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Peculiarities of flow rate measurement of viscous liquids

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Introduction

Fluids used in industry could be conditionally allotted into viscous and non-viscous. Viscosity by definition given in [2] describes the physical property of the fluid to resist shear-induced flow. The same definition for viscosity could be used for gases as well but they won't be considered here. Actually most of the fluids could be described as non-viscous and the most popular non-viscous fluid is water or some other liquids with the base of water and some other additives that don't change rheological characteristics of water much. Some other chemical fluids (as petroleum, alcohol, acetone, vinegar, etc.) could be ascribed as non-viscous as well.

As fluids are flowing through pipes, hydraulic losses in the pipelines depend not only upon the construction of the pipelines and the value of flow rate but also upon viscosity of the fluid. When the fluid with a high value of viscosity is flowing through the pipeline, hydraulic losses will be greater that with the one of the low viscosity. It is not recommended to have big hydraulic losses in pipelines because of needs to have more resistible pipelines and more powerful pumps and engines what leads to bigger expenses for the whole system. In order to avoid that it is necessary to decrease the flow rate in the pipeline and the same the average velocity of the flow in the pipe will decrease as well because one is dependant upon other:

$$Q_V = \frac{\pi D^2}{4}\bar{v} \qquad (1)$$

Here Q_V - volumetric flow rate in the pipe, D - diameter of the pipe and $\bar{v}$ - average velocity of the flow.

Thus in the same pipeline with the same engine power consumption the average velocity of the flow due to hydraulic losses will decrease accordingly with increase of viscosity. Thereafter we can state that the average velocity in the pipe will be greater for non-viscous fluids than for viscous. That also means that in order to have the same flow rates for viscous fluids in comparison with non-viscous when the pumps used are standard it will be necessary to use pipes of bigger diameter. High rates of average velocity of the flow in pipes for non-viscous fluids are usually reached, as low values of viscosity mean low hydraulic losses. That fact enables the use of methods of volumetric flow measurement for non-viscous fluids and these methods are quite spread. However, in the case of viscous fluids as described above high values of average velocity of the flow are not reachable so easy because of significant financial and technical problems. Thereafter in practice for measuring of flow rates of high viscous fluids, Coriolis mass flowmeters or electromagnetic flowmeters are mostly used. However, Coriolis mass flowmeters are highly priced and electromagnetic flowmeters have requirements for the electric conductivity of the fluid and are very dependable upon the changes of the conductivity of the fluid.

Recently low-priced ultrasonic flowmeters that are on the market are suitable for the measurement of the flow rate of non-viscous fluids. However high-viscous fluids are much spread in the industry and are mostly involved into the dosing tasks. The use of low-priced ultrasonic flowmeters for measurement of non-stationery flow of high viscous fluids, could be an economic solution for a variety of industrial problems. In order to implement ultrasonic flow measurement for high-viscous fluids it is necessary to analyze possible flow profiles and their dependence upon viscosity and dynamics of the fluid. That is necessary for estimation of requirements for ultrasonic flowmeter, designed non-stationery flow rate measurements of viscous fluids in a wide temperature range.

Viscosity

Viscosity as a physical property of the fluid depends on up to 6 different parameters, which are described in [2] and [9]. However as the object is a liquid and it is in a 'normal state' (no extremely high pressure, viscosity isn't considered in long time terms, calculated in years, etc.) the temperature has the biggest influence on the viscosity of it. That means that the change of temperature may change the viscosity of the fluid as much that it may even influence the flow profile in the pipe. As flow profile has a great importance for the measurement of the flow rate by the means of an ultrasonic flowmeter, it is necessary to analyze the temperature influence on the viscosity of the fluid. In order to understand the range of change of viscosity of the fluid upon change of temperature there had been performed measurements on viscous fluids used in the food industry: sunflower oil 'Brolio', emulsifier - lecithin E322 and palm oil. The measurements of viscosity had been performed in the temperature range 5…95^{O}C in steps of 5K for sunflower oil and lecithin and in the range of 20…95^{O}C for the palm oil in the same steps. At temperatures bellow 20…25^{O}C the palm oil is becoming greasy, thus measurements of its viscosity at lower temperatures have no sense and have not been performed. Measurements of viscosity had been performed by means of the rotational controlled-rate viscometer Haake VT550 with a temperature-controlled water jacket. The temperature in the water jacket had been as steady as +/-0,02K. The measurement uncertainty of the dynamic viscosity didn't exceed +/-1% (just for palm oil at low temperatures it reached more than 5% because of the changes of the structure of the fluid). All three fluids had appeared to be Newtonian liquids; thus, measurements had been made at different shear rates from the both sides of shear rate change. There had been made more than 200 measurements for the each temperature point and results had been averaged. As rotational viscometers enable measurement of dynamic viscosity, there was a need to measure density as well because kinematic viscosity may be expressed from dynamic viscosity and temperature via following formula:

$$\upsilon = \frac{\eta}{\rho}. \qquad (2)$$

Here υ is the kinematic viscosity, η is the dynamic viscosity and ρ is the density of the fluid. All three variables are temperature dependent thus, this formula is valid only for the values at the same temperature. There had been performed measurements of density of all three fluids by the means of glass density meters at different temperatures in about 20 temperature points each. Approximation had been made for each fluid using method of the least squares and temperature dependencies upon temperature appeared to be linear in all the cases. Average error of approximation hadn't exceeded 0.1% for each fluid. For calculation of the kinematic viscosity υ, linear coefficients of approximation of the density ρ had been used.

All the measurements had been performed in a wide temperature range that corresponds to almost all-possible conditions of these fluids. Calculated from the measurement data kinematic viscosity dependencies upon temperature for all three substances are presented in Fig. 1, 2 and 3.

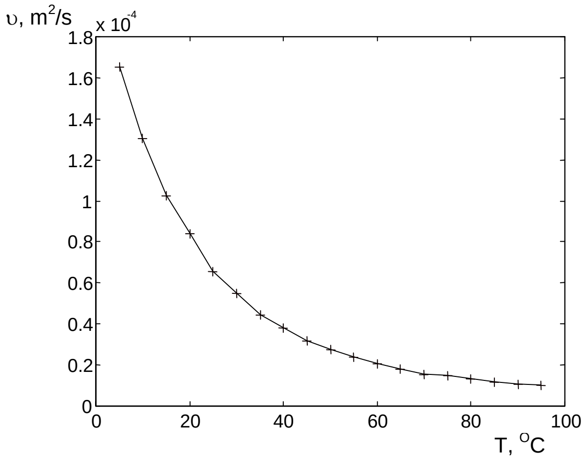

Fig. 1**. Experimental dependence of the kinematic viscosity of the oil "Brolio" upon temperature**

It is seen from the Fig. 1 to 3 that kinematic viscosity of one analyzed fluid may differ from the other at the same temperature up to 500 times. The viscosity of the same fluid in the analyzed temperature range may change as much as 17 times for the sunflower oil, 200 times for the lecithin and 9 times for the palm oil. Actually rheological properties for both sunflower and palm oil at temperatures above 20…25^{O}C seem to be similar but they very differ from the lecithin very much. Thus at the same temperature, the pipe diameter, and the flow rate flow profiles may be different for different fluids. The same way for the only one substance change of temperature may influence change of the flow profile. In addition, it is seen from the results presented that sunflower oil has viscosity values much smaller than both other analyzed fluids. Thereafter it is possible to call the sunflower oil as conditionally semi-viscous.

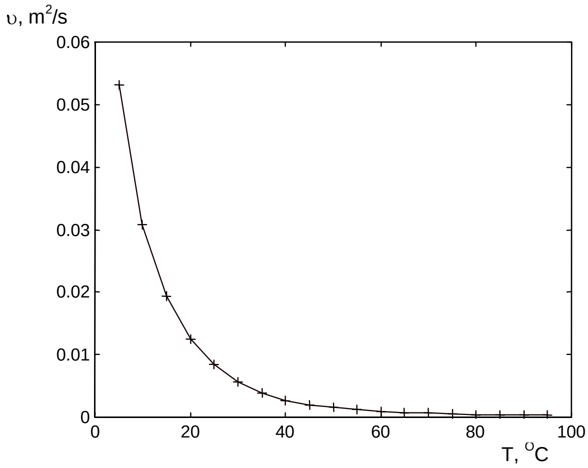

Fig. 2. **Experimental dependence of the kinematic viscosity of the Emulsifier Lecithin E322 upon temperature**

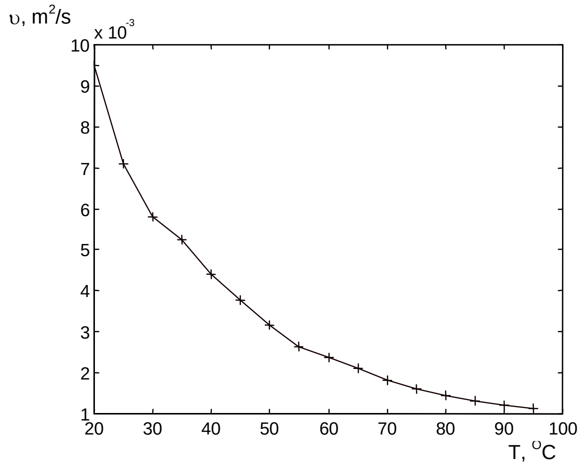

Fig. 3. **Experimental dependence of the kinematic viscosity of the Palm oil upon temperature**

If the aim of measurement is mass flow rate and the measured parameter is volumetric flow rate, that afterwards will be recalculated into mass flow rate using (2), it should be considered that the density of the fluid also highly depends upon temperature. Therefore fast and high-sensitive temperature measurements should be implemented.

Dynamics of the flow

The same way as viscosity, the average velocity of the flow has also influence on the Reynolds number. Hence, change of the average velocity of the flow shall change the flow profile in the pipe. Thus, it is important to analyze possible flow dynamics influence on the flow profile. Usually, for the dosing tasks in the industry there are used dosing impulses that generally may be presented as in Fig.4. Usually there are dosing fronts A and C and some semi-stationery flow zone – B. The shape of fronts may vary (especially of the front C) however the form of B is almost always the same.

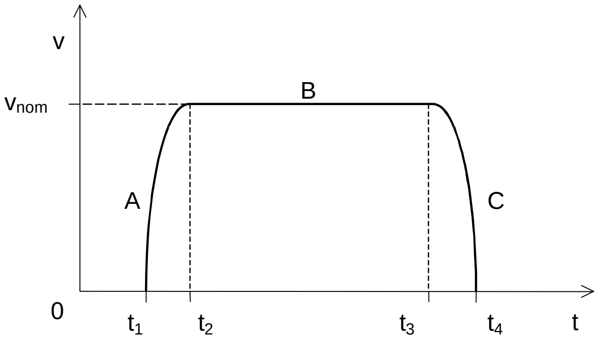

Fig. 4. **The simplified form of dosing impulse.**

In the very beginning of the dosing impulse and at the very end of it the average velocity of the flow almost equals zero. Thereafter the flow starts and ends with the zero values of the Reynolds number. It means that the flow profile in the beginning and at the end of the dosing is always laminar. Part B of the dozing impulse presents the normal state in the pipe when the nominal velocity of the flow v_{nom} in the pipe is reached. Variations in the velocity of the flow in the zone B are usually insignificant. The duration of the zone B $\tau_B = t_3 - t_2$ is much longer than the total duration of fronts A and C $\tau_{A,C} = t_4 - t_3 + t_2 - t_1$; $\tau_B >> \tau_{A,C}$ and the biggest values of velocity of the flow are reached in this zone. Therefore, accurate measurement the average velocity of the flow in this zone is of a greater importance than in the zones A and C. The nominal value of the average velocity of the flow in the zone B forms the upper limit for the changes of the Reynolds number (the flow velocity dependable part). It is even possible to redraw the same figure 4 with the Reynolds number values on the y-axis under condition that the viscosity of the fluid is constant and known. If because of the viscosity of the fluid, the flow would be laminar in the zone B; it will be laminar during the dozing impulse. If the flow would be turbulent in the zone B, there would be some intermediate zone of the flow in the fronts A and C of the dozing impulse. Then the change of temperature could change the viscosity of the fluid as much that even could change the flow profile in the zone B. The similar effect would appear if the zone B would lie in the zone of intermediate flow profile.

Temperature doesn't influence the dynamics of the volumetric flow in the pipe. However, if the mass flow would be measured, the temperature would change the density of the fluid and at the constant volumetric flow rate, the change of density of the fluid would change the mass flow of it. Nevertheless, ultrasonic flowmeters measure the volumetric flow rate thus there is no temperature influence on the dynamics of the flow.

Flow profiles

The possible flow profiles in a circular pipe are divided into laminar, turbulent and intermediate. The character of the profiles depends on the Reynolds number:

$$\mathrm{Re}_D = \frac{D\bar{v}}{\upsilon} = \frac{D\bar{v}\rho}{\eta} \qquad (3)$$

Here D is the diameter of the pipe. If the value of the Reynolds number is $\mathrm{Re}_D < 2000$, the flow profile is considered as laminar, if $\mathrm{Re}_D > 4000$ it is considered as turbulent. Between these limits $2000 < \mathrm{Re}_D < 4000$ the flow is considered as intermediate. The values of the Reynolds number for these limits are presented differently by the number of authors, but these are mentioned most often. In any profile of the flow the greatest velocity of the fluid is on centreline of the pipe and it decreases to the walls of the pipe. Fluid on the inside wall of the pipe has zero velocity. When the flow is laminar, profile of velocities of the flow at different radial distances from the centreline of the pipe, forms parabola. Thus a flow profile is given by:

$$\frac{v(r)}{v_{\max}} = 1 - r^2 . \qquad (4)$$

Here $v(r)$ is the local velocity of the flow in a radial distance r from the centerline of the pipe, $v_{\max}$ is the maximum velocity (centerline velocity) of the flow and r is the normalized distance from centerline of the pipe:

$$r = \frac{2x}{D} . \qquad (5)$$

Here x is the radial distance center, D is the pipe diameter.

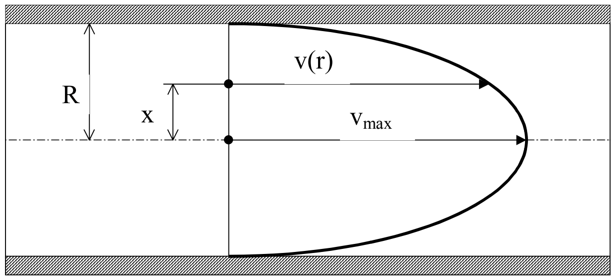

Fig. 5. **Cross-section of the pipe with the flow profile**

When the flow is laminar, the flow profile doesn't depend upon Reynolds number and the same way viscosity, density and temperature of the fluid. It means that in such a case there is no need in measurement of the temperature of the flow.

For turbulent flows the expression for the profile of velocities is given by:

$$\frac{v(r)}{v_{\max}} = (1 - r)^{\frac{1}{n}} . \qquad (6)$$

Here n is the coefficient, which depends upon the Reynolds number. Thus when the flow is turbulent its profile depends upon the Reynolds number and the same way upon the viscosity, density and temperature of the fluid. It means that in this situation the flow profile depends upon viscosity of the fluid and the same way upon its temperature. So temperature measurements here are necessary and important.

In the intermediate zone, the profile of the flow is constantly changing from laminar to turbulent and these changes are unpredictable used to avoid this zone in the most of volumetric flowmeters. Authors in [5] give some considerations about the profile of the flow in the intermediate zone but anyway they are not so accurate as in turbulent and especially in the laminar zone. If in some case it there was necessity to measure the flow rate in the intermediate zone, in the expression for the flow profile given in [5] there also is a coefficient which also depends upon the Reynolds number as in the case of the turbulent flow. Thus, viscosity of the fluid and its temperature are important here as well.

It is necessary to know the exact value of the Reynolds number if the flow profile is turbulent. Otherwise, it is enough to know the limits where this number is thus allowing predicting the profile of the flow.

In order to analyze where are the limits for all these three zones, there had been made calculations, based on the experimental data of the mentioned above three foodstuff fluids. The diameter of the pipe had been taken DN=50mm, the size quite common in the industry. There had been calculated values of average velocity of the flow and temperature, that correspond to the Reynolds number limits $\mathrm{Re}_D = 2000$ and $\mathrm{Re}_D = 4000$. The results are presented in Fig. 4 to 6.

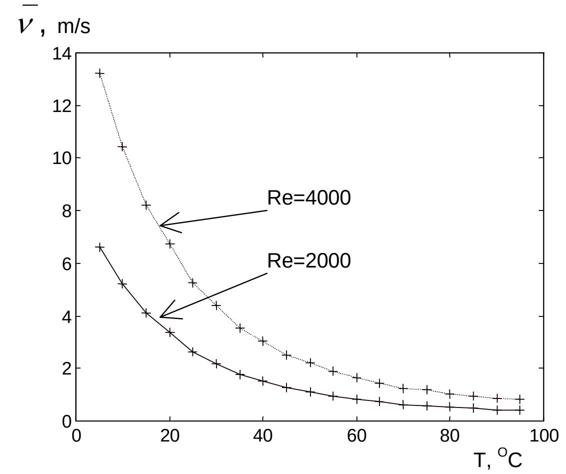

Fig. 6. **Influence of temperature on an average velocity of the flow of the sunflower oil in the circular pipe DN=50 in which the limits of Re_D=2000 and Re_D=4000 would be reached**

Data in the figures are presented in a linear scale except lecithin. Because of its viscosity great dependence upon temperature, the lines of $\mathrm{Re}_D = 2000$ and $\mathrm{Re}_D = 4000$ in the very beginning of analyzed temperature range go almost straight down. Therefore, *y*-axis for lecithin is made logarithmic. It is seen from the figures that both palm oil and lecithin reach the intermediate flow zone only on the highest temperatures at the average flow velocity above 10m/s.

If the sunflower oil would be considered as semi-viscous and the lecithin and palm oil as high viscous it would be correct to state that in practice the flow profile for high viscous fluids is always laminar. Nevertheless, for the semi-viscous fluids, the flow profile may reach the intermediate zone and with the rise of temperature, it may even change into turbulent. However, it may only happen at high temperatures or at high velocities. The flow profile in the intermediate zone is unpredictable thus, that zone should be avoided. However, high flow velocities require powerful pumps and that means expenses thereafter even turbulent zone should be avoided. The laminar zone as it was said before has two contradictory features: advantageous and disadvantageous. Advantageous – well defined flow profile. Disadvantageous – it means low average flow velocities and short duration of informative signals that require high-speed calculations. The duration of the informative signal could be extended by placing ultrasonic transducers farther form each other. If the analyzed flow were stationary, that could be the best solution for the measurement of the flow rate. However, a long distance between transducers means longer time intervals between two informative signals. In the case of non-stationary flow this fact could lead to bigger measurement uncertainties as some of the information about behavior of the flow would be lost. Therefore, more dynamic the flow is, shorter time intervals between two neighboring measurements and shorter period of transmission of the ultrasound should be.

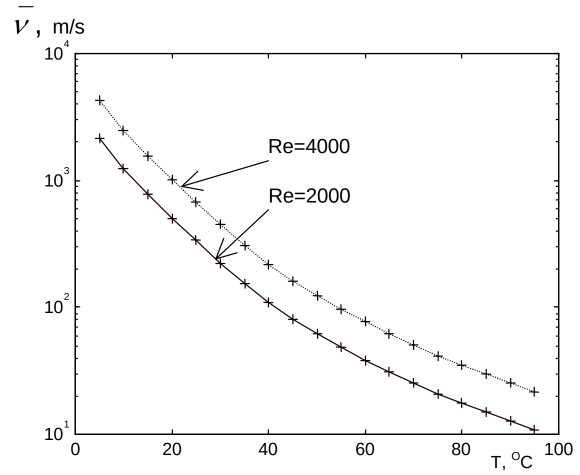

Fig. 7. **Influence of temperature on an average velocity of the flow of the emulsifier lecithin in the circular pipe DN=50 in which the limits of Re_D=2000 and Re_D=4000 would be reached**

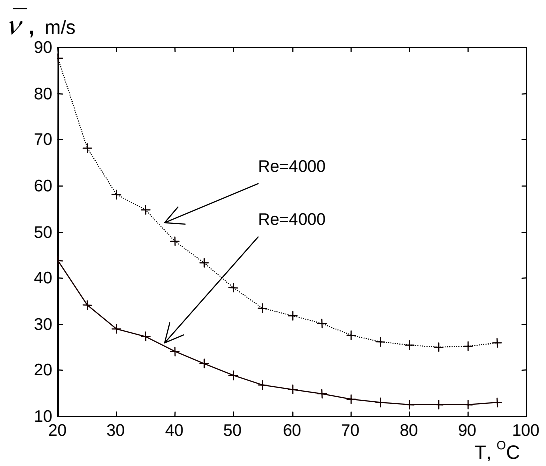

Fig. 8. **Influence of temperature on an average velocity of the flow of the palm oil in the circular pipe DN=50 in which the limits of Re_D=2000 and Re_D=4000 would be reached**

Conclusions

Measurements and calculations performed show that rheological properties of three analyzed fluids are quite different. Fig.1 and 3 show that viscosity of the palm oil is bigger than of sunflower oil in about 100 times, and viscosity of the lecithin is only about 5 times bigger than of the palm oil. The same way their dependencies upon temperature are very different, though viscosity of all the analyzed liquids decreased with the increase of temperature. Neither of liquids showed any rheological anomalies in analyzed temperature range $+5^{O}\ldots+95^{O}$C. Solidification of the palm oil in the temperatures bellow $+20^{O}$C is characteristic feature of fat based fluids; the same would happen with the sunflower oil in temperatures bellow $+5^{O}$C and any other liquid in temperatures bellow their crystallization point.

There had been made approximation on the viscosity dependence upon temperature for the sunflower oil in [9]. The aim of approximation was to estimate the dependence of the flow profile upon temperature when the intermediate or turbulent zones were reached. However, the viscosity measurements of lecithin and palm oil revealed that sunflower oil is semi-viscous liquid on the contrary to both others. Intermediate zone of the flow profile for high viscous fluids as the lecithin or the palm oil may be reached only on comparatively very high values of average flow velocity and temperature. Turbulent flow practically isn't reached for them at all. Composition of high flow velocity and high viscosity leads to undesirably high hydraulic losses and has to be avoided. Usually in order to avoid high hydraulic losses lower flow rates or pipes of bigger diameter are used. Therefore, in most cases the flow would be laminar. When the flow profile is laminar, it doesn't depend upon viscosity via the Reynolds number thus there is no need to approximate the viscosity dependence upon temperature and it hadn't been performed here.

In the case of low viscous fluids, the way of reaching turbulent flow profile seems easier. However, hydraulic losses in pipelines even for low viscous fluids is high, it is inadmissible to increase them even more by means of peculiarities of the flowmeter design. That means, it is inadmissible to decrease diameter of the pipe in order to reach greater flow velocity and ensure the turbulent flow profile in the majority of the dosing impulse. If a fluid under investigation is of a low viscosity, at high flow rates on the top of the dosing impulse intermediate or even turbulent profile zone of flow may be reached. However, these profiles here are undesirable and the only laminar profile is acceptable. The flow profile may be modified creating a laminar flow by increasing diameter of the pipe. That is why the diameter of the pipe in the zone of measurement should be of diameter the same or greater than in the general pipeline. However, increase in a pipe diameter leads to decrease of the informative signal duration, which has to be measured.

The dynamics of the flow also appeared to have no influence on its profile just because at the maximal values of the average velocity of the flow the profile is laminar.

Measurement of the non-stationary flow rate of viscous liquids by the means of ultrasonic flowmeter is purposive. The diameter of the pipe in the measuring part of the flowmeter has to be chosen in such a way, that at highest flow rates and at highest temperatures of the fluid, the Reynolds number were nearby $\mathrm{Re}_D = 2000$ but didn't reach that limit. The criteria for that is the maximum flow rate and kinematic viscosity of the fluid at highest permissible temperature. Then flow profile in all the possible conditions of flow and fluid were laminar. The limitations there are for liquids of very low viscosity. The increase of a diameter of the pipe leads to decrease of an average velocity of the flow. Duration of the informative signal of an ultrasonic flowmeter depends on the flow velocity. When an extremely slow flow is reached, the duration of informative signal becomes too short for accurate measurement.

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Klampių nestacionarių srautų debito matavimo ypatumai

Reziumė

Neklampių medžiagų sąlygiškai stacionarių srautas debitas neretai matuojamas ultragarsiniais debitmačiais. Gana dažnai beveik visose pramonės šakose prireikia tiksliai dozuoti vien1 ar kelius skysčius siekiant gauti receptūrinį komponentų santykį Jei dozuojamasis skystis neklampus, tam galima efektyviai pritaikyti esamus ultragarsinius debito matavimo metodus, tačiau klampiam skysčiui, jie netinka. Pagrindinė to netikimo priežastis yra ta, kad rinkoje esantys ultragarsiniai debitmačiai skirti skysčio debitui matuoti, kai srauto profilis yra turbulentinis.

Norint nustatyti, kas darosi apvalaus skerspjūvio vamzdyje, kai juo teka klampi medžiaga, buvo ištirti trys skirtingų reologinių savybių maistiniai skysčiai: saulėgrąžų aliejus "Brolio", emulsiklis lecitinas E322 ir palmių aliejus. Buvo išmatuotos jų dinaminės klampos bei tankio priklausomybės nuo temperatūros, šiai kintant plačiame diapazone: $T=+5\ldots+95^{O}C$. Klampiausias iš tirtų skysčių buvo lecitinas, mažiausiai klampus – saulėgrąžų aliejus. Šis sąlygiškai pavadintas pusklampiu. Nustatyta, kad esant tai pačiai temperatūrai vienos iš tirtų medžiagos kinematinė klampa yra apie 500 kartų didesnė nei kitos. Keičiantis temperatūrai per visą tirtą diapazoną, saulėgrąžų aliejaus klampa kito 17 kartų, lecitino 200 kartų, o palmių aliejaus - 9 kartus. Norint nustatyti, koks bus vyraujantis srauto profilis vamzdyje, buvo apskaičiuotos vidutinio srauto greičio priklausomybės nuo temperatūros apvaliame vamzdyje DN50, srauto profiliui pereinant laminaraus ir tarpinio bei tarpinio ir turbulentinio profilių ribas. Nustatyta, kad šios ribos pasiekiamos tik esant dideliems srautų vidutiniams greičiams ir aukštoms temperatūroms.

Ultragarsinio debitmačio matuojamosios dalies vamzdyje susidarantis srauto profilis turi būti laminarus. Todėl, žinant skysčio kinematinę klampą esant maksimaliai galimai temperatūrai ir maksimaliam galimam debitui, parenkamas toks matuojamosios dalies vamzdžio skersmuo, kad šiomis sąlygomis Reinoldso skaičiaus reikšmė būtų kaipgalima artimesnė 2000, bet šios ribos neviršytų.