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Application of ultrasonic techniques for measurement of a flowrate of viscous liquids in a wide temperature range

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Introduction

Ultrasonic flowmeters use mechanical ultrasonic waves and ultrasound speed in media is influenced by temperature. Temperature of the fluid in industrial applications may vary a lot. Thus, it is important to know the influence of temperature on the speed of the ultrasound in viscous liquids, analyzed in [1] and [2]: the sunflower seed oil 'Brolio', the emulsifier lecithin E322, and the palm oil. In the course of design of ultrasonic flowmeters used for specific fluids and specific conditions of ariable flows, it is important to investigate possible influence of at on a behavior of the fluid in a pipe. The influence of temperature on viscosity of the fluid in a wide temperature range hads been investigated in [1] and [2]. There also had been investigated the influence of viscosity and dynamics of the flow on formation of the flow profile in the pipe. It had been established that the flow of viscous fluids in a circular pipe would be laminar. In some particular situations when the fluid is semi viscous, the temperature is high and the velocity of the flow reaches maximal values, the flow profile may shift into intermediate profile zone. In order to compensate this effect, the part of the pipe used by flowmeter has to be widened. In such a way, the laminar flow even in extreme conditions will be ensured. It has been determined [2], that it is inadmissible to change the interval construction of the pipe just because of flowmeter design, as it would increase hydraulic losses in the pipe, that are already high enough for viscous fluids. The only exception is the mentioned above increase of the diameter of a pipe in the measuring part of the flowmeter. However, the increase of the diameter of the pipe in front of flowmeter and decrease of it behind doesn't increase noticeable hydraulic losses. If a low viscosity of the fluid were taken into account, the local hydraulic losses become insignificant.

The first of the aims of this work is to analyze present ultrasonic flow measurement methods in order to estimate their suitability for measurement of non-stationary flows of viscous liquids. The second one is to analyze temperature influence on the speed of the ultrasound in viscous fluid and the same way its influence on the measurement results.

Suitability of the flowmeter designs

Ultrasonic flowmeters by their design are divided into transit time, ultrasound beam shift, Doppler and correlation meters.

In the transit time ultrasonic flowmeters the ultrasound waves are sent along or diagonally to centerline of the pipe. If there is a flow in the pipe the change of the transit time of the ultrasound along the flow and against it gives information about the velocity of the flow in the path of the ultrasound. In the simplest way, the path of the ultrasound lies in parallel to the centerline of the pipe (Fig. 1.).

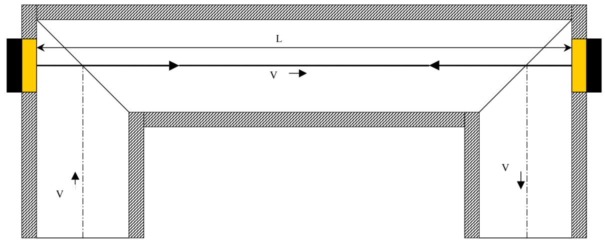

Fig. 1.**Transit time ultrasonic flowmeter with the path of the ultrasound parallel to the centerline of the pipe.**

The difference of the transit times of the ultrasound against the flow τ_2 and along it τ_1 is proportional to an average velocity of the flow:

$$\Delta t = \tau_2 - \tau_1 = \frac{2Lv}{c^2 - v^2} \approx \frac{2Lv}{c^2}. \qquad (1)$$

Here L is the length of the path of the ultrasound, c is the speed of ultrasound in a fluid and v is the average velocity of the flow in the path of the ultrasound.

The length of the path of the ultrasound is usually unknown. However, it may be expressed as:

$$L = \frac{1}{2} c(\tau_1 + \tau_2). \qquad (2)$$

In the course of the prime calibration of the flowmeter, the ultrasound speed in the media used for calibration (for example, distilled water) is known and the average velocity of the flow is known as well. Therefore, the precise value of L may be determined. The ultrasound speed in the fluid may be calculated from the directly measured values of τ_1 and τ_2 and the known value of L:

$$c = \frac{2L}{\tau_1 + \tau_2} \qquad (3)$$

If c were put into Eq.1 the average velocity of the flow v may be excluded:

$$v = \frac{2L(\tau_2 - \tau_1)}{(\tau_1 + \tau_2)^2} \qquad (4)$$

Here the difference of delays in electronic circuits of both measuring channels is not taken into account.

If the mass flow rate has to be recalculated, and ultrasound speed in the media dependence upon temperature is known, Eq.3 may be used for determination of the temperature. The instant kinematic or dynamic viscosity of the fluid in a similar way may be computed if a viscosity dependence upon temperature is known.

The sending of the ultrasound beam in parallel to the centerline of the pipe has an another advantage. It is possible to make the length of the ultrasound path almost as long as it requires; that increases accuracy of the measurement. Therefore such an installation is used for many non-viscous fluids. In such a case the ultrasonic transmitters - receivers have to be inserted inside the pipe, the ultrasound reflectors have to be mounted inside the pipe, or there has to be a bending on the pipe. However all these changes of geometry of the pipe would increase hydraulic losses and for viscous liquids these losses are not allowable. Thus, axial ultrasound path installation is not suitable for viscous liquids.

Another solution for the measurement of the flow velocity is to ensure the path of the ultrasound to lie under some angle α to the centerline of the pipe (Fig. 2). It may be called an angular installation.

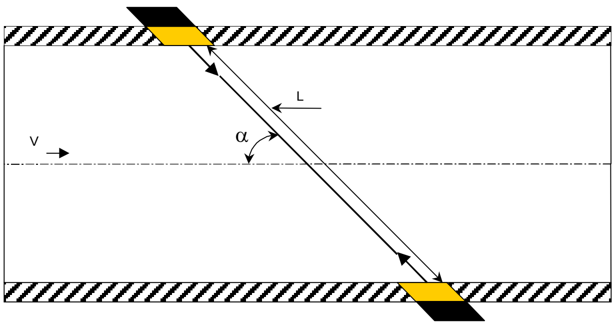

Fig. 2. **Transit time ultrasonic flowmeter with angular installation of the ultrasound path**

Advantages are following no bending of a pipe is required, ultrasound transmitters – receivers may be mounted on the wall of the pipe with no any change to the geometry of the pipe, or even mounted on the outside wall of the pipe. In such a manner, there won't be any additional hydraulic losses because of the ultrasound transmitter – receiver mounting therefore, angular installation is acceptable for the viscous fluids.

The difference of transit time of the ultrasound against the flow τ_2 and along it τ_1 is proportional to an average velocity of the flow:

$$\Delta\tau = \tau_2 - \tau_1 = \frac{2Lv\cos\alpha}{c^2 - v^2\cos^2\alpha} \approx \frac{2Lv\cos\alpha}{c^2} \qquad (5)$$

Here α is the angle between the path of the ultrasound and centerline of the pipe. The length of the path of the ultrasound L and the ultrasound speed in the fluid c are given by:

$$L = \frac{1}{2}c\left(\tau_1 + \tau_2\right). \qquad (6)$$

$$c = 2L\frac{1}{\tau_1 + \tau_2}. \qquad (7)$$

If to put Eq.7 into Eq.5, the ultrasound speed may be excluded:

$$v = \frac{\left(\tau_2 - \tau_1\right)}{\left(\tau_1 + \tau_2\right)}\frac{2L}{\cos\alpha}. \qquad (8)$$

This expression doesn't cover the electronic circuits influence.

In the course of the prime calibration of the flowmeter, the ratio $L/\cos\alpha$ may be precisely calculated. Therefore the average velocity of the flow depends only upon transit times τ_1 and τ_2. If ultrasound speed in the fluid dependence upon temperature is known, the instant temperature values may be calculated. If the fluid density dependence upon temperature is known, the mass flow rate may be computed. If the both mentioned above quantities, and viscosity of the fluid dependence upon temperature are known as well, instant viscosity values may be computed. In the same way the values of the Reynolds number may be calculated.

Ultrasound beam shift flowmeters use the effect that the flow carries off the ultrasound beam (Fig. 3.).

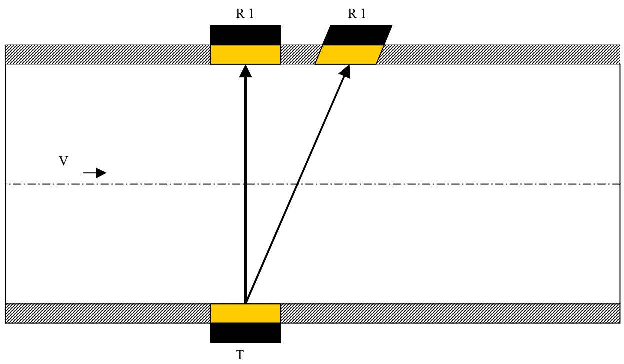

Fig. 3. **Ultrasound beam shift flowmeter.**

The ultrasound is transmitted from the transmitter T on one side of the pipe perpendicularly to the centerline of the pipe. On the other side of the pipe there are at least two ultrasound receivers R1 and R2. One of them (R1) is in line with the transmitter T. Another one R2 is a little bit further from R1 in direction of the flow. When there is no any flow in the pipe, the entire ultrasonic signal transmitted by T is received by R1. With increase of the flow, the signal received by receiver R2 strengthens and by R1 weakens. Ratio of magnitudes of signals received by R1 and R2 gives information about velocity of the flow. There may be a few receivers instead of one R2. The additional receivers mounted on the wall of the pipe along the flow from R1 would give more accurate information about the velocity of the flow. The requirements for the ultrasound beam geometry are high because the unsymmetrical beam or variations of its symmetry from expected might cause noticeable measurement uncertainties. However, this method is suitable when velocities of the flow are sufficiently high. In the case of low velocities of the flow ratio of magnitudes of signals from R1 and R2 may become immeasurably small. In addition, the receivers R1 and R2 would have to be mounted extremely near from each other and the requirements for the geometry of ultrasonic beam would become unrealizable high. In order to decrease hydraulic losses, the flow may be slowed via increasing diameter of the pipeline. Therefore, it is inadmissible to decrease diameter of the pipe in the measuring part of flowmeter thus, the velocity of the flow would be small.

In the case of dosing impulse, the velocity of the flow in the beginning of impulse and at the end of it would change from zero to its nominal value and backwards. If it even were possible to measure accurately the top of the impulse, there surely will be immeasurable parts in the fronts of the impulse. Therefore, such a method of measurement of the flow rate isn't suitable for viscous liquids and dosing tasks.

The Doppler ultrasonic flowmeters use well known Doppler effect. The frequency f_0, transmitted from the moving object or reflected by it, changes into f_1 and the difference between these two frequencies $f_D = f_1 - f_0$ is proportional to the radial velocity of the object with respect to the transmitter – receiver. By definition of the Doppler effect, there must be some reflective particles in the flow whose velocities along the pipe were proportional to the velocity of the flow. Transmitter and receiver may be mounted diagonally or along the centerline of the pipe. However, longitudinal installation of the ultrasound transformers (similar as in Fig. 1) would change velocities of 'moving objects' in the fluid in hardly predictable manner and hydraulic losses in the pipeline would increase. Diagonal installation is more often used (Fig. 4).

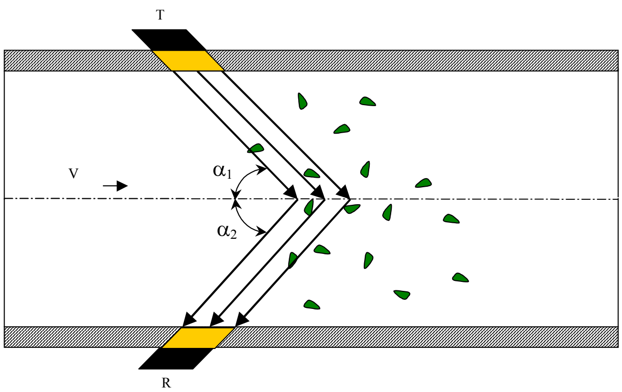

Fig. 4. **Doppler ultrasonic flowmeter.**

The harmonic waves of the ultrasound of known frequency f_0 are transmitted under some angle α_1 to the centerline of the pipe. They are reflected by axially moving particles in the fluid. The transmitted frequency of ultrasound waves f_0 changes to f_1 and these waves are gathered by ultrasound receiver R, mounted under some angle α_2 to the centerline of the pipe. The difference between these two frequencies, called Doppler frequency, is proportional to the velocity of these reflective particles. If velocity of a reflective particle is the same as of the flow then local flow velocity:

$$v = \frac{f_D c}{f_0(\cos\alpha_1 + \cos\alpha_2)}. \quad (9)$$

When the ultrasound reflects from a lot of reflective particles, located at different normalized distances from the centerline of the pipe, a lot of Doppler frequencies are generated and each of them represents flow velocity at different normalized distance. The spectrum of Doppler frequencies is formed. If impulses of frequency f_0 are sent, the time of transition of the impulse allows defining the location of the reflective particle. From here, the whole flow profile with the values of velocities on it may be computed. It is known that the flow for viscous fluids in a dosing regime is laminar. Thus, if a single value of velocity of the flow at certain point and coordinates of this point are known, all the velocities of the flow at any point of the cross-section of the pipe may be computed. In the same way the average velocity of the flow may be computed. In order to arrange one point measurement the ultrasound beams have to be as narrow as possible.

Implementation of Doppler meters requires presence of reflective particles in the fluid and these particles have to move with the same axial velocity as the fluid does. These particles may be air bubbles, particles of other nature than the fluid is, or some formations of the same fluid with the different conductivity to the ultrasound than the entire fluid is (parts with the different temperature or pressure). The reflective particles may be a composite part of the fluid; otherwise - they have to be formed. In practice, not all the viscous fluids contain such the particles; rather just a few of them do. Reflective particles or reflective layers of the fluid may be formed in two main ways. The air or some other gas bubbles may be injected into a flow. As their ultrasonic conductivity varies from the one of the fluid a lot, a good reflectance is ensured. However not always it is acceptable the presence of gases in the investigated fluid. If a body were inserted into a pipe, turbulation zones would be formed along the pipe after it. That body may be heated or cooled therefore, waves of the fluid with different temperature and pressure along the pipe would be formed. These boundaries of the layers of the fluid with different temperature and pressure are sufficiently reflective for the ultrasound. However the fluid is viscous, and as it had been said before, it is inadmissible to increase hydraulic losses in the pipe. Thus, no any foreign body in the pipe is allowed to be. There is another reason for unsuitability of the Doppler flowmeter. As the fluids under investigation are viscous and sometimes high viscous, the reflective particles or layers won't be distributed equally in the fluid. They would represent only the velocities of the particles or layers in some geometrical part of the pipe that isn't mathematically predictable. In addition, because of high viscosity of the fluid these particles or layers may move along the pipe not with the same axial velocities as the fluid does.

Correlation flowmeters are based on the analysis of random fluctuations in the fluid at different axial positions along the pipe. These fluctuations may be detected as the change of the ultrasound speed in the cross-section of the pipe or as the distance variations of reflective particles from the wall of the pipe. The fluctuations in some cross-section of the pipe at some time interval $\Delta t_1 = t_{12} - t_{11}$ are correlated to the one after some distance L along the pipe at time interval $\Delta t_2 = t_{22} - t_{21}$ (Fig. 5.).

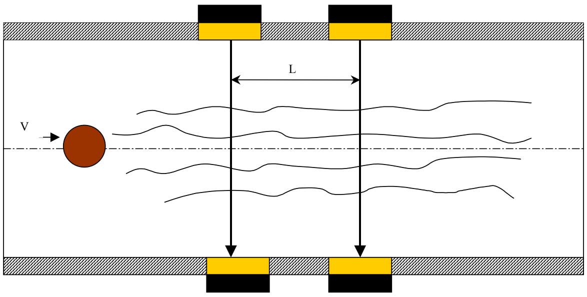

Fig. 5. **Correlation ultrasonic flowmeter.**

Here $t_{22} > t_{21} > t_{12} > t_{11}$ and $\Delta t_1 = \Delta t_2$. If the distance L is known and the time shift between Δt_2 and Δt_1 is computed, the flow velocity may be calculated:

$$v = \frac{L}{t_{22} - t_{12}} = \frac{L}{t_{21} - t_{11}}. \qquad (10)$$

The fluctuations may naturally be in the flow or they may be formed in it. These fluctuations are characteristic to the turbulent flow and to the intermediate profile zone of the flow. However, it had been considered in [2] that the flow for viscous fluids would be laminar. Even if there were some irregularities in the laminar flow, because of the high viscosity of the fluid they were damped fast enough. If a dosing regime of the flow were used, the velocity of the flow on the short fronts of the dosing impulse would change fast. That would influence forming of the irregularities of the flow along the entire pipe. At such a moment, the correlation flowmeter may be successfully used for the measurement of the velocity of the flow.

However, the fronts of the dosing impulse are short enough, after reaching the zone of constant velocities, the irregularities would be damped, and measurement would be impossible. When fluctuations are formed in the flow, some flow disturbing body is inserted into the pipe, as shown in Fig. 8. In such a case there were not enough time or distance for the flow to damper these irregularities of the ultrasound wave even if the flow were laminar and the fluid high viscous. However, as it is stated in [2], the hydraulic losses in the pipeline may not be increased because of the design of the flowmeter. Therefore, even correlation flowmeters are not suitable for measurement of the non-stationary flow rate of viscous fluids.

Transmission of the ultrasound

The speed of the ultrasound varies from fluid to fluid and it may differ for the same fluid with the change of its physical condition. The direct measurant is not the velocity of the flow but the transit time of the ultrasound that is proportional to the velocity of the flow and depends on the ultrasound speed in the fluid. Therefore, the knowledge of the ultrasound speed in the analyzed media is of high importance. The change of temperature of the fluid influences its density and elasticity. An ultrasound speed depends on these parameters, thus it is temperature dependent.

In order to analyze this dependence, there had been made measurements of ultrasound speed in the sunflower oil, the emulsifier lecithin and the palm oil in a wide temperature range. Temperature had been changed in the same range as in the case of measurement of viscosity and density of these fluids [2]. Measurements were performed by a sensor with a piezo transmitter – receiver with the perpendicular reflectance area. The sensor had been inserted into fluid analyzed, temperature of the fluid had been kept constant by the means of thermostat. The temperature had been considered as constant if its change didn't exceed the value of 0,1K/10min while the analyzed fluid was constantly stirred. At the beginning of all the measurements, calibration of the sensor had been made. Actually, it means measurement of the transit time required for the ultrasound to go forwards and backwards between the surface of the transmitter – receiver and the reflectance area in the distilled water of known temperature. As ultrasound speed in the distilled water at certain temperature is known, it wasn't difficult to calculate the distance from the surface of the transmitter – receiver to reflectance area via following formula:

$$c = \frac{2L}{\tau}. \qquad (11)$$

Here c is the ultrasound speed in the analyzed media, L is the distance between the surfaces of the transmitter – receiver and reflector, and τ is one direction transit time of the ultrasound. As the distance L had been calculated from (11), there had been performed measurements of transit time τ in the distances of $2L$ for the analyzed fluids at fixed and known temperatures. Ultrasound speed dependencies upon temperature via (11) had been calculated. As all the three dependencies seemed to be very similar to linear (12), thus linear approximation using the method of least squares had been performed. Linear model used:

$$c = a + bT. \qquad (12)$$

Here a and b are the linear coefficients and T - is the centigrade temperature of the fluid. The values of coefficients a and b for the linear approximation of investigated materials are presented in the Table 1.

Table.1. **The coefficients of linear approximation**

	Sunflower oil	Lecithin	Palm oil
a	1531.0	1575.1	1525.1
b	-3.1514	-3.3543	-3.1507

As it is seen from the Table 1, ultrasound speed dependence upon temperature in all investigated fluids is similar. Ultrasound speed in the lecithin is a little bit more dependent on temperature than it is in oils. The coefficient a differs from oil to oil in about 0.4%, the coefficient b in about 0.02%. The coefficient a differs from lecithin to average values of oils as much as 3% and the coefficient b – 6.5%.

The average of absolute values of relative errors of approximation at experimental points (further – the average error of approximation) $\overline{\delta}_{ca}$ had been calculated by means of the following formula:

$$\bar{\delta}_{ca} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{c_{ai}(T) - c_i(T)}{c_i(T)}\right| 100\% . \quad (13)$$

Here N is the number of experimental points used for approximation, i is the number of the point, $c_{ai}(T)$ is the approximated value of the speed of ultrasound in the analyzed fluid, and $c_i(T)$ is the experimental value of the speed of ultrasound. The following values of average error of approximation for the linear model had been obtained:

Sunflower oil - $\bar{\delta}_{ca} = 0.063\%$;

Emulsifier lecithin - $\bar{\delta}_{ca} = 0.085\%$;

Palm oil - $\bar{\delta}_{ca} = 0.055\%$.

The experimental data (shown as '+') and linear approximation (shown as continuous line) of the ultrasound speed in the analyzed fluids at different temperatures are presented in Fig. 6 to 8.

In order to obtain a better accuracy of approximation the second order polynomial (14) had been used as a model:

$$c = a + bT + cT^2 . \quad (14)$$

The polynomial coefficients had been found using the method of the least squares. The average errors of approximation, calculated by the means of the same formula (13), are a little bit smaller:

- Sunflower oil - $\bar{\delta}_{ca} = 0.05\%$;
- Emulsifier lecithin - $\bar{\delta}_{ca} = 0.0153\%$;
- Palm oil - $\bar{\delta}_{ca} = 0.0178\%$.

However, these values don't differ much from the linear method, thus the linear model as most adequate to the experimental data had been chosen for all the analyzed fluids.

As it is seen from the Fig. 6 to 8, the change of temperature of the fluid in 90K changes the speed of the ultrasound in it for almost 20%. Temperature coefficients for the ultrasound speed via (12) are [b]=(m/s)/K. The values of b for each analyzed fluid are presented in the Table 1. If the flow were steady, there rarely were big changes in temperature of the fluid. In the case of dosing, some of the fluid is kept in tanks where it is stored and some of it is in a pipeline. The flow and steady state in the pipeline is changing periodically. The ambient temperature of the pipeline may be different along it. If time intervals between dosing impulses are long enough, and temperature difference of fluid in the pipe and the surrounding of the pipeline is significant, there may occur noticeable temperature changes between them, and after some time the temperature along the pipeline would be affected. Even the bigger temperature difference would appear, if the pipeline is heated or cooled and especially when not all the pipeline is thermally treated in a similar manner. A fluid in a tank is usually kept at constant temperature but because of the tank surrounding temperature, difference in comparison with the one of the fluid, there may form some temperature gradients inside the tank. Keeping in mind that temperature of the fluid in the pipeline may be even more different from the one in the tank, the temperature difference in some 90K doesn't seem unbelievably great.

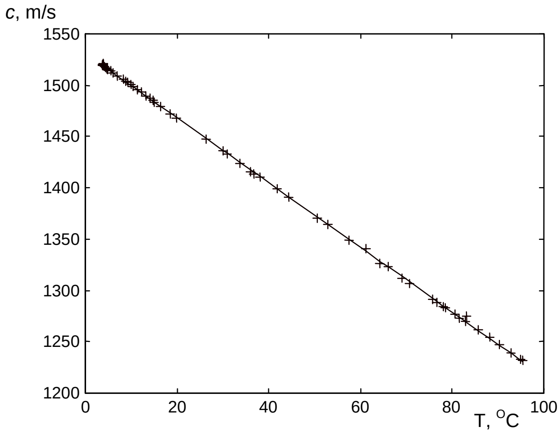

Fig. 6. **Influence of temperature on an ultrasound speed in the sunflower oil and its approximation.**

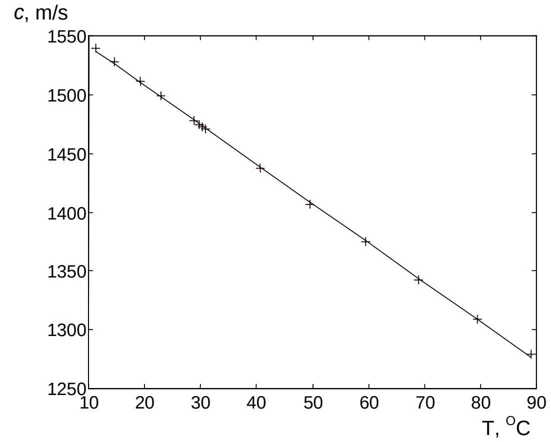

Fig. 7. **Influence of temperature on an ultrasound speed in the emulsifier lecithin and its approximation.**

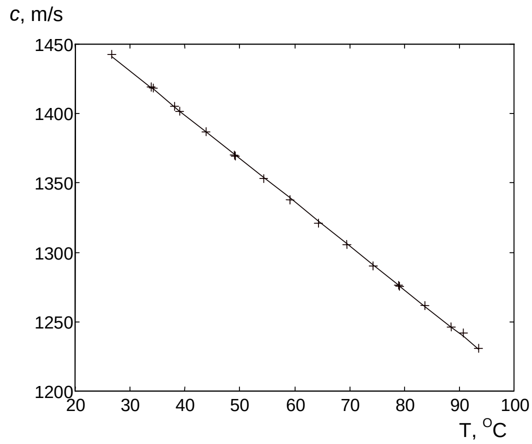

Fig. 8. **Influence of temperature on an ultrasound speed in the palm oil and its approximation.**

There also should be mentioned an effect of the 'inside heating' of the fluid. When the high viscous fluid is flowing through the pipe, because of its molecular friction the temperature of the fluid increases.

Therefore, temperature should be measured directly before the inlet of the flowmeter or that should be done before the inlet of the flowmeter and after the outlet of it. An average value of temperature of the fluid in the measuring part of the flowmeter should be calculated. The other solution for fast measurement of the temperature of the fluid would be the use of known ultrasound speed in the fluid dependence upon temperature. The best solution would be the elimination of temperature influence on the measurement results by the means of the measurement method.

Conclusions

In analysis of suitability of the existing ultrasonic flow measurement methods, it had been referred to the investigated properties of viscous fluids and dynamics of the flow. It had been established that all these methods, except one are not suitable for the measurement of the dynamic flow of viscous fluids in spite of some their useful features. The only method that meets requirements of the specifics of the fluid and the flow is the transit time flowmeter with angular installation of the ultrasonic path. However, there still remain requirements for the speed and accuracy of measurements when the velocity of the flow is low.

The dependencies of the ultrasound speed upon temperature in three viscous foodstuff liquids: the sunflower oil 'Brolio', the emulsifier lecithin E322 and the palm oil had been investigated. These dependencies turned out to be linear. These dependencies had been approximated via line and it had been ascertained that coefficients of these lines are quite similar for all three liquids despite their very different rheological properties, established in [2]. That let us to make a conclusion that ultrasound speed in the fluid doesn't depend on the viscosity of the fluid just both viscosity and ultrasound speed depend on the same certain property of the fluid that is temperature dependent. The ultrasound speed in both the oils had been practically identical at any temperature in all the investigated range of its change. It also should be mentioned that all the three investigated fluids are of the vegetable origin. The ultrasound speed in these fluids is highly temperature dependent: the change of temperature in 4.5K changes the speed of the ultrasound in 1%. Therefore the ultrasound speed in the fluid should be eliminated from the measurement results or ultrasound speed dependence upon temperature should be estimated. In order to estimate the influence of temperature on the ultrasound speed, the temperature in the fluid has to be measured, and the functional dependence of the ultrasound speed in the fluid under investigation has to be known.

Acknowledgment

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Ultragarsinių debito matavimo metodų taikymas klampiems skysčiams plačiame temperatūrų diapazone

Reziumė

Norint nustatyti, ar esami ultragarsiniai debito matavimo metodai tinka klampiems skysčiams ir dinaminiams srautams, buvo analizuojami sklidimo trukmės pokyčių, nunešamo ultragarso, dopleriniai bei koreliaciniai matavimo metodai. Nustatyta, kad daugumą keliamų reikalavimų tenkina sklidimo trukmės pokyčių matavimo metodas, kai ultragarso kryptis su vamzdžio ašimi sudaro kampą. Šis metodas turi ir kitą pranašumą – galima išvengti temperatūros įtakos matavimo rezultatams.

Tiesioginiai matavimo rezultatai priklauso nuo ultragarso greičio klampiame skystyje. Norint įvertinti galimus ultragarso greičio pokyčius, kintant temperatūrai, ir šių priklausomybių skirtumus skirtingiems skysčiams, buvo išmatuotos ultragarso greičio trijuose klampiuose skysčiuose: saulėgrąžų aliejuje 'Brolio', emulsiklyje lecitine E322 ir palmių aliejuje, priklausomybes nuo temperatūros, šiai kintant plačiame diapazone. Gauti eksperimentiniai duomenys rodo, kad ultragarso greitis visuose tirtuose skysčiuose labai priklauso nuo temperatūros: temperatūrai kylant, jis mažėja. Temperatūrai pakitus 4,5K, ultragarso greitis pakinta 1%.

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