.40	0.39	-2.5
	+41	0.28	0.29	+3.6
Aniline	0	10.2	9.8	-3.9
	100	0.83	0.84	+1.2
Glucose	100	2.5×10^4	2.8×10^4	+12
Mercury	100	1.24	1.22	-1.6
	150	1.13	1.19	+5.3
	200	1.05	1.10	+4.8
	250	0.99	0.91	-8
	300	0.95	0.88	-7.4

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LITERATURE CITED

BOZORTH, R.M. 1951. Ferromagnetism, Van Nostrand, New York, Pp. 60-81.

CRAIK, D.J. and R.S. TEBBLE. 1966. Ferromagnetism and ferromagnetic domains, North Holland, Pp. 11-45.

KITTEL, C. 1986. Introduction to solid state physics. Wiley Interscience, New York, 465 pp.

SARKAR, S.N. 1978. Ultrasonic viscometer. Unpublished M.Sc dissertation. Birla Inst. of Tech. and Sc., Pilani, India.

WEAST, R.C. 1986-87. Handbook of chemistry and physics, CRC Press, Pp. F38-42.

WILLARD, H.H., L.L. MERRITT, J.A. DEAN, and F.A. SETTLE. 1985. Instrumental methods of analysis, 6th Ed., CBH Publishers, New Delhi, Pp. 66-96 and Pp. 177-237.