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AN EXPERIMENTAL INVESTIGATION OF THE NEW VIBRATION VISCOMETER

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from the true value, a range of 15 to 30 measurements is sufficient.

Conclusion

The method developed for assessing and analyzing the overall measurement error of the capacitance electrode wet meter fully satisfies the requirements of informational measurement techniques. It also has the potential to be applied in determining the measurement error of other measuring devices. This method offers a high likelihood of moisture binding, indicating that the scaling characteristic closely approximates its true value. Consequently, entropy serves as a measure of the correlation between the output signal of a capacitive electrode moisture meter and the moisture content of the material being studied.

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AN EXPERIMENTAL INVESTIGATION OF THE NEW VIBRATION VISCOMETER

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Abstract: *The characteristics of the new oscillating-plate viscometer have been investigated experimentally. The results obtained are as follows: the resonant frequency of plate oscillation decreases with increasing viscosity; the apparatus constant K determined experimentally includes the end and slip effects; the dimensions of the plate should be determined by referring to empirical relations between* $\rho\mu$ and $\Lambda\left(\equiv\left\{\left(\frac{E_a}{E}\right)-1\right\}^n\right)$ *for various dimensions of the plate; where* ρ *is the density,* μ *is the viscosity;* E_a *the resonant amplitude of plate in the air; E the amplitude of plate in a liquid, and* n *a constant.*

If the distance between the plate and the wall of the vessel is longer than about one wavelength of the wave produced by the plate, the effect of the reflected wave from the wall can be neglected.

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Keywords: *Resonant amplitude, the resonance frequency in the air, the resonance frequency in the liquid, thickness, wavelength, viscosity, vibration, device*.

Annotatsiya: *Yangi tebranuvchi plastinkali viskozimetrning xarakteristikalari eksperimental tarzda o‘rganildi. Olingan natijalar quyidagicha: plastinka tebranishining rezonans chastotasi qovushqoqlik oshishi bilan kamayadi; eksperimental tarzda aniqlangan K qurilma konstantasi yakuniy va sirpanish effektlarini o‘z ichiga oladi; plitaning o‘lchamlarini plastinkaning har xil o‘lchamlari, "ρ zichlik", "μ qovushqoqlik", "E_a plastinkaning havodagi rezonans amplitudasi" va "E plastinkaning suyuqlikdagi amplitudasi" "n konstanta", o‘rtasidagi $\Lambda\left(\equiv\left\{\left(\frac{E_a}{E}\right)-1\right\}^n\right)$ va $\rho\mu$ empirik munosabatlarga asoslanib aniqlash kerak; agar plastinka va idish devori orasidagi masofa plastinka tomonidan ishlab chiqarilgan to‘lqinning taxminan bir to‘lqin uzunligidan uzunroq bo‘lsa, devordan aks ettirilgan to‘lqinning ta’sirini e’tiborsiz qoldirish mumkin.*

Tayanch so‘zlar: *rezonans amplitudasi, havodagi rezonans chastotasi, suyuqlikdagi rezonans chastotasi, qalinlik, to‘lqin uzunligi, qovushqoqlik, tebranish, qurilma.*

Аннотация: *экспериментально исследованы характеристики нового вискозиметра с качающейся пластиной. Полученные результаты, следующие: резонансная частота колебаний пластины уменьшается с увеличением вязкости; аппаратная постоянная, определенная экспериментально, включает эффекты торца и скольжения; азмеры пластины следует определять, обращаясь к эмпирическим соотношениям между $\rho\mu$ и $\rho\mu = \mathrm{K}\left\{\left(\frac{E_a}{E}\right)-1\right\}^2$ для различных размеров пластины, где - ρ плотность, μ вязкость, E_a резонансная амплитуда пластины в воздухе, E амплитуда пластины в жидкости и n константа; если расстояние между пластиной и стенкой сосуда больше примерно одной длины волны, создаваемой пластинкой, то влиянием отраженной волны от стенки можно пренебречь.*

Ключевые слова: *резонансная амплитуда, резонансная частота в воздухе, резонансная частота в жидкости, толщина, длина волны, вязкость, вибрация, устройство*.

Introduction

For instantaneously and continuously measuring the viscosity change of a melt that flows irregularly with high accuracy, the authors developed a viscosity/signal deviation device in which a vibration signal separator is connected to a vibrating bar viscometer. A simultaneous and rapid measurement device was designed and prototyped (see [1]).

A theoretical formula (viscosity calculation formula) has been derived. However, it should be noted that several assumptions are made as shown below before deriving the viscosity calculation formula. Even with the current technology, it is tough to measure viscosity in a state that satisfies all of these assumptions.

Therefore, when measuring viscosity, it is necessary first to consider the assumptions used when deriving the viscosity calculation formula and the problems arising from these assumptions.

It may be better to measure under conditions and add a correction to obtain the viscosity, or, depending on the purpose of the measurement, to obtain an empirical formula based on a theoretically derived viscosity calculation formula. And from the point of view of measurement accuracy, it may be convenient in some cases.

In this report, the relationship between the assumptions used in deriving the viscosity calculation formula and the vibrating arm viscometer that the authors prototyped, i.e., the deviation from the assumptions, was discussed. An experimental investigation was added to the treatment. Although many of the measurement treatments for each assumption have been clarified in general terms, it is thought that there are problems specific to the prototype viscometer. Therefore, an experimental study from the standpoint of metrology is considered essential (see [2]).

Research Methods and the Received Results

1. Viscosity calculation formula and assumptions for it

When the vibrating bar is sinusoidally vibrated parallel to its plane at the resonance frequency under a constant driving force, the viscosity calculation formula for the vibrating bar viscometer is given by the following equation (1) (see [3]).

$$\rho\mu = \frac{R_M^2}{\pi f A^2}\left(\frac{f_a}{f}\frac{E_a}{E}-1\right)^2 = K\cdot\Lambda_0 \qquad (1)$$

here,

$$K = \frac{R_M^2}{\pi f_a A^2}$$

$$\Lambda_0 = \frac{f_a}{f}\left(\frac{f_a}{f}\frac{E_a}{E}-1\right)^2$$

$\rho -$ density of sample liquid;

$\mu -$ Viscosity of sample liquid;

$E_a -$ Vibration amplitude in air;

$E -$ Vibration amplitude in the sample liquid;

$R_M -$ Resistance component of mechanical impedance specific to the viscometer;

f_a – resonance frequency in air;
f – resonance frequency in the sample liquid;
A – Area of both sides of the vibrating bar.

However, the following assumptions are made in deriving equation (1).

a. The sample is a Newtonian fluid.

b. Turbulence does not occur due to the vibration of the vibrating bars.

c. There is no slip between the surface of the vibrating bars and the liquid.

d. The size of the vibrating bar is sufficiently large compared to the wavelength of the wave generated by the vibration, the effect of the edge of the vibrating bar can be ignored, and the wave can be regarded as a plane wave.

e. The container of the sample is large, and the influence of the wave reflected by the wall can be ignored (see [4]).

f. Assuming that the resonance frequency in air and the resonance frequency in the sample liquid are the same, the following viscosity calculation formula can be obtained from formula (1).

$$\rho\mu = K\left(\frac{E_a}{E} - 1\right)^2 = K \cdot \Lambda \qquad (2)$$

here,

$$\Lambda = \left(\frac{E_a}{E} - 1\right)^2$$

Therefore, if the device constant K is determined in advance using a reference liquid (viscosity standard liquid) with known density and viscosity, the ratio of the vibration amplitude E_a in the air to the vibration amplitude E in the sample liquid can be obtained. $\rho\mu$ of the sample liquid from equation (2).

Since we can know the value of Λ, we can obtain the viscosity of the sample liquid given the density.

Among the above assumptions, (*a*) relates to the properties of liquids, while (*b*)-(*f*) relates to both liquid properties and equipment. To examine the assumptions, the kinematic viscosity of the liquid, the vibration frequency of the vibrating bars, and the vibration (see [5]).

It is necessary to think about the dimensions of the pieces.

Assumption (*c*) concerns the wetting between the liquid and the vibrating bars, so we must consider both the properties of the liquid and the vibrating bars. However, the phenomenon of wetting is extremely complicated, and it seems impossible at present to conduct a theoretical study on this problem, so an experimental study is necessary.

To consider the assumption of (*d*), the relationship between the dimensions (area, thickness) of the vibrating bar and the wavelength of the wave generated by the vibrating bar must be examined. is determined by the frequency of the vibrating bars and the properties of the liquid. In addition, to examine assumption (*e*), we must consider the frequency of the vibrating bars and the physical properties of the liquid. Assumptions (*a*) to (*e*) above are made to derive equation (1), but equation (1) can be simplified to equation (2) by assumption (*f*). According to equation (2), if the vibration amplitude E_a in the air is obtained immediately before the measurement, the $\rho\mu$ value can be determined simply by reading the vibration amplitude E of the vibrating bar immersed in the sample liquid. Therefore, from the standpoint of rapid viscosity measurement, equation (2) is much more convenient than equation (1). However, the resonance frequency of the viscometer that we prototyped is considerably lower than that of the WOODWARD viscometer. Since the viscosity dependence of the resonance frequency is also considered to vary depending on the performance of the vibration drive unit, the relationship between the resonance frequency and the viscosity for each viscometer was clarified (see [6]).

Examination of assumptions

Examination of the resonance frequency of the vibrating bar

As already mentioned, the viscosity calculation formula for viscosity measurement with a vibrating-arm viscometer is valid when the vibrating arm is vibrated at the resonance frequency under a constant driving force. Therefore, it is known that the resonance frequency changes (see [7,8]). However, it is considered necessary to consider the viscosity dependence of the resonance frequency in examining some of the assumptions. In addition, since the quantity directly measured by the vibrating bar viscometer is not the viscosity μ but the density × viscosity ($\rho\mu$), strictly speaking, the resonance frequency and the density × viscosity ($\rho\mu$) In this study, we used viscosity standard fluids to experimentally investigate some problems. It can be regarded as the difference in viscosity μ. Now, the resonance frequency when the viscous damped vibration system is forced to vibrate is given by the following equation (3).

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}\sqrt{1 - 2\xi^2} \qquad (3)$$

$$\xi \equiv \frac{C}{2\sqrt{mk}}$$

k – spring constant;
m – Effective oscillating mass;
ξ – damping coefficient ratio;

C – damping coefficient.

Here, in the case of a vibrating bar viscometer, the vibration is caused by the resistance component R_M of the mechanical impedance peculiar to the vibrating system and the viscous resistance received by the vibrating bar from the liquid (the resistance component of the mechanical impedance due to the liquid load) (see [9]). cause attenuation, that is

$$C = R_M + A\sqrt{\pi f \rho \mu} \qquad (4)$$

Substituting equation (4) into equation (3), we obtain the following relational expression between the resonance frequency and $\rho\mu$.

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}\sqrt{1 - \frac{\left(R_M + A\sqrt{\pi f \rho \mu}\right)^2}{2mk}} \qquad (5)$$

From the relationship of equation (5), it is clear that if $\rho\mu$ changes, the resonance frequency f will also change accordingly. Therefore, it is impossible to calculate the value of f for various $\rho\mu$ values at present. Specifically, a frequency measuring device was connected to an optical displacement meter to determine the frequency at which the vibration amplitude of the vibrating bar reaches its maximum value, that is, the resonance frequency. The piece was made of stainless steel and was 0.3 mm thick and square with a side length of 30 mm. As is clear from the figure, as $\rho\mu$ increases, f decreases, and in the case of this viscometer, at $\rho\mu = 1900\ kg^2m^{-4}s^{-1}$, it is about 15% of the resonance frequency in the air ($\rho\mu = 0$). It can be seen that it decreases [10].

Here, to further examine the problem arising from the $\rho\mu$ dependence of *f*, Fig. 2 shows the relationship between $\rho\mu$ and the attenuation factors (Λ_0, Λ). As is clear from the figure, $\rho\mu$, and Λ. On the other hand, a linear relationship does not hold between $\rho\mu$ and Λ, so it can be seen that equation (2) is a rough approximation. Fig. 3 shows the relationship between the logarithm of $\rho\mu$ and the logarithm of the attenuation factor. The following equation is obtained from the relationship between

$$\rho\mu = 10^{3.96} \cdot \Lambda_0^{0.982} = 9.12 \cdot 10^3 \left(\frac{f_a}{f}\right)^{0.982} \cdot \left(\frac{f_a}{f}\frac{E_a}{E} - 1\right)^{1.96} \qquad (6)$$

As is clear from equations (1) and (6), the damping factor Λ in those equations. are 1.00 and 0.982, respectively. In the viscosity range where the $\rho\mu$ value is about 3 to 8%. Considering that the measurement accuracy of vibrating bar viscometers is generally about 3 to 5%, it can be said that equations (1) and (6) agree. Since the device constant *K* is determined experimentally, eqs. (6) and (1) have the same meaning, so it can be seen that the relationship of Eq. (1) holds true. Since the value is about $2000\ kg^2m^{-4}s^{-1}$, and the change in resonance frequency is about 15%, in the viscosity range shown in Fig. 1, (f_a/f) 0.982 is a very good approximation and can be set as f_a/f. Therefore, in this case, equation (6) can be rewritten as follows (see [11]).

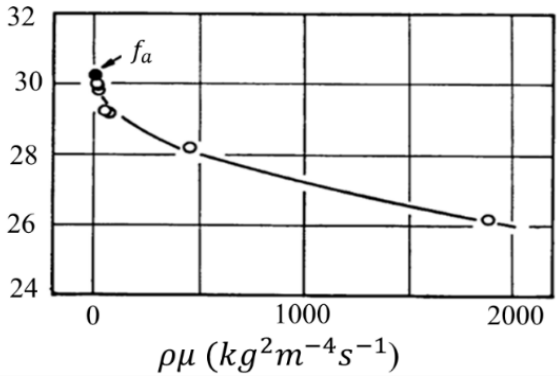

Fig. 1. Dependence of the resonant frequency on $\rho\mu$ values.

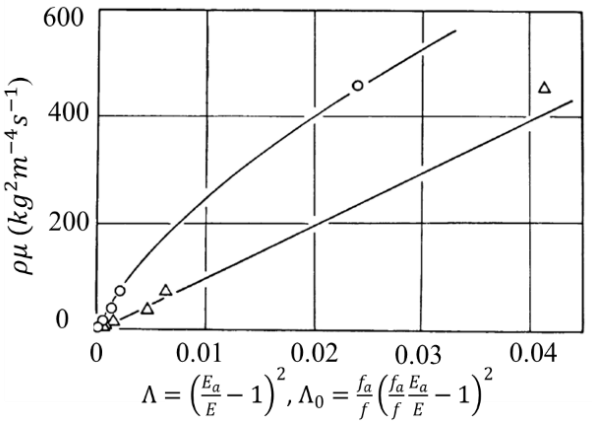

Fig.2. Relations between $\rho\mu$ values and damping factors (Λ_0, Λ), O –resonant frequency in air were used for f, Δ –resonant frequency in liquids were used for f.

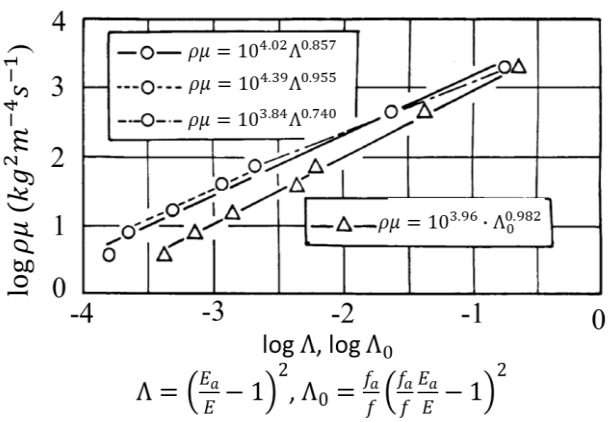

Fig. 3. Log-log plots of $\rho\mu$ vs. Λ_0 and $\rho\mu$ vs. Λ, O –resonant frequency in air were used for f, Δ –resonant frequency in liquids were used for f.

$$\rho\mu = 9.12 \cdot 10^3 \frac{f_a}{f} \cdot \left(\frac{f_a}{f}\frac{E_a}{E} - 1\right)^{1.96} \qquad (7)$$

A linear relationship also holds between log($\rho\mu$) and logΛ, which is formulated as follows.

$$\rho\mu = 10^{4.02}\Lambda^{0.857} = \left(\frac{E_a}{E} - 1\right)^{1.71} \qquad (8)$$

The above result is a relational expression obtained for a wide range of viscosities from $\rho\mu$, 4

to 2000 $kg^2m^{-4}s^{-1}$. If the viscosity range is somewhat narrowed, the relationship between $\rho\mu$ and Λ can be expressed by the following equation (see [12]).

For the range of 10 to 100 $kg^2m^{-4}s^{-1}$,

$$\rho\mu = 10^{4.39}\Lambda^{0.955} = 2.45 \cdot 10^4 \left(\frac{E_a}{E} - 1\right)^{1.91} \quad (9)$$

For the range of 100 to 2000 $kg^2m^{-4}s^{-1}$,

$$\rho\mu = 10^{3.84}\Lambda^{0.740} = 6.92 \cdot 10^3 \left(\frac{E_a}{E} - 1\right)^{1.48} \quad (10)$$

Table 1 compares the calculated values from eqs. (9) and (10) with experimental values, that is, $\{(\rho\mu)_{cal} - (\rho\mu)_{expt}\}/(\rho\mu)_{cal}$. As is clear from the table, the above equation reproduces the experimental values well. It was stated in the previous paper that the formula reproduces experimental values relatively well (see [13]).

Now, it has become clear that the viscosity calculation formula, that is, formula (1), which was theoretically derived under some assumptions, holds true for this viscometer with considerable accuracy (see [14]). This viscometer seems to satisfy the assumptions made before deriving the formula. The effect of the thickness of the piece and the effect of the slip will be examined.

Table 1.

Comparision of calculated $\rho\mu$ values with experimental data.

Λ	$(\rho\mu)_{expt}$	$(\rho\mu)_{cal}$	$\{(\rho\mu)_{cal} - (\rho\mu)_{expt}\}/(\rho\mu)_{cal}$
$2.27\cdot10^{-4}$	8.23 ($kg^2m^{-4}s^{-1}$)	8.01 ($kg^2m^{-4}s^{-1}$)	-2.7 (%)
$4.79\cdot10^{-4}$	16.1 ($kg^2m^{-4}s^{-1}$)	16.4 ($kg^2m^{-4}s^{-1}$)	1.8 (%)
$1.32\cdot10^{-3}$	40.8 ($kg^2m^{-4}s^{-1}$)	43.2 ($kg^2m^{-4}s^{-1}$)	5.6 (%)
$2.12\cdot10^{-3}$	71.5 ($kg^2m^{-4}s^{-1}$)	67.8 ($kg^2m^{-4}s^{-1}$)	-5.5 (%)

$\rho\mu = 10^{4.39}\Lambda^{0.955}$ ($10 < \rho\mu < 100\ kg^2m^{-4}s^{-1}$)

Λ	$(\rho\mu)_{expt}$	$(\rho\mu)_{cal}$	$\{(\rho\mu)_{cal} - (\rho\mu)_{expt}\}/(\rho\mu)_{cal}$
$2.12\cdot10^{-3}$	71.5 ($kg^2m^{-4}s^{-1}$)	73.0 ($kg^2m^{-4}s^{-1}$)	2.1 (%)
$2.38\cdot10^{-2}$	458.3 ($kg^2m^{-4}s^{-1}$)	437.5 ($kg^2m^{-4}s^{-1}$)	-4.8 (%)
$1.76\cdot10^{-1}$	1871.7 ($kg^2m^{-4}s^{-1}$)	1919.8 ($kg^2m^{-4}s^{-1}$)	2.5 (%)

$\rho\mu = 10^{3.84}\Lambda^{0.740}$ ($100 < \rho\mu < 2000\ kg^2m^{-4}s^{-1}$)

Discussion of the results obtained. Measurement treatment for assumptions

Up to this point, we have discussed mainly the assumptions related to the device of the vibrating bar viscometer, among the assumptions made before deriving the viscosity calculation formula. Here, let us consider the measurement treatment for each hypothesis based on the results of those studies. The assumption (see [15]), that is, the laminar flow condition, is indispensable for obtaining the molecular viscosity, but the Reynolds number that satisfies the laminar flow condition has not yet been clarified in the case of viscosity measurement with a vibrating element viscometer. However, within the range in which a good linear relationship is established in Fig. 6, it seems safe to assume that the laminar flow condition is satisfied. In the case of vibrating reeds of large magnitude, it is observed that the relationship between $log\rho\mu$ and $log\Lambda$ deviates from a straight line for Λ less than $log\Lambda = -4$. As a countermeasure for the problem of slippage, it is recommended to use a reference liquid that exhibits the same level of wettability as the liquid to be measured to determine the device constantly (see [16]).

In order to satisfy assumption (4), generally speaking, it is necessary to use a large and thin vibrating bar. The relationship between $\rho\mu$ and Λ is obtained experimentally (because the performance of the vibration driving part is generally different). It is important to determine the size of the vibrating bar according to the target measurement accuracy. If the above is the case, the influence of the reflected wave from the wall can be ignored.

Equation (2), which was derived on the assumption that $f = f_a$, is a rough approximation for this viscometer. E should be measured at the same time as the resonance frequencies fa and f, and the viscosity calculated from equation (1), $\rho\mu$, and Λ should be empirically determined. holds, it is convenient and appropriate to experimentally obtain the values of K and π and to calculate the viscosity or viscosity change of the sample liquid based on the relational expression (see [17]).

Conclusion

Based on the theoretically derived viscosity calculation formula for the performance and characteristics of the vibrating arm viscometer that the authors prototyped, an experimental study was added from the standpoint of rapid continuous measurement of viscosity. As a result, (i) The resonance frequency decreases as the viscosity ($\rho\mu$) increases.

(ii) Due to the influence of the thickness of the vibrating bars and the effect of slip, it can be considered that the apparent area of the vibrating bars has increased or decreased. The constant K should be determined experimentally.

(iii) The larger the area of the vibrating bars, the wider the range of viscosity from low to high viscosity can be measured.

(iv) If the distance between the surface of the vibrating bar and the wall surface of the sample container is greater than about one wavelength of the wave generated by the vibration of the vibrating bar, the effect of the wave reflected by the wall can be ignored. etc. became clear.

From the above study results, the theoretically derived viscosity calculation formula (formula (1)) holds true for this viscometer with considerable accuracy, but the resonance frequency can be rapidly adjusted according to the viscosity of the sample liquid. It was found that it is extremely difficult to carry out rapid and continuous measurements of viscosity according to formula (1).

Also, when performing rapid continuous measurement of viscosity, it is advisable to calculate the viscosity or viscosity change using an experimentally determined formula for the relationship between the viscosity $\rho\mu$ and the attenuation factor Λ (assuming $f = f_a$). It is convenient and reasonable, and although the viscosity calculation formula obtained experimentally with $f = f_a$ lacks theoretical rigor, it was found that the experimental values can be reproduced well if the applicable viscosity range is limited to some extent (see [18]).

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