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OSCILLATORY VISCOMETERS AND WAYS TO ENHANCE THEM

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Abstract. *The article provides information on measurements of vibration viscosity, related methods and formulas for their calculation. The article also describes devices for measuring vibration viscosity and ways to improve them. Similarities and differences between viscosity measuring instruments are also listed. The article discusses ways of raising efficiency of measuring instruments and their expression; factors influencing the efficiency are also shown. Expressions for determining required parameters and properties of the vibration viscosity measuring device depending on the test design are also given. Development stages of new measurement methods of vibration viscosity measuring instruments and their scheme, have been elucidated. In conclusion, it can be said that the vibratory viscosity measuring equipment, which is based on a new design and measurement method, is promising.*

Keywords: *oscillatory viscometers, amplitude, probe vibrations, density, the moment of inertia, Newtonian, frequency.*

TEBRANISH QOVUSHQOQLIKNI O‘LCHASH ASBOBLARI VA ULARNING RIVOJLANISH YO‘LI

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Annotatsiya. *Maqolada vibratsiyali qovushqoqlikni o‘lchash haqida ma’lumotlar, vibratsiyali qovushqoqlikni o‘lchash usullari va ularni hisoblash formulalari keltirilgan. Shuningdek, vibratsiyali qovushqoqlikni o‘lchash asboblari va ularning takomillashuv yo‘llari bayon etilgan. Qovushqoqlikni o‘lchash asboblarining o‘xshash va farqli jihatlari*

Introduction

Oscillatory viscometers are currently being used widely in scientific laboratories and industry. Even the instruments of the first generation, using electromechanical, mechanical, and optical devices for excitation and registration of probe vibrations, had such high sensitivity that they were used to measure viscosity of gases. In terms of sensitivity, they could not compete with all other existing methods. Despite this, apparently, because of their complexity, they were popular less than other methods, and their enhancement from the moment they had been created by Coulomb before the forties of the 9th century, made little progress. This was also explained by the lack of an element base.

With the development of electronics and electroacoustics, things changed, and during the war, a number of upgraded models of second-generation devices emerged. Additional attention of specialists to the possibilities of the method was attracted by the works of W. Mason, as well as the development of an industrial ultrasonic viscometer by Rich and Roth.

Now there is an intensive development of devices of the second generation, in which electroacoustic and electromechanical converters are widely used together with electronic devices based on vacuum tubes and transistors [1].

Materials and methodology

The present piece of work is aimed at giving an overview of existing design models of devices, however an attempt is being made to characterize the state of affairs in general.

Table 1 shows a classification of existing oscillatory viscometers and indicates possible areas of application of individual methods.

Nowadays, methods which are based on measuring logarithmic damping decrement of probe oscillations, its quality factor, and the amplitude of harmonic self-oscillations, have found widest application. These methods are practically equivalent and have a high sensitivity at low damping, which ensures higher quality factor of probes. With an increase in damping, the measurement error increases relatively slowly, which allows them to be used in a relatively wide range of viscosities. Other methods given in the table have gained some distribution. As it is indicated below, development of new methods is expected in the future. It is expected that, third-generation devices with digital meters based on integrated and solid circuits will appear next decade [2].

Theoretical pieces of work have played an important role in the classification of viscometers. One of the achievements that should be mentioned is the creation of a dimensionless apparatus, which enables visual comparison of the most diverse models of devices in various conditions. A.N. Soloviev and A.B. Kaplun introduced a concept of dimensionless viscosity for a probe in the form of a thin flat plate. Independently of them, the viscous damping coefficient was introduced somewhat later for probes with distributed and lumped parameters of any mode, and for a thin flat plate it coincided with dimensionless viscosity, definitions were equivalent. Then the definition of viscous damping for probes of relaxation self-oscillations was given [3].

Existing definitions of viscous damping are based on an assumption that viscous waves generated in a fluid can be considered plane. In many practical cases, this condition is easily satisfied.

Research findings

We give here these definitions of viscous damping with asterisks, which are close in terms of metrological characteristics, methods,

sanab o‘tilgan. O‘lchash asbobining samaradorligini oshirish va ularning ifodalari, samaradorlikka ta’sir etuvchi omillar ko‘rsatilgan. Vibratsiyali qovushqoqlikni o‘lchash asbobining zondi konstruksiyasiga bog‘liq bo‘lgan parametrlari va xususiyatlarini aniqlash ifodalari o‘rganilgan. Vibratsiyali qovushqoqlikni o‘lchash asboblari yangi o‘lchash usullarining rivojlanish bosqichlari va ularning sxemalari haqida ma’lumotlar berilgan. Yangi konstruksiyali va o‘lchash metodiga asosan ishlaydigan vibratsiyali qovushqoqlikni o‘lchash jihozlarining istiqbolli natijalari keltirilgan.

Kalit so‘zlar: *tebranish qovushqoqlikni o‘lchagich, amplituda, zond tebranishlari, zichlik, inersiya momenti, nyutoniy, chastota.*

КОЛЕБАТЕЛЬНЫЕ ВИСКОЗИМЕТРЫ И ПУТИ ИХ СОВЕРШЕНСТВОВАНИЯ

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Аннотация. *В статье приведены сведения об измерении вибрационной вязкости, а также методы измерения вибрационной вязкости и формулы для их расчета. В статье также описаны приборы для измерения вибрационной вязкости и пути их усовершенствования. Также перечислены сходства и различия между приборами для измерения вязкости. Указано, как повысить КПД измерительного прибора и их выражения, также определены факторы, влияющие на КПД. Приведены также выражения для определения параметров и свойств измерителя вибрационной вязкости в зависимости от конструкции зонда. Указаны этапы разработки новых методов измерения вибрационной вязкости и их схем. В заключение сделан вывод, что вибрационная вязкость-измерительная аппаратура, основанная на новой конструкции и методе измерения, является перспективной.*

Ключевые слова: *вибрационный вискозиметр, амплитуда, колебания зонда, плотность, момент инерции, ньютоний, частота.*

1) Probes of translational oscillations with lumped parameters:

$$D = \frac{S\sqrt{\rho_0 \eta}}{m\sqrt{2\omega}}, \quad (1)$$

where: S – the area of contact of the probe with the liquid; m – probe mass; ρ_0, η – density and viscosity of a liquid; ω – circular oscillation frequency.

2) Probes of rotational oscillations with lumped parameters:

$$D = \frac{S_i\sqrt{\rho_0\eta}}{I\sqrt{2\omega}}, \quad (2)$$

where: S_i – moment of inertia of the area of contact of the probe with the liquid; I – probe moment of inertia.

3) Pitch probes with distributed parameters:

$$D = \frac{S_p\sqrt{\rho_0\eta}}{\rho\sqrt{2\omega}}, \quad (3)$$

where: S_p – ratio of probe cross-section perimeter to area; ρ – probe material density.

4) Torsional vibration probes with distributed parameters:

$$D = \frac{S_m\sqrt{\rho_0\eta}}{\rho\sqrt{2\omega}}, \quad (4)$$

where: S_m – the ratio of the moment of inertia of the perimeter of the probe cross section to the moment of inertia of the area of this section.

5) Probes of relaxation self-oscillations:

$$D = \frac{S\sqrt{\rho_0\eta}}{m\sqrt{2f}}, \quad (5)$$

where: f – frequency of relaxation self-oscillations; S и m – have a previously introduced meaning depending on the type of a probe.

The oscillatory characteristics of the probe also depend on the internal energy losses in the undamped probe [4].

It is convenient to operate with the tangent of the mechanical loss angle χ, which is the inverse of the quality factor of the undamped probe Q_0.

Let us consider some of the main patterns of development of oscillatory viscometers that have emerged in recent years.

A. Transition to low frequencies

If the fluid is Newtonian, then it does not matter at what frequency the measurements are made. In practice, however, many liquids are not purely viscous.

The behavior of viscoelastic fluids can be unambiguously described by assuming that the viscosity and shear elasticity of the fluid depend continuously on frequency. It is obvious that the equilibrium viscosity is best measured at a steady flow or, which is the same, at zero frequency; therefore, the more accurate the measurements of the equilibrium viscosity with vibrating viscometers, the lower the probe oscillation frequency is.

The set of viscoelastic fluids, whose equilibrium viscosity control is required, is very broad, so low-frequency probes should be used in vibrating viscometers for general applications [5].

Table 1

Classification of oscillatory viscometers

Probe oscillation mode	Measured vibrational characteristic	Lumped Probes		Distributed Probes	
		Resonance	Aperiodic	Resonance	Traveling wave
Forced harmonic vibrations	Amplitude	High sensitivity at χ ≪ 1	-	Application at D ≪ 1	
	Quality factor		Application at D > 1		Application at D > 1
	Phase shift	Application at D ~ 1	-	Application at D ~ 1	-
	Resonance frequency	-	-	-	-
	Traveling wave propagation speed	-	-	-	-

Free vibrations	Logarithmic damping decrement	High sensitivity at $\chi \ll 1$	-	High sensitivity at $\chi \ll 1$	-
	Natural frequency	Application at $D \sim 1$	-	Application at $D \sim 1$	-
Harmonic self-oscillations	Amplitude	High sensitivity at $\chi \ll 1$	-	High sensitivity at $\chi \ll 1$	-
	Frequency	Poor accuracy due to frequency phase instability	-	Poor accuracy due to frequency phase instability	Equivalent to the speed method when using the probe in the feedback link
Relaxation self-oscillations	Amplitude	-	The methods are applicable in a wide range of D	-	-
	Frequency	-		-	-

Some real media, for example, suspensions, emulsions, polymer solutions, and other discrete structures, can be considered continuous media when calculating the shear wave impedance only at sufficiently low frequencies, since with increasing frequency, the shear wave penetration depth decreases and can become commensurate with sizes of discrete inclusions and a distance between them.

The higher the oscillation frequency of the probe, the thinner the liquid layer surrounding the probe is involved in the oscillatory motion. If a continuous viscometer is to be used to measure the viscosity of coagulating or sticky liquids, the probe is often covered with a thin film of coagulome during operation. The ultrasonic viscometer in this case will give readings depending on the shear module of this film, but not on the viscosity of the liquid under study.

The use of low-frequency probes, which involve more fluid in motion, makes it possible to achieve good results when measuring the viscosity of coagulating fluids.

From what has been said, it is obvious that lowering the oscillation frequency of the probe is beneficial for increasing accuracy of viscosity measurements. The use of low-frequency probes makes it possible to significantly broaden the set of media, the viscosity of which can be controlled by vibratory viscometers.

One of the most important consequences of reducing the oscillation frequency is also the possibility of using probes with non-ideal configurations [6].

B. Use of non-ideal probes

The most important advance in the design of oscillating viscosity sensors is a transition to the use of non-ideal probes, which makes it possible to design sensors that meet many of the stringent requirements dictated by conditions of their use in industry or research.

Let a body of an arbitrary shape perform translational oscillations (oscillate) in a viscous compressible fluid. Due to the compressibility of a liquid, energy is removed by emitting sound waves into the liquid. As the oscillation frequency decreases, the conditions for sound emission into the liquid worsen due to the fact that the transverse dimensions of the probe become small compared to the length of the sound waves. In this case, a body oscillating in a liquid can be considered a dipole source of radiation, the field of which in an infinite medium is practically independent of its shape and is determined only by the created dipole moment [7].

Replacing on the basis of what has been said an arbitrary translationally oscillating body with an oscillating ball of such a radius that during oscillations it creates the same dipole moment as the oscillating body under consideration, we have an expression for pressure in an infinite medium [8] in spherical polar coordinates τ, θ, φ:

$$p = 2\pi U_0 r^3 \omega \rho_0 \cos\theta \frac{ik\tau - 1}{4\pi\tau^2} e^{ik\tau - i\omega t}, \quad (6)$$

where: U_0 – amplitude of harmonic vibrations of the center of the ball; ρ_0 – liquid density; $k = \omega / c$ – wave number for longitudinal plane waves; c – speed of sound in a liquid; r – ball radius; angle θ is measured from the straight line along which the center of the ball oscillates.

The pressure in the liquid on the surface of the sphere is:

$$p(\alpha, \theta) = \rho_0 c U_0 \cos\theta \frac{(k\alpha)^4 - ik\alpha[2 + (k\alpha)^2]}{4 + (k\alpha)^4} e^{-\omega t} \quad (7)$$

The total resistance force of the liquid to the movement of the ball is defined as the land of the projections of pressure forces normal to the surface of the ball on the direction of oscillation:

$$F = \iint_{(S)} p(\alpha, \theta) \cos\theta dS = \frac{4}{3}\pi \rho_0 c U_0 \alpha^2 \frac{(k\alpha)^4 - ik\alpha[2 + (k\alpha)^2]}{4 + (k\alpha)^4} e^{-\omega t} \quad (8)$$

The impedance of the liquid loading the ball, due to sound radiation, is equal to:

$$Z = \frac{F}{U} = \frac{4}{3}\pi \alpha^2 \rho_0 c \left\{ \frac{(k\alpha)^4}{4 + (k\alpha)^4} - i \frac{k\alpha[2 + (k\alpha)^4]}{4 + (k\alpha)^4} \right\} \quad (9)$$

and consists of active and inertial components [9]. We emphasize once again that it depends on the modulus of longitudinal volumetric deformation of the medium by means of the speed of propagation of sound waves included in expression (9).

With a decrease in the transverse dimensions of the probe and a decrease in frequency so that $ka \ll I$, the impedance tends to the:

$$Z \approx -\frac{4}{8} i\pi \alpha^2 \rho_0 c (k\alpha) = -i\omega \rho_0 \frac{V}{2} = i\omega \frac{m_0}{2}, \quad (10)$$

where: V – ball volume; m_0 – mass of fluid contained in a sphere.

Thus, in general case, the impedance loading of a body oscillating in a viscous fluid consists of the following components [10]:

a) active component due to emission of viscous waves into the liquid;

b) reactive component of the impedance of viscous waves, due to the attached mass of fluid;

c) active component of the impedance of sound radiation into the liquid;

d) reactive component due to the presence of drag caused by the fluid flow around the oscillating body.

The following circumstances are essential, which take place at small transverse dimensions of the oscillating body ($ka \ll I$) compared to the sound wavelength, which enables to use bodies of arbitrary shape as probes of oscillatory viscosity sensors and greatly simplify the calculation of the characteristics of such probes.

1. The active component of the impedance of sound radiation into a liquid, according to formula (9), is negligible compared to the active component of the impedance of viscous waves and can be discarded with an accuracy no worse than Δ, and:

$$\Delta \leq \frac{(k\alpha)^4}{4\sqrt{\frac{\omega}{2\nu}}\alpha}, \quad (11)$$

where: a – characteristic transverse dimension of the probe [11].

2. This condition corresponds to neglecting the influence of the liquid compressibility on the characteristics of the probe,

The reactive component of the impedance due to drag can be calculated with accuracy of the order of $(ka)^2$ under the following simplifying assumptions [12]:

a) the calculation is made without an account of viscosity of the liquid;

b) the liquid is considered incompressible;

c) does not take into account the shape of the body and replaces it with steam, which creates the same satisfied moment as the oscillating body.

3. When calculating impedance of viscous waves, it is necessary that the shape of the body is taken into account, however the calculation is greatly simplified taking into account points (9) and (11); moreover, at $\sqrt{\frac{\omega}{2\nu}}\alpha \gg I$ (which is often the case in practice), viscous waves can be considered plane. In this case, the shape of the body is not taken into

account, and the total impedance of viscous waves is obtained by multiplying the specific impedance of plane viscous waves:

$$Z_0 = \sqrt{\frac{\omega \rho_0 \tau}{2}}(i-1), \qquad (12)$$

to the surface area of the probe in contact with liquid.

The theory which is based on the latest assumption is equivalent to the theory of a boundary layer by A. Prandtl in hydrodynamics [13].

4. When measuring viscosity, it is possible to partially get rid of the influence of the added mass on the vibrational characteristics of the probe, if we use characteristics that depend primarily on the active component of the impedance associated with the loss of the vibrational energy of the probe (quality factor, logarithmic damping decrement of free vibrations, amplitude of harmonic self-oscillations). In this case, non-ideal probes make it possible to obtain almost the same results as ideal ones.

5. To measure density of liquids by oscillatory methods, non-ideal probes are better than ideal ones, and for measurements it is necessary to use the characteristics of the probe associated with the attached mass (resonant frequency, frequency of the resonant maximum; frequency of free oscillations, as well as phase shift with slightly worse results).

Above considerations form a theoretical basis for the use of non-ideal probes for measuring viscosity and indicate ways to calculate characteristics of non-ideal probes of oscillating viscosity sensors [15].

Let us give some examples of nonideal probes.

I. Probe of flexural-rotational vibrations used in industrial vibrating viscometers VVN-I, VVN-2 and VVN-3.

The probe is made as a single piece with an elastic suspension and has a shape of a cylinder of circular cross section. The shape of the elastic suspension ensures its high flexibility with respect to rotational vibrations around the suspension point (point 0) in the plane of the drawing, which reduces the resonant frequency of the probe. At the same time, the suspension withstands relatively high hydrostatic fluid pressures (of the order of 500-1000 kg/cm^2).

The calculation of its vibrational characteristics leads to the following results.

Probe impedance equal to the ratio of complex amplitudes perturbing moment and angular velocity of the cylinder axis at harmonic vibrations, is determined by the expression [16]:

$$Z = Z_x\left\{\frac{\chi}{\nu} + D\nu F_1(\tau) - i\left[\nu\left(1+m+DF_2(\tau)\right) - \frac{1}{\nu}\right]\right\} \qquad (13)$$

where: $Z_x = \omega_0 I$ – characteristic impedance of the probe;

χ – tangent of the angle of mechanical energy loss of an undamped probe;

$\nu = \omega/\omega$ – dimensionless frequency;

ω_0 – circular resonance frequency of the undamped probe;

$m = \rho_0/2\rho$ – dimensionless fluid density;

$\tau = \sqrt{\omega\rho_0/\eta} \cdot \alpha$ – dimensionless probe radius;

$D = \dfrac{\sqrt{\rho_0 \tau}}{\alpha\rho\sqrt{2\omega}}$ – viscous damping coefficient;

α

α – probe cross section radius.

$$F_1(r) = 1 - \frac{3}{16r^2} + \frac{3}{16r^3} - \frac{63}{1024r^4} + \cdots \qquad (14)$$

For the resonant frequency of the probe, we obtain the expressio

$$\nu_p = (1+m)^{1/2} - \frac{3}{4}(1+m)^{-\frac{5}{4}}D_0 + \frac{9}{16}(1+m)^{-2}D_0^2 - \cdots \qquad (15)$$

where: $D_0 = D(\omega_0)$ – reduced damping factor.

Hence, it is possible to estimate the efficiency of using a non-ideal probe as a liquid density sensor, since, in the first approximation, ν_p depends only on the value of m. The amplitude of harmonic self-oscillations of the probe, normalized by its static angular displacement under the action of a static moment numerically equal to its amplitude, is equal to:

$$A_x = \frac{1}{\chi + \frac{3}{2} D_0 v_p^{\frac{3}{2}} F_2(r)} = Q, \qquad (16)$$

where Q – the quality factor of the probe.

Hence it follows that the amplitude of the self-oscillations of the probe, its quality factor, and hence the logarithmic damping decrement do not depend on the value of m, due to the drag of the flow - a conclusion that we made earlier. Amplitudes of self-oscillations of the angular velocity of the probe and its angular acceleration, equal to [17]:

$$A_v = Qv_p,$$
$$A_a = Qv_p^2,$$

depend on m by means of the resonant frequency included in the expressions. This condition determines the viscosity measurement technique and requires the use of transducers that are sensitive to probe displacement.

The possibility of using the considered probe for measuring viscosity is obvious.

II. The tuning fork sensor of A.A. Stepichev and V.P. Kremlevsky differs from the one mentioned in that it contains two vibrators. This provides a number of advantages, the most important of which is a significant reduction in the removal of vibrational energy through the body of the viscosity sensor, which increases the quality factor of the probe.

Since the propagation of elastic perturbations along the body occurs at such a high speed that the wavelength is much greater than the distance between the vibrators, then in the first approximation it can be assumed that the vibrators oscillate at one point, and since they oscillate in antiphase, the waves emitted by them are almost entirely are mutually compensated [18].

The second advantage of the sensor is that the sound fields in the liquid created by the vibrators also practically cancel each other, which reduces the effect of compressibility of the liquid as to characteristics of the viscosity sensor.

The fluid flow around vibrators and emission of viscous waves are practically independent for each of the vibrators; therefore, the oscillatory characteristics of the tuning fork sensor are equivalent to those for the sensor with one vibrator when the damping coefficient is doubled, which allows using the above relations.

The disadvantage of a tuning fork viscosity sensor compared to a single vibrator one is the more complex shape of the surfaces flowing around the flow, which can lead to clogging of the probe with coagulum and foreign objects, as well as large dimensions.

III. The torsional viscosity sensor by Yu. Merten and M.M. Robinson contains an axisymmetric probe suspended on flat springs. With a sufficiently rigid suspension design, a low natural frequency of the probe of the order of 30-40 Hz is ensured. When the probe is twisted, the spring takes the form of an oblique plane. Such deformations of the squads make us consider the considered probe to be imperfect.

Since the logarithmic decrement of the damping of free vibrations is measured, the measurement results do not depend on the additional fluid overflow caused by the deformation of the springs.

IV. The string viscometer of Tuf, McCormick and Dash uses a tightly stretched string fixed at the ends as a probe. The dipole radiation of sound is very small.

A separate report is devoted to the characteristics of such a probe, and we do not consider them here.

Thus, from a small number of examples given, it is clear how diverse the designs of non-ideal probes can be. When the above conditions are met, almost any vibrating body can be used as the probe of an oscillatory viscometer. One of the most unexpected is a possibility of constructing a probe in the form of a membrane that performs oscillations normal to its plane. In this case, it is required that different sections of the membrane oscillate in antiphase, and the "finer structure" of the vibration modes of the membrane, the less sound emission and the higher the sensitivity to viscosity. Lamb and Love waves can also be used to build viscosity sensors [19].

Thus, the use of non-ideal probes opens up new opportunities in the design of probes for oscillating viscosity sensors.

C. Mastering new measurement methods

The next major trend in the improvement of oscillatory viscometers is the development of new measurement methods. It implies the use of soul measurements of new oscillatory characteristics of probes, new modes of their oscillations, new functional schemes for controlling probe oscillations and measuring ones.

Here are a few examples of such recent achievements.

1. Explosion-proof viscometer VVN-3 for general industrial purposes. The device uses harmonic self-oscillations of the probe. However, unlike the existing designs, the mode of constant oscillation amplitude is used, which is achieved by automatically changing the amplitude of the driving force, which is used as a measure of the measured viscosity.

As a result, the viscosity range of 3 × 104 is easily covered, the scale of the device is straight and close to linear.

2. Viscometer VVN-2 for measuring viscosity in oil wells. Thanks to the use of a bridge circuit in the feedback link of the oscillator, the possibility of remote measurements using a single-core logging cable several kilometers long has been achieved, while the viscosity sensor contains only one reversible electromechanical transducer.

3. Development of relaxation self-oscillating viscometers.

This new type of oscillatory viscometer has a number of significant advantages, the environment of which is as follows:

– the ability to work at infra-low and ultra-low frequencies with very small oscillation amplitudes;

– easy provision of constant shear rate or constant stress modes;

– scale linearity in relation to viscosity;

– wide and easily changeable measurement range;

– high accuracy.

For the first time, a device of this type was built by Zaitsev and Tsarevsky, however, they did not appreciate the enormous advantages of the method, which emerged after its theoretical analysis.

We don't stop in detail here at the discussion of the listed structures and methods, since separate reports at this meeting are devoted to them.

4. Let us pay attention to the promise of one of the classical methods, which, unfortunately, has not yet been widely used for a number of reasons – the phase method for measuring viscosity.

The method is based on the measurement of viscosity by determining the phase shift between the voltage or current in the transducer that excites the probe oscillations, and emf. on the receiving transducer.

Regardless of the type of lumped-parameter probe oscillations, if the latter creates practically plane shear waves in the viscous fluid under study (which can be observed in most real cases), the phase shift created by the probe and transducers is determined by the expression [20]:

$$\psi = arctg\frac{D_0\nu^{3/2}+\nu^2-1}{\chi+D_0\nu^{3/2}} + \psi_0, \qquad (17)$$

where ψ_0 – constant phase shift created by resonant converters.

Then, from the measurement results, the viscosity is determined by formula

$$\sqrt{\rho_0\eta} = \frac{A}{ctg(\psi-\psi_0)-1}, \qquad (18)$$

where A – instrument constant.

The sensitivity C of the phase viscometer, characterized by the phase shift increment $\Delta\psi$, related to the change in viscosity $\Delta\eta/\eta$, is equal to:

$$C = \frac{D_0 \nu^{\frac{3}{2}}(1+\chi-\nu^2)}{2\left\{\left(\chi+D_0\nu^{\frac{3}{2}}\right)^2+\left(\nu^2+D_0\nu^{\frac{3}{2}}-1\right)^2\right\}} \quad (19)$$

The maximum C is reached in the vicinity of the resonant frequency and is the following value

$$C = \frac{D_0\nu^{\frac{3}{2}}}{2\left(\chi+D_0\nu^{\frac{3}{2}}\right)} = \frac{1}{2}\left(1-\frac{Q}{Q_0}\right), \quad (20)$$

where Q, Q_0 – quality factors of the damped and undamped probes.

Hence it follows that an increase in loss χ always reduces the sensitivity in the considered case of near-resonance measurements. The ultimate sensitivity, equal to I /2 radians, is achieved in the absence of losses.

When $v^2 = 1 + \chi$ the sensitivity of the phase viscometer is equal to zero. At this frequency, the phase-frequency characteristics of the probe at different damping coefficients intersect at one-point ψ = π/4. With a further increase in the oscillation frequency of the probe, the instrument scale becomes reversed. Therefore, the construction of a single-reading viscometer is associated with the use of probe excitation frequencies either above or below:

$$v = \sqrt{1+\chi},$$

and the use of low frequencies is more appropriate both to increase the sensitivity and accuracy of the device.

Viscosity measurement error is caused by phase shift measurement error, drive oscillator frequency instability, as well as probe resonant frequency instability due to temperature changes and other factors.

The phase shift instability that occurs in the converter and the electronic elements of the phase meter amplifier can be attributed directly to the phase meter error.

Let us represent the total maximum error of the viscometer in the form:

$$\frac{\Delta\eta}{\eta} = N_\psi \Delta\psi + N_{\psi\nu}\Delta\nu, \quad (21)$$

where: N_ψ – error coefficient showing how many times the main error of the device is greater than the error of the phase meter;

$N_{\psi\nu}$ – phase shift frequency instability factor;

$\Delta\nu$ – generator frequency instability.

The error rate is given by:

$$N_\psi = 2\frac{(\chi+D_0\nu^{\frac{3}{2}})^2+(D_0\nu^{\frac{3}{2}}+\nu^2-1)}{D_0\nu^{\frac{3}{2}}(1+\chi-\nu^2)} \quad (22)$$

and takes the smallest value during measurements in the vicinity of the resonance frequency of the probe, equal to:

$$N_{\psi\nu} = 2\frac{1+\chi-\nu_p^2}{1-\nu_p^2} = 2\frac{Q_0}{Q_0-Q}. \quad (23)$$

Figure 1 shows the dependences of $N_{\psi\nu}$ on v_p and χ, where it can be seen that in order to increase the accuracy of near-resonance measurements, it is necessary to increase the intrinsic quality factor of the probe and the damping factor.

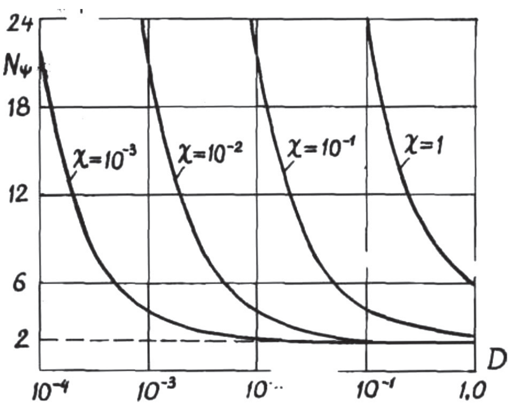

Figure 1.

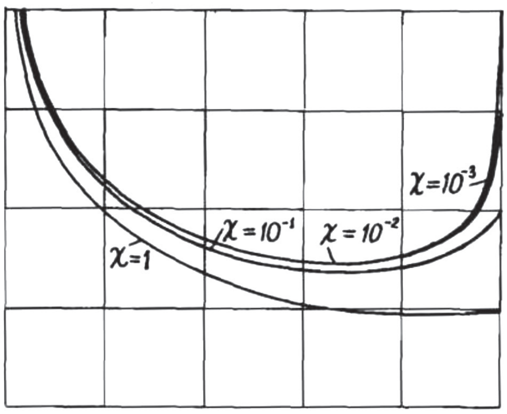

Figure 2.

The coefficient of frequency instability of the phase shift is equal to:

$$N_{\psi\nu} = \frac{[3/2(1-\nu_p^2)/\nu_p^2]+2\nu_p}{1+\chi-\nu_p^2} \quad (24)$$

and is graphically presented in Figure 2. The figure shows that as χ increases, it decreases, which is achieved at the cost of a decrease in sensitivity and an increase in $N_{\psi\nu}$, especially at low viscosities. In the latter case, $N_{\psi\nu}$ is approximately equal to twice the quality factor of the damped probe (2Q).

Depending on the ratio of $\Delta\psi$ and $\Delta\nu$, you can choose the value of χ at which the total error in measuring viscosity is minimal in a given measurement range.

As can be seen from a comparison of Figs. 1 and 2, the highest values of viscosities that can be measured by the phase method at certain measurement accuracy and frequency instability $\Delta\nu$ are limited by the fact that $N_{\psi\nu}$ increases with decreasing ν_p. To increase the viscosity measurement limit with a given accuracy, it is advisable to reduce the intrinsic quality factor of the probe, as well as increase the frequency stability of the exciting generator and the thermal stability of the probe characteristics.

In general, very high viscosities are achievable, which can be measured quite accurately by the method under discussion. For example, with $x = 10^{-2}$ and

$\Delta\nu = 10^{-3}$ with a given error $\Delta\eta/\eta = 2 \cdot 10^{-2}$, measurements can be made up to ν_p = 0,283, which corresponds to D = 11,5. With a practically easily achievable device constant A equal to $2.5 \cdot 10^3$ kg/m$^2 \cdot$ s, and liquid density of 1000 kg/m^3, this corresponds to a viscosity of 8.3 · 105 Pa·s, which is far from being the limit.

In practice, near-resonance measurements are feasible with a jump in the probe excitation frequency, so that it is close to resonant when the probe is damped by the liquid under study. Since a discrete set of frequencies is used, it is easy to build oscillators with high generation frequency stability, thereby reducing $\Delta\nu$.

Thus, the phase vibrational method for measuring viscosity makes it possible, using only one probe, to cover a wide range of measured viscosity values by appropriately changing the excitation frequency and intrinsic losses of the probe. The method has high accuracy.

In the coming years, apparently, some other now poorly mastered oscillatory methods for measuring viscosity will also become widespread.

D. Use of new instrument elements

The first generation of oscillatory viscometers used mechanical, optical and electromagnetic devices to control the oscillation of the probe and measure its characteristics.

The use of electronic circuits gave birth to the second generation of viscometers.

The third generation of viscometers, which will use integrated circuits, solid circuits, as well as digital meters, will not do without the use of a phase method for measuring viscosity and some other methods.

Let us use this specific example to explain the fact that the use of new elements makes it possible to achieve qualitatively new results and often decides the fate of the method.

Despite the fact that, in principle, the phase method is two orders of magnitude more accurate than the amplitude method, the measurement of the phase shift is now carried out by devices containing several (up to ten) stages. Taking into account the fact that devices for controlling probe oscillations usually contain several stages, the use of the phase method complicates the device by two or three times. Apparently, for this reason, now the phase method has not received due distribution.

With the advent of integrated and solid circuits and digital meters, such a complication will not lead to a significant increase in the dimensions of the circuit and its cost, which will make it possible to use the phase method.

In the future, standard meters, in particular digital ones, will be used more widely, as well as new elements of probe oscillation control and registration circuits, such as new converters, optoelectronics, lasers, Ronchi gratings, fiber optics, photosensitive semiconductor devices, chemotronic elements, pneumatic and hydraulic devices (for example, on superfluid helium), devices using the Mossbauer effect, and others [21].

The expansion of the element base of devices will lead to their qualitative changes.

Conclusions

We have listed some goals and objectives, some of which need to be addressed in the coming years.

1. Mastering some new measurement methods.

2. Improving the accuracy of measurements and the creation of reference absolute oscillatory instruments.

3. Expansion of the measurement range.

4. Mastering the infra-low-frequency and super-low-frequency ranges, which requires the provision of the necessary speed and the development of new meters for the oscillatory characteristics of the probes.

5. Accumulation of experience and creation of theoretical foundations for the design of oscillatory viscosity sensors that meet the harsh conditions of use in industry and research. Use of new types of probe oscillations. Creation of high-quality low-frequency viscosity sensors.

6. Improvement of the element base of devices.

7. Unification and standardization of oscillatory viscometers, both laboratory and industrial.

8. Creation of more accurate (than VPJ-1) standard instruments, especially for high viscosities; improvement of the metrological service and methods of calibration of instruments.

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