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Analysis of flow profiles of liquid food products in a wide temperature range

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Introduction

In recent days ultrasonic flowmeters are widely used in many areas of industry and their application field is steadily expanding. Their performance depends on a knowledge of a flow profile. Different areas of industry have different requirements for flowmeters because of a big variety of parameters of flow and flowing media. Considering a food production flowing media and flow properties differs very much from other areas of industry and even in itself. For example, temperature of flowing media may be very different and it may vary in a quite wide range. Depending on media in most cases it is in the range of $t^\circ = (-20...+170)^\circ\mathrm{C}$. In the same way we are facing here dosing tasks thus velocity of the flow isn't steady but varies: in the beginning of dosing it begins from $v = 0$ and increases up to $v = v_{nom}$, v_{nom} itself also isn't steady and at the end of the dosing the velocity falls from $v = v_{nom}$ down to $v = 0$. In some special cases when the flowing media is high viscous or (and) has a high yield point there is necessity to use so called stage dosing which makes the main dosing pulse and some short pulses afterwards in order to reach some specified dosing volume (Fig. 1).

In the most cases when the product is dosed the nominal flow rate is comparably high and the time of dosing is short so there isn't much sense to consider the stage dosing as the different way of dosing.

Flowing media used in food production may be very different: water, oil, cream, chocolate, syrup, salad dressing and others which physical properties are very

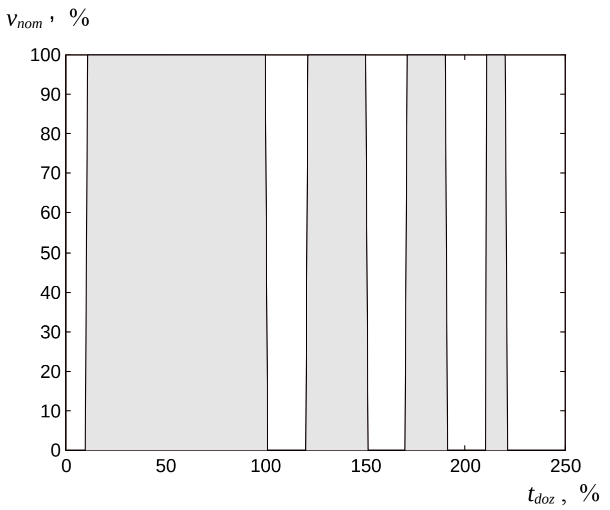

Fig. 1. **The principle of stage dosing**

different. Water as the simplest and most popular fluid is analyzed in a lot of other works therefore it won't be considered here. All other fluids have different physical properties such as dynamic viscosity and density, which are strongly influenced by their temperature. That, correspondingly, affects the profile of the flow and influences the accuracy of ultrasonic flowmeters. However, to our knowledge, the data characterizing physical properties of liquid food products in a wide temperature range are missing, what complicates development of novel ultrasonic flowmeters for a food industry.

The main objective of this research was to determine variations of viscosity and density of such the liquids in a wide temperature range and to estimate their influence on the flow profiles.

Physical background

Actually the viscosity, which describes the physical property of a liquid to resist shear-induced flow, may depend on up to 6 independent parameters:

$$\eta = f\left(S, t^\circ, p, \gamma, t, V\right),$$

here S parameter denotes the physical-chemical nature of substance; t° is the temperature - one of the most viscosity influencing factors, p is the pressure, which increases intermolecular resistance of liquids, thereafter the viscosity of liquid - it may be observed only if the pressure is high, γ is the shear rate - is doesn't influence the viscosity only for the Newtonian liquids, for non - Newtonian liquids increasing of the shear rate effects decreasing of viscosity for pseudoplastic and plastic liquids and increasing of viscosity for dilatant liquids, t - is the time, which denotes the phenomenon that the viscosity of some substances depends on the previous shear history, V is the parameter related to a family of suspensions characterised by the phenomenon that their flow behaviour is strongly influenced by the magnitude of electrical fields acting upon them.

The main influence upon viscosity has change in a fluid temperature. Change of temperature in some 50°C may cause the change of viscosity in more than 10 times. The profile of a flow depends not on the dynamic viscosity η but on kinematic viscosity υ which may be expressed from dynamic viscosity:

$$\upsilon = \frac{\eta}{\rho}. \qquad (1)$$

Here ρ is the density of the liquid. Both dynamic viscosity and fluid density are highly dependent on temperature therefore the kinematic viscosity is temperature dependent as well:

$$\upsilon(t^\circ) = \frac{\eta(t^\circ)}{\rho(t^\circ)} . \quad (2)$$

As temperature of the fluid changes it causes the change of the fluid dynamic viscosity and density and in the same way the kinematic viscosity of it. Since the Reynolds number depends on the kinematic viscosity it is also temperature dependent:

$$\mathrm{Re}_D(t^\circ) = \frac{D\bar{v}}{\upsilon(t^\circ)} = \frac{D\bar{v}\rho(t^\circ)}{\eta(t^\circ)} . \quad (3)$$

Thus even if the flow rate is constant the changes in fluid temperature causes the change of the Reynolds number and the same way profile of flow. It even may change the type of profile from laminar to turbulent or backwards. The change of other properties of substance may also influence changes in its density and dynamic viscosity and via kinematic viscosity that also changes the Reynolds number and the profile of flow.

In dosing tasks there is different situation in comparison with conventional flow rate measurements. In the case of a steady flow there is measured some flow rate, the magnitude of which doesn't change much or does it slowly. In dosing tasks duration of a steady flow is much shorter and here is much bigger importance of dosing "fronts". When the flow rate changes, an average velocity of the flow changes as well because the volume flow rate is expressed as:

$$Q_V = \frac{\pi D^2}{4}\bar{v} . \quad (4)$$

The change of average velocity of the flow cause change of the Reynolds number which the same way changes the profile of the flow. Laminar, turbulent and even intermediate ($\mathrm{Re}_D = 2000...4000$) flow types should be considered here.

Thus the velocity of the flow in some defined point of cross-section of the pipe depends not only upon the position of that point in the cross-section but also upon temperature of the fluid (via dependencies $\eta = f(t^\circ)$ and $\rho = f(t^\circ)$) and time as well (because the flow in dosing tasks is dynamic and $\bar{v} = f(t^\circ)$. Therefore dynamic time and temperature dependent flow should be considered.

Experimental results

The objective of the experiments was to determine temperature dependencies of the viscosity and density of oils used in a food industry and to develop an empirical model enabling to predict profiles of the flow in a wide temperature range.

For this purpose the popular sunflower oil "Brolio" had been selected. The temperature of the oil had been changed from +5°C up to +95°C in steps of 5°C and there had been measured its dynamic viscosity by means of rotational viscometer HAAKE VT550 which enables measurement of the dynamic viscosity with a relative error less than 0.5% of the measured value. The dynamic viscosity of the oil hadn't depended on a shear rate, thus

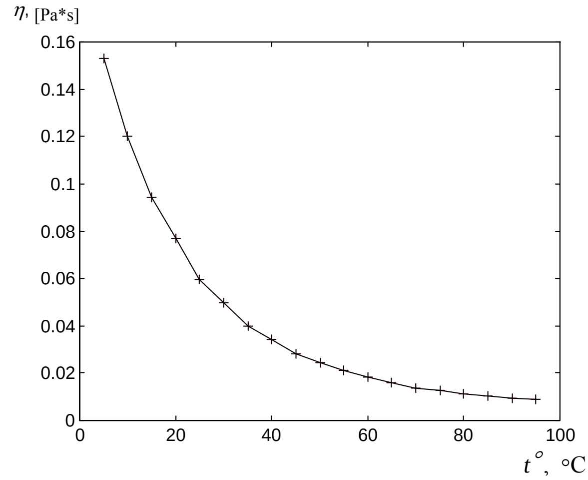

Fig. 2. **Experimental dependence of the dynamic viscosity of the oil "Brolio" upon temperature**

the conclusion had been made that this oil is the Newtonian liquid. There had been obtained not less than five values of dynamic viscosity for each temperature point and each of these values had been obtained as average viscosity in 60 seconds of shearing the oil. All these five values had been averaged and that was a way for obtaining an average dynamic viscosity value for one point of temperature. The same averaging had been performed for all 19 points of temperature thus allowing to obtain dynamic viscosity dependence upon temperature experimental curve (Fig.2).

There also had been investigated dependence of density of the oil upon temperature. By means of the density meter KLP there had been measured density of the oil in ten not even points of temperature in the range from +145°C up to +58°C. The density at each temperature had been measured three times and the average value had been calculated for further analysis. All these measurements and averagings gave the curve of the oil density dependence upon its temperature (Fig.3).

For further analysis it is necessary to have an analytic expression of dependencies $\eta = f(t^\circ)$ and $\rho = f(t^\circ)$. For the approximation of oil density dependence upon temperature there had been chosen the simplest function - line:

$$\rho = a + bt^\circ . \quad (5)$$

By means of the least square method there had been found coefficients of an approximating function a and b :

$a = 927.05$,

$b = -0.6695$.

The average of absolute values of relative errors (further - the average error) of approximation in experimental points had been calculated according to:

$$\bar{\delta}_{\rho a} = \frac{1}{10}\sum_{i=1}^{10}\left|\frac{\rho_{ai}(t^\circ) - \rho_i(t^\circ)}{\rho_i(t^\circ)}\right| \cdot 100\% . \quad (6)$$

Its value with given above coefficients is $\bar{\delta}_{\rho a} = 0.071\%$.

According to [1] and [3] an approximating function for the dynamic viscosity dependence upon temperature had been chosen as follows:

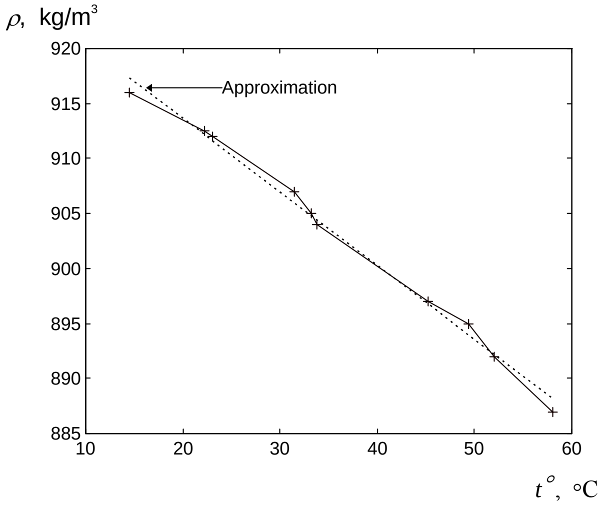

Fig. 3. **Experimental and approximated dependence of the density of the oil "Brolio" upon temperature**

$$\eta = \frac{K}{\left(\frac{t^\circ + 273}{100}\right)^C} . \qquad (7)$$

However the average error of approximation in experimental points calculated according to:

$$\bar{\delta}_{\eta a} = \frac{1}{19}\sum_{i=1}^{19}\left|\frac{\eta_{ai}(t^\circ) - \eta_i(t^\circ)}{\eta_i(t^\circ)}\right| \cdot 100\% , \qquad (8)$$

had been rather noticeable $\bar{\delta}_{\eta a} = 9.0\%$ and that is also seen from Fig. 4.

Such the big average error of approximation indicates that the referred model doesn't confirm the experimental data well enough. There had been chosen some more simple models however their average errors of approximation were even bigger. The best choice was polynomial

$$\eta(t^\circ) = A_0 + \sum_{i=1}^{n} A_i t_i^{\circ n} . \qquad (9)$$

Here n is a rank of the polynomial. In order to find the best compromise between increase of the rank of the model and decrease of the average error some calculations had been made. The rank of the model had been changed

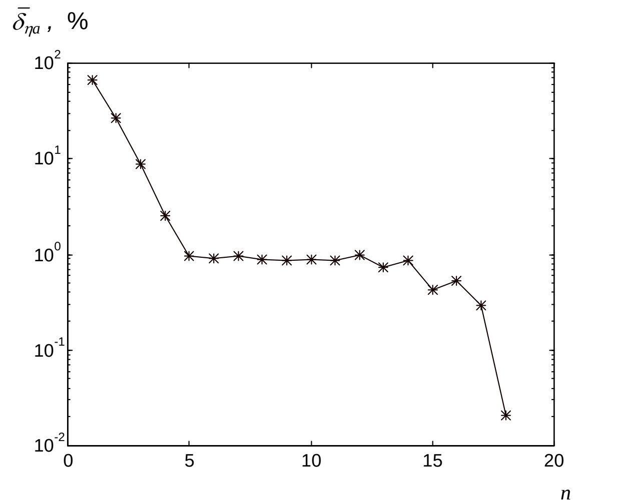

Fig. 5. **Dependence of the average error of approximation upon the rank of the model**

from 1 up to 18 and for each model by means of method of the least squares coefficients A_i and the average error of approximation $\bar{\delta}_{\eta a}$ had been calculated.

According to Fig. 5. the rank of polynomial had been chosen equal $n = 5$ and then the average error of approximation $\bar{\delta}_{\eta a} = 0.96\%$. The coefficients of the polynomial are:

$A_0 = 1.944 \cdot 10^{-1}$,

$A_1 = -9.39 \cdot 10^{-3}$,

$A_2 = 2.232 \cdot 10^{-4}$,

$A_3 = -2.944 \cdot 10^{-6}$,

$A_4 = 2.044 \cdot 10^{-8}$,

$A_5 = -5.788 \cdot 10^{-11}$.

The approximation is in a very good correspondence with the experimentally obtained data (Fig.6).

The kinematic viscosity is simply expressed via approximating functions of dynamic viscosity and density:

$$\upsilon(t^\circ) = \frac{\eta(t^\circ)}{\rho(t^\circ)} = \frac{A_0 + A_1 t^\circ + A_2 t^{\circ 2} + A_3 t^{\circ 3} + A_4 t^{\circ 4} + A_5 t^{\circ 5}}{a + bt^\circ}$$

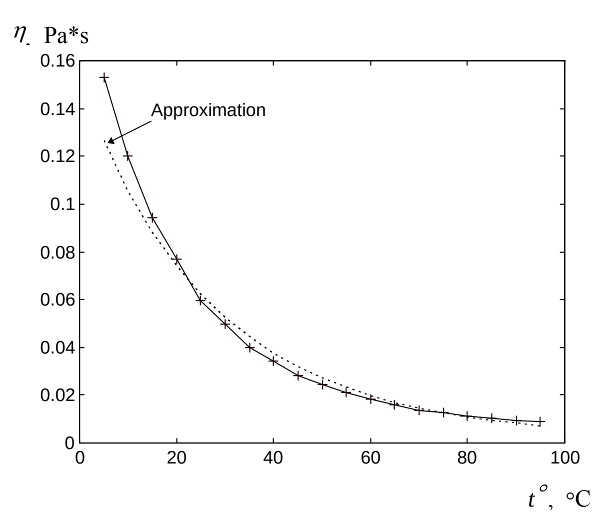

Fig. 4. **Experimental and approximated dependence of the dynamic viscosity of the oil "Brolio" upon temperature**

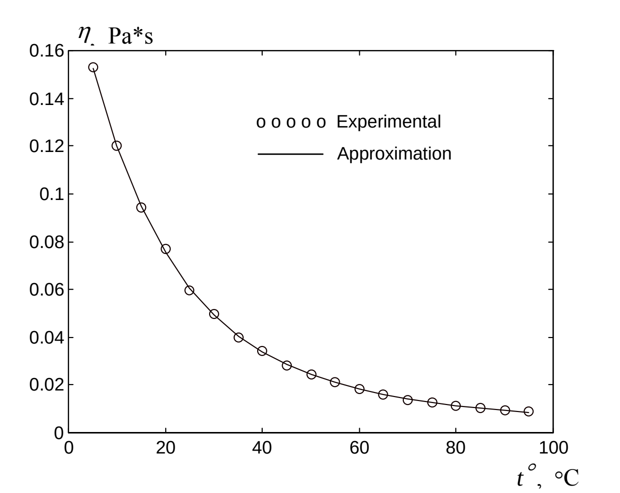

Fig. 6. **Experimental and approximated dependence of the dynamic viscosity upon temperature**

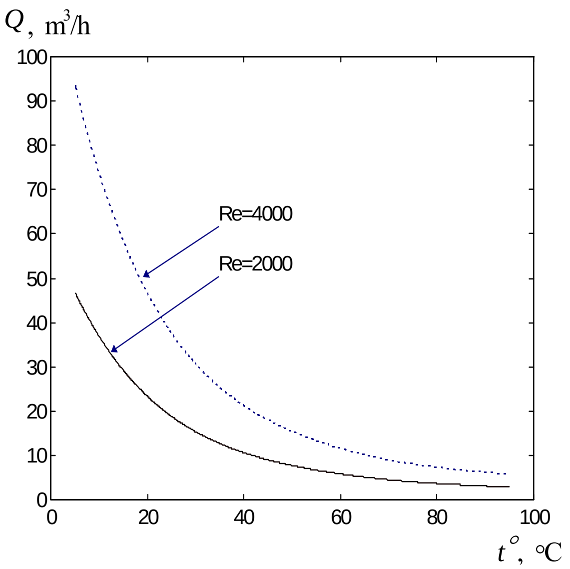

Fig. 7. **Influence of temperature on flow rate of oil in the round pipe DN50 in which the intermediate zone (Re=2000...4000) would be reached**

(10)

As we know the biggest errors of measurement arise in the intermediate zone of flow when the Reynolds number is $\mathrm{Re}_D = 2000...4000$, therefore there had been made some calculations in order to know at which flow rate the limits of $\mathrm{Re}_D = 2000$ and $\mathrm{Re}_D = 4000$ may be reached in a round pipe DN50, when temperature of the oil is rising from $t°_{min} = +5°\mathrm{C}$ up to $t°_{max} = +95°\mathrm{C}$, $Q = f(t°)\Big|_{\mathrm{Re}_D=2000}^{\mathrm{Re}_D=4000}$.

The temperature of liquid has a direct influence on its viscosity, therefore Fig. 7 could be redrawn with the kinematic viscosity on x-axis.

The average velocity of the flow $\bar{v}$ is related to the volumetric flow rate Q_V via expressions (3) and (4), therefore the average velocity is also influenced by the change of temperature (Fig.8 and 9).

That obviously indicates that decrease of temperature

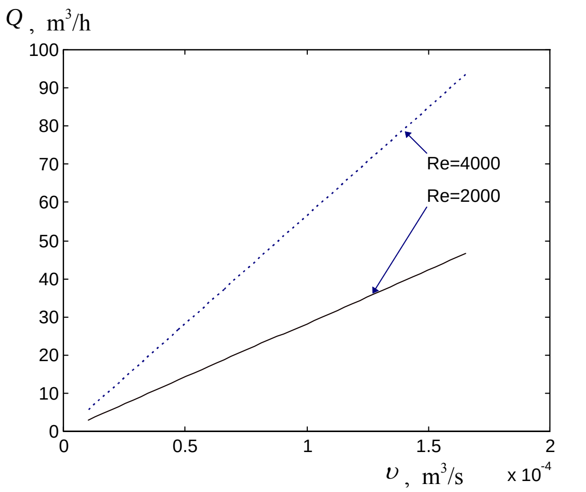

Fig. 8. **Influence of the kinematic viscosity on a flow rate of oil in the round pipe DN50 in which the intermediate zone (Re=2000...4000) would be reached**

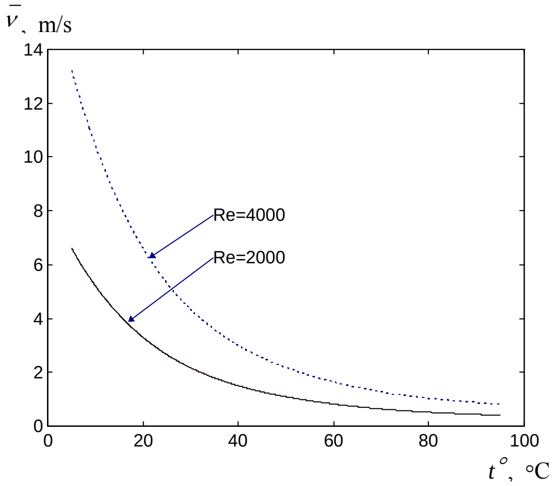

Fig. 9. **Influence of temperature on an average velocity of the flow of oil in the round pipe DN50 in which the intermediate zone (Re=2000...4000) would be reached**

and increase of the viscosity of liquid increases a width of the intermediate zone and increases influence of the laminar flow onto entire profile of the flow in the dosing period.

According to Eq. (3) the Reynolds number depends upon temperature and average velocity of the flow which according to Eq. (4) may be expressed via the flow rate. When the Reynolds number is $\mathrm{Re}_D < 2000$ the flow is laminar and its profile is expressed as follows:

$$\frac{v(r)}{v_0} = 1 - r^2, \tag{11}$$

where $v(r)$ is the local velocity of the flow in radial distance r from center-line of the pipe, v_0 is the maximum velocity (center-line velocity) of the flow, r is the normalized distance from center-line of the pipe

$$r = \frac{2y}{D}, \tag{12}$$

where y is the radial distance center, D is the pipe diameter. Thus when $\mathrm{Re}_D < 2000$ the shape of the flow conforms to a parabola and doesn't depend upon Re_D and the same way upon temperature of the fluid.

When $\mathrm{Re}_D > 4000$ the flow is turbulent and its profile is given by

$$\frac{v(r)}{v_0} = (1 - r)^{\frac{1}{n}}, \tag{13}$$

where n is the coefficient which depends upon the Reynolds number. Thus when the flow is turbulent its profile depends upon Reynolds number and the same way upon temperature of the fluid.

In order to estimate an influence of Reynolds number and the same way temperature upon the profile of the flow of the oil "Brolio" there had been made calculations with two different flow rates (Fig.10 and 11).

The low flow rate Q_{V1}=10 m³/h via (4) corresponds to average velocity of the flow $\bar{v}_1$=1.415 m/s. At temperature $t_1° = +30°\mathrm{C}$ according to (3) the Reynolds number is

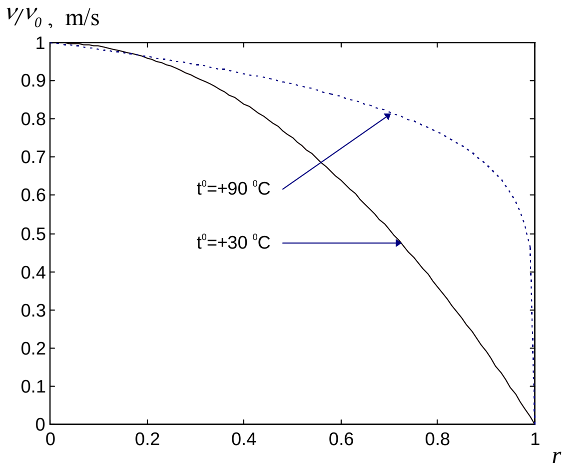

Fig. 10. **The profile of flow of the oil “Brolio” in round pipe when the volumetric flow rate is** $Q_{V1} = 10\,\mathrm{m^3/h}$

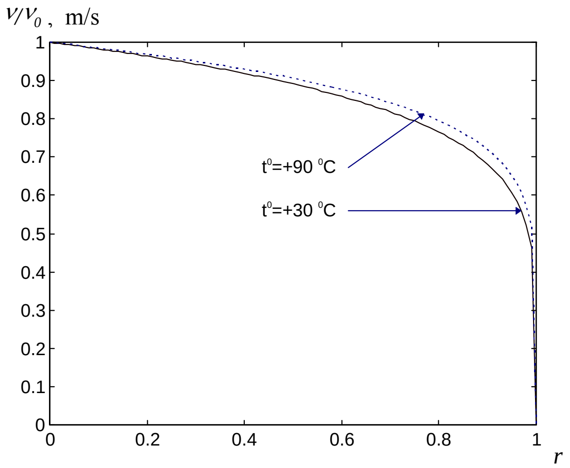

Fig. 11. **The profile of flow of the oil “Brolio” in round pipe when the volumetric flow rate is** $Q_{V2} = 40\,\mathrm{m^3/h}$

$\mathrm{Re}_{D11} = 1304$. The flow is laminar and its profile may be calculated using (11). When the temperature is $t_2° = +90°\mathrm{C}$, the Reynolds number increases up to $\mathrm{Re}_{D12} = 6453$. There is the turbulent flow which profile may be calculated using (13). The coefficient n according to [5] is equal $n = 6$.

The low flow rate $Q_{V2} = 40\,\mathrm{m^3/h}$ corresponds to average velocity of the flow $\bar{v}_2 = 5.659\,\mathrm{m/s}$. At temperature $t_1° = +30°\mathrm{C}$ according to (3) the Reynolds number is $\mathrm{Re}_{D21} = 5217$. The flow is turbulent and its profile may be calculated using (13). The coefficient n according to [5] is equal $n = 6$. When the temperature is $t_2° = +90°\mathrm{C}$, the Reynolds number increases up to $\mathrm{Re}_{D22} = 25810$ the profile is turbulent and according to [5] $n = 7$.

From Fig. 10 and Fig. 11 it is seen that the profile of the flow of the oil perceptibly depends upon the change of temperature.

Conclusions

The performance of ultrasonic flowmeters highly depends on the profile of a flow. The profile of the flow of viscous liquids used in the food industry depends not only on the flow rate but also on their physical properties such as dynamic viscosity and density which are influenced by temperature. In order to minimize uncertainty of measurement of flow rate of foodstuff by means of ultrasonic flowmeter it is necessary to determine the profile of the flow.

There had been analyzed dependence of profile of flow of concrete foodstuff - sunflower oil “Brolio” upon its physical properties - dynamic viscosity and density and their dependencies upon temperature. There had been chosen approximating functions for experimental data and there had been calculated values of parameters of these functions. Obtained models define experimental data well enough. It had been determined that the viscosity of the oil which depends upon temperature has very big influence on profile of the flow. In case of conventional fluids with low viscosity (such as water) only turbulent flow regime is important because the Reynolds number is high and influence of laminar flow and intermediate zone into combined performance of the flowmeter is comparably low. In case of the oil the main working zone is concentrated in laminar flow regime and intermediate zone and only in case of very big flow rates (which actually isn’t common because of big hydraulic losses) the turbulent zone is reached. It may be affirmed that in many cases of dosing regime the nominal flow rate $Q_V = Q_{Vnom}$ is reached when the Reynolds number is in limits of $\mathrm{Re}_D = 2000...400$ that means intermediate zone or somewhere around it. The temperature has decisive influence on profile of the flow - the change of temperature in some decades of degrees changes profile of the flow from laminar to turbulent or backwards. The change of flow rate may also have decisive influence on profile of the flow because all the working area is in the intermediate zone or somewhere around it. The profiles of laminar and turbulent flow are known well and they are very different between each other therefore it is necessary to determine possible dependencies of the change of profile of the flow in the intermediate zone upon Reynolds number and the same way temperature and flow rate.

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Maistinių skysčių srautų profilių tyrimas plačiame temperatūrų diapazone

Reziumė

Maisto pramonėje naudojamų skysčių savybės labai skiriasi tiek nuo kitų skysčių savybių, tiek tarpusavyje. Ultragarsinių debitmačių debito matavimo neapibrėžčiai didelę įtaką turi srauto profilis. Jei skystis neklampus, dirbama turbulentinio srauto zonoje. Dozuojant vidutinis srauto greitis kinta, tuo keisdamas Reinoldso skaičių, apibūdinantį srauto profilį. Reinoldso skaičius taip pat priklauso ir nuo skysčio kinematinės klampos, kuri yra dinaminės klampos ir tankio santykis. Abu šie dydžiai priklauso nuo skysčio temperatūros. Šioms priklausomybėms įvertinti išmatuota vidutinės klampos skysčio - saulėgrąžų aliejaus "Brolio" kinematinės klampos ir tankio priklausomybė nuo temperatūros. Gauti duomenys aproksimuoti pasirinktomis funkcijomis, o jų parametrai apskaičiuoti, taikant mažiausiųjų kvadratų metodą. Nustatyta, kad aliejaus dinaminė klampa labai priklauso nuo jo temperatūros ir dėl to jos kelių dešimčių laipsnių pokyčiai smarkiai pakeičia Reinoldso skaičių, o kartu ir srauto profilį. Daugeliu atvejų srauto profilis būna laminarus arba tarpinio pobūdžio, rečiau - turbulentinis. Dozavimo metu, esant tam tikroms temperatūroms ir nominaliems debitams, tarpinė zona užima iki pusės galimo srauto debito kitimo. Srauto profilis tarpinėje zonoje nėra tiksliai aprašytas, o laminaraus ir turbulentinio srautų profiliai tarpusavyje labai skiriasi, todėl, siekiant mažinti matavimo neapibrėžtį, iškyla būtinybė nustatyti tarpinės zonos srauto profilio priklausomybę nuo Reinoldso skaičiaus.