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Investigation of liquid viscosity influence on flow rate measurement by rotary vane meters

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1. Introduction

Until now, liquid and gas flow measurements using various type of meters with rotors, whether it would be turbine or positive displacement meters, cover a wide field of energy resource measurements and its precision relevance is getting more important.

In the field of liquid fuel flow measurements, positive displacement meters with sliding vanes, often called rotary vane meters, occupy the particular place due to volumetric measurements principle application, reliability of operation and high accuracy. Their measurement errors are determined by liquid leakages through the gaps between sliding rotor vanes that comprise separate chambers, and the housing.

Despite the fact that the performance of these meters was investigated rather widely, increasing demands for measurement accuracy at changing viscosity of liquids and complicated possibilities to conduct accuracy assessments of such meters, taking into account the range of liquids and conditions used in practice, require deeper knowledge on internal flow structure and physical factors, determining the regularity patterns of meter errors variation.

Since the error of rotary vane meter is determined by liquid leakages through gaps between rotor vanes and the housing, a numerical simulation is grounded on equations [1-3], defining flow in the channel which contains a moving wall. This is not a simple task since leakages depend on the gap parameters, liquid viscosity, pressure drop in the meter, rotor spin speed, directly related with flow rate and some other parameters, among which centrifugal forces may be particularly important. Therefore, the results of numerical calculation obtained by applying simplified assumptions usually deviate from the results of real flow conditions [4].

Useful information on the flow structure in rotary vane meter can be obtained by analysis of research results related with flow over cavity or when a flat surface moves over cavity where a complicated vertical movement is formed whose structure significantly varies considering cavity dimensions, shape and Reynolds number [5]. Usually at low *Re* number, large scale and low frequency structures are observed where largest amount of flow energy is accumulated. With *Re* number increase, high frequency pulsations indicating the occurrence of thinner structures are more vivid [6, 7]. Centrifugal forces enable the formation of 3D instabilities. Such investigation results should be estimated in numerical simulation of rotary vane meter performance since liquid leakages from the meter chamber through gaps as well as meter errors may be greatly related with the structure of liquid movement in chambers. In general, by analyzing the impact of extremely turbulized flow properties on the errors of meters with rotors clear evidence of certain analogies may be observed, such as stabilization of turbine meters errors under the influence of strongly increased pressure [8, 9], or at the presence of high frequencies flow pulsation [10]. From the physical point of view, it means that the impact of fluid physical properties and other additional factors on certain outcomes becomes less significant in comparison with impact of strongly turbulized flow properties.

In all cases, knowledge of regularity patterns of the impact of varied properties provides important information and enables (having the results of calibration in one liquid) to foresee changes of measurement accuracy when meter operates in other liquid flows and to correct measurement results. Experimentally most investigated was the measurement accuracy of turbine meters under the influence of different factors, including viscosity of liquid or gas. The most significant result of these investigations is the identification of universal pattern, which links meter factor with rotation frequency and kinematic viscosity [11, 12] as well as acceptance of *Re* number as distinctive parameter for the process characterization.

Since resistance to rotation of meter rotor, whether it is turbine or rotary vane meter, strongly depends on hydrodynamic forces rising in the vicinity of meter housing wall, certain analogies may be sought in regularity patterns of pressure losses and errors variation, particularly at high *Re* number, when influences of mechanical and viscous drag becomes less significant than the influences induced by turbulent viscosity. Namely, in fully developed turbulent flow regime, the approach to universal dependencies based on *Re* number must be observed.

Therefore, the objective of this investigation is to investigate experimentally the impact of liquid viscosity on the measurement accuracy of liquid flows, giving main attention to rotary vane meters and striving to justify their measurement accuracy changes in different viscosity liquids.

2. Testing procedures

2.1. Experimental setup

The basic scheme of rotary vane meter is presented in Fig. 1. Experimental research was conducted in 4 different liquids (diesel fuel, aviation kerosene, Exxsol D80 kerosene and petrol), the characteristic properties of which are given in Table, and:

- on-site conditions (fuel terminals) using portable measurement equipment;
- in the laboratory conditions using stationary equipment.

In all cases, conducting experiments under on-site or laboratory conditions, the measurement scheme presen-

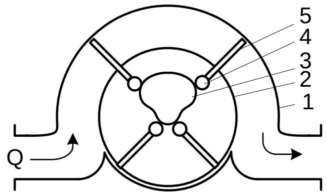

Fig. 1 Rotary vane meter: *1* - housing; *2* - rotor; *3* - cam; *4* - bearing; *5* - vane

Table

Properties of liquids used in research at temperature (10 - 25)°C

Liquid	Density ρ, kg/m^3	Kinematic viscosity $\nu \times 10^6$, m^2/s
Petrol A-95	731 - 719	0.79 - 0.67
Kerosene Jet-A1	806 - 795	1.9 - 1.5
Kerosene Exxsol D80	802 - 791	2.6 - 1.9
Diesel	838 - 827	5.5 - 3.7

ted in Fig. 2 was used. The real flow liquid volume was measured using reference measures of volumes 0.5, 2.0 and 5.0 m^3, taking into account flow rate, which was changed in the range from 3.3×10^{-3} m^3/s to 3.3×10^{-2} m^3/s.

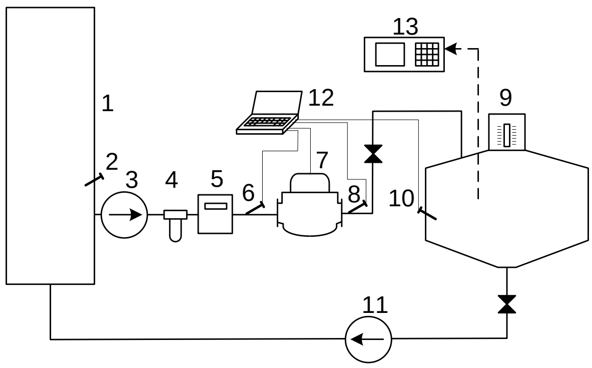

Fig. 2 Scheme of experimental facility: *1* - liquid reservoir; *2*, *6* and *10* - liquid temperature sensors; *3* - pump; *4* - filter/air separator; *5* - density/viscosity measurement system; 7 - rotary vane meter; *8* - pressure sensor; *9* - reference measure; *11* - pump; *12* - data collection and processing system; *13* - liquid density and viscosity meter

As it is shown in Fig. 2, at determined flow rate, liquid is supplied from the reservoir *1* through the meter under the investigation *7* to the reference measure *9*. Flowing liquid volume is calculated taking into account calibration results of the reference measure, liquid densities in the meter and the reference measure as well as its volume expansion coefficient considering liquid temperature measured by the temperature sensors *2*, *6*, *10*:

$$V = V_{so}\left(1+\beta\left(t_s - t_o\right)\right)\frac{\rho_s}{\rho_d}, \tag{1}$$

here V_{so} is volume of the reference measure at reference temperature; β is volumetric expansion coefficient of the reference measure; t_s is liquid temperature in the reference measure; t_o is reference temperature; ρ_s is liquid density in the reference measure; ρ_d is liquid density in the meter under the investigation.

To determine liquid density and dynamic viscosity, liquid samples were taken, whereas density and viscosity were measured using meter SVM 3000 at temperatures measured during the experiment. Density measurement uncertainty was ± 0.5 kg/m^3, viscosity was ± 0.35%. Best volume measurement capability using volumetric measurement method, taking into account liquid flow rate, varied within range from ± 0.060% to ± 0.065%. Under laboratory conditions at flow rate up to 1.4×10^{-2} m^3/s, weighing method was also applied to measure the mass of flowing liquid, which guaranteed the measurements uncertainty ± (0.040 - 0.045)%.

Pressure drop in the meter was measured using differential pressure devices. Since in all cases the liquid outflow to the open reference measure or to reservoir on balances, the influence of pressure on measurement results was not estimated. Measurement data were collected in computer *12* and processed by calculating average values of measured quantities and their uncertainties.

2.2. Numerical simulation

Numerical simulation was pointed not that much to determination of main influencing factors, but more to highlighting the aspects which restrict calculation accuracy. Therefore the numerical simulation was based on the scheme presented in Fig. 3 and the use of experimental outcomes related with pressure losses and measurement errors variation.

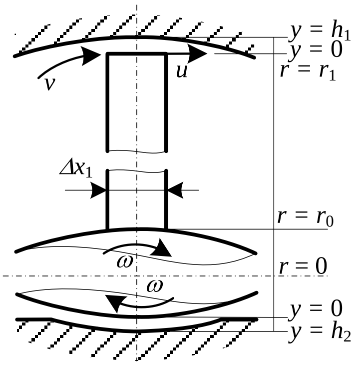

Fig. 3 Numerical simulation scheme

It was assumed that the prevailing mechanism in the gap flow is defined by Navier-Stokes equation system [1-3]. Assuming that flow in the gap is laminar, stable and the influence of mass forces is not estimated, this system can be written in the following way:

$$\begin{cases} \mu \dfrac{\partial^2 v}{\partial^2 y} = \dfrac{\partial p}{\partial x} \\ \dfrac{\partial p}{\partial y} = 0 \end{cases}. \tag{2}$$

Taking into account the fact that the wall moves towards the flow direction as well as towards the opposite direction, the liquid flow rate through the gap is obtained from equation system (2) by integrating and applying boundary conditions:

$$\int_0^h v_x dy = -\frac{1}{12\mu}\frac{\partial p}{\partial x_i} h_i^{\,3} \pm \frac{u_i h_i}{2}, \tag{3}$$

here v_x is local velocity of liquid; μ is dynamic viscosity of liquid; h_i is height of gap; u_i is velocity of wall's movement; dp/dx_i is pressure gradient in the gap; the sign (–) of second member on the right side of equation is related with wall movement opposite flow.

In order to estimate the real total leakages $Q_{\Sigma p}$, the gap length L, differences of the leakages through gaps at the top and the bottom of the rotor as well as the side surface were considered, i.e.:

$$Q_{\Sigma p} = Q_{vu} + Q_{vd} + 2Q_{vsu} + 2(Q_{rsu} + Q_{rsd}), \tag{4}$$

here Q_{vu} is flow rate through vane's upper gap; Q_{rd} is flow rate through rotor's lower gap; Q_{vsu} is flow rate through one vane's sided gap; Q_{rsu} and Q_{rsd} are flow rates through the upper and the bottom parts of rotor's sided gap respectively.

Thus the relative error of the meter is:

$$\delta = -\frac{Q_{\Sigma p}}{Q}, \tag{5}$$

here Q is the real liquid flow rate through the meter.

Since rotation period of vane is $T = 1/f$ and chamber volume – V_k, the measured flow rate $Q_m = V_k f$. Velocity of the vane's movement $u = \omega r = 2\pi f r$, here f is frequency of rotations, whereas ω *is* angular velocity.

Integrating Eq. (3) for horizontal gaps according L, whereas for vertical gaps according r and considering that in Eq. (4) moving gap walls with index *"**u**"* move towards flow direction, whereas "***d***" – opposite flow direction, and taking that in the gaps $\partial p/\partial x = \Delta p/\Delta x = const$, the Eq. (5) is written in the following way:

$$\delta = -\frac{\dfrac{|\Delta p|}{12\mu} c_0}{Q} - \frac{Q_m c_1}{Q V_k}, \tag{6}$$

here geometric meter's parameters:

$$c_0 = h_1^{\,3}\pi + \frac{h_2^{\,3}}{\Delta x_2}L + \frac{h_1^{\,3}}{\Delta x_1}L + \frac{2h_1^{\,3}(r_1 - r_0)}{\Delta x_1} \tag{7}$$

and

$$c_1 = \pi\Big(L\big(h_1 r_1 - h_2 r_0\big) + h_1\big(r_1^{\,2} - r_0^{\,2}\big)\Big), \tag{8}$$

here Δx_1 is vane's thickness (the length of the gap nearby vane); Δx_2 is the length of the gap under the rotor; r_0 *is* rotor radius; r_1 is the distance from the rotor's centre to the upper chamber wall.

3. Results and discussions

Experimentally determined variation of regularity patterns of rotary vane meter errors in different liquid flows are given in Figs. 4-7. It should be noted that experimental data obtained under laboratory and on-site conditions correlate very well.

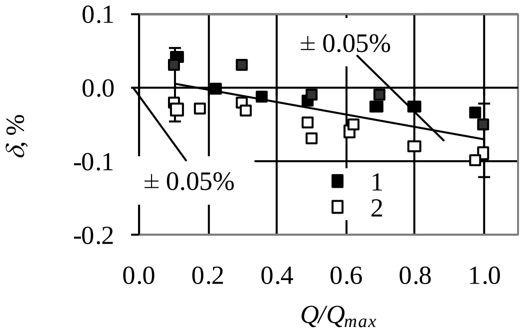

Fig. 4 Rotary vane meter errors (DN 100) in diesel flow ($\bar{\nu}$ = 4.6×10^{-6} m^2/s): *1* and *2* – measurements under laboratory and on-site conditions respectively

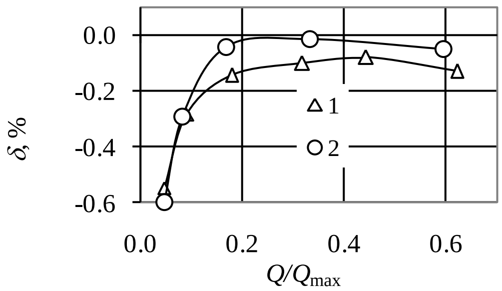

Fig. 5 Rotary vane meters errors in kerosene Exxsol D80 flow ($\bar{\nu}$ = 2.3×10^{-6}): *1* and *2* - DN 100 and DN 65 under laboratory conditions respectively

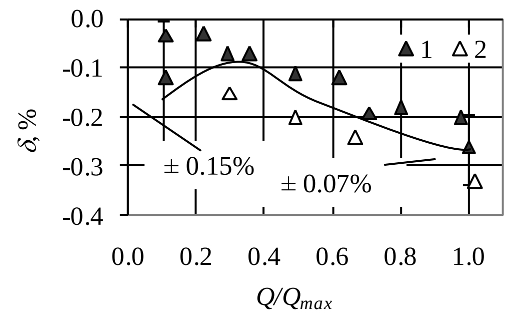

Fig. 6 Rotary vane meter errors (DN 100) in aviation kerosene flow ($\bar{\nu}$ = 1.7×10^{-6} m^2/s): *1* and *2* - measurements under laboratory and on-site conditions respectively

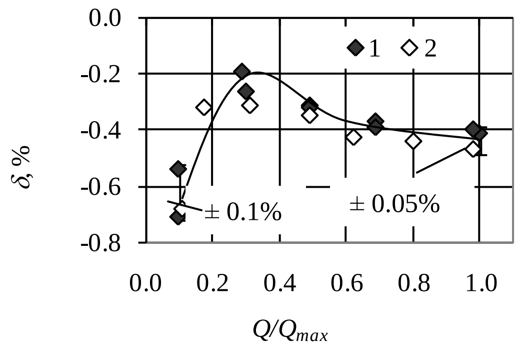

Fig. 7 Rotary vane meter errors DN 100 in petrol flow ($\bar{\nu}$ = 0.73×10^{-6} m^2/s): *1* and *2* - measurements under laboratory and on-site conditions respectively

From Figs. 4-7, the following variation trends of errors can be observed taking into account liquid viscosity:

- dispersion of errors in diesel fuel flow at any flow rates does not exceed ± 0.05%. Since the liquid is viscous, leakages through the gaps and error changes towards negative values are the smallest compared to the values in the liquids with lower viscosity;
- with decrease of liquid viscosity, the smaller liquid viscosity, the more errors move towards higher negative values due to increasing leakages through the gaps .Also, certain changes of errors variation are revealed. Their physical reasons may be related with regularity patterns characteristic to other type meters with rotors. In some extent, it finds confirmation in analysis of research results of turbine meters given in [8, 9].

From Figs. 6 and 7 it can be observed that the error curves have the denominated peak, up to which the negative errors decrease with increase of flow rate. This is the consequence of increase of rotating forces due to which the influence of mechanical friction and retarding viscosity forces relatively decrease till the equilibrium of rotating and retarding forces are reached. The peak of errors moves towards higher flow rates when viscosity decreases. It may be stated that at high liquid viscosity, the peak of errors also prevails although it is not expressed, whereas approach of errors towards negative values is revealed only at low flow rates.

Comparison of the curves of errors and pressure losses shows that the peak of errors correlates with the sharp change of pressure variation point (Fig. 8). From physics perspective, it means that analogous regimes are inherent for flow in rotary vane meter passage, as for the flow in the channel. In the range of low Re_D (Reynolds number considering DN), pressure losses are proportional to flow velocity, whereas physical parameters of liquid determine the error variation. In the range of high Re_D number, the pressure losses change proportionally to velocity square due to significantly increasing turbulent viscosity, thus the ratio of retarding and rotating forces with the increase of flow rate increase as well, and errors again start to approach more negative values.

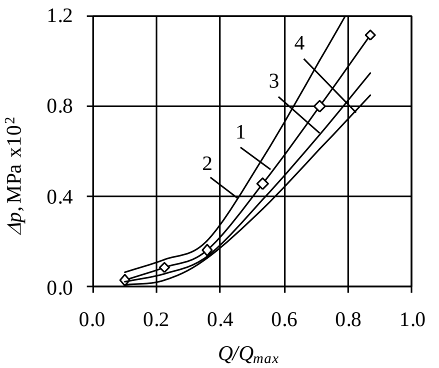

Fig. 8 Pressure losses in rotary vane meter (DN100): *1* - kerosene Exxsol D80 (experimental data) and numerical evaluation: *2* - diesel; *3* - aviation kerosene; *4* - petrol

Attention should be drawn to the shape of error variation in the field of higher flow rates taking into account liquid viscosity. For low viscosity liquid (Fig. 7), the curvature of error curves is observed in the range of higher flow rates as well as approach to certain asymptotic level when higher and more consistent error variation gradient prevails for higher viscosity liquid (Fig. 6).

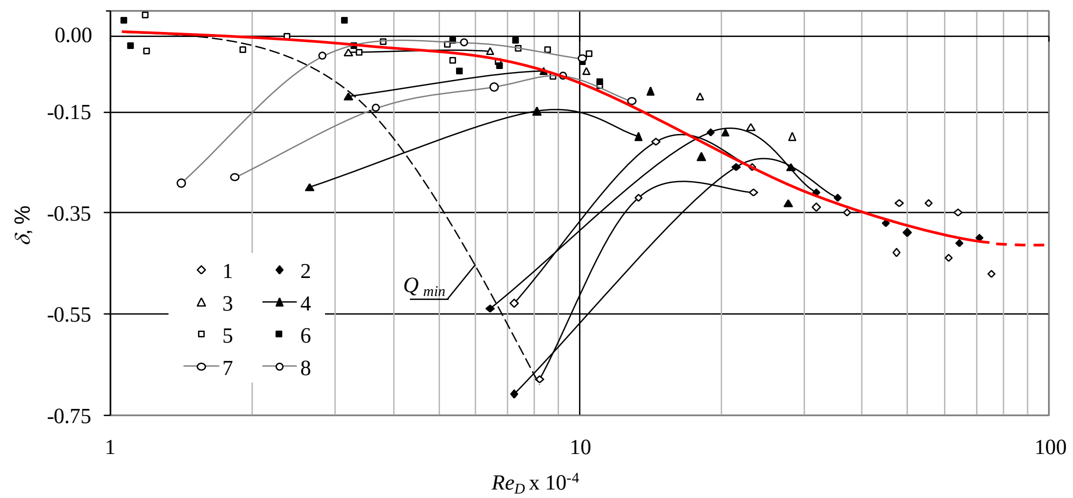

Fig. 9 Regularity patterns of rotary vane meter errors' variation considering Re_D number: *1, 2* - diesel fuel ($\bar{\nu}$ = 4.6×10^{-6}); *3, 4* - aviation kerosene ($\bar{\nu}$ = 1.7×10^{-6} m^2/s); *5, 6* - petrol (0.73×10^{-6} m^2/s); *7, 8* - kerosene Exxsol D80 ($\bar{\nu}$ = 2.3×10^{-6} m^2/s), respectively DN100 and DN65 meters

This error's variation may be summarized by analyzing its dependence on Re_D number (Fig. 9). The diameter of meter inflow was taken as the defining value in Re_D number. From these data it is seen that errors up to their peak values are strongly stratified for influence of mechanical friction and hydrodynamic forces induced by liquid viscosity. However, as it was mentioned above, the error's peak corresponds to the transition of flow in the meter's passage to the turbulent flow regime, which determines the formation of universal regularity pattern of error variation. It does not mean that the influence of viscosity on flow leakages through the narrow gaps between vanes and housing jointly discontinues. It is more reliable to consider that even in the gap the flow becomes turbulent when Re_D

number approaches 10^6. Errors variation rate decreases and its tendencies to get a certain asymptotic value in this Re_D number range indirectly confirm such presumption.

In further analysis, two aspects of this task are presented. The first one is related with the objective to obtain an answer how the numerical model presented in section 2.2 estimates basic factors influencing error variation. The analysis of the second aspect aims to reveal analogous universal error variations which are characteristic of different type meters with rotors.

Conducting numerical simulation, Eq. (6) was rearranged into more appropriate form, since $\delta+1 = Q_m/Q$:

$$\delta = -\frac{|\Delta p|}{12\mu Q}\frac{c_0}{1+\frac{c_1}{V_k}} - \frac{c_1}{V_k + c_1}. \qquad (9)$$

Eq. (9) was solved in pursuance of minimum discrepancy between numerical results and averaged measurement error curves, given in Figs. 4 - 7.

The obtained results (Fig. 10) confirmed that the basic mechanism, which determines the meter error variation, is substantially depicted by the conventional equations for flow through the gap with moving wall. The differences between experimental errors and numerical simulation results are higher than ± 0.05% only at low flow rates and high Re_D number. At the lowest viscosity and flow rates, the influence of the meter's rotor mechanical friction is rather significant.

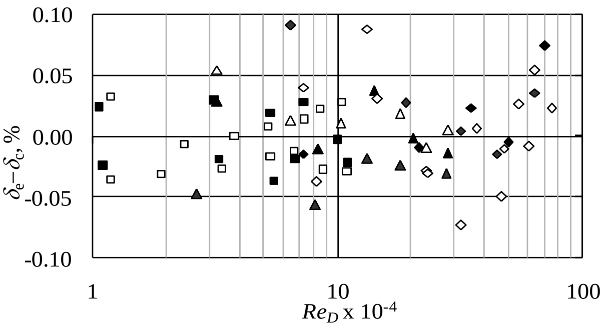

Fig. 10 Comparison of errors determined in experiments and numerical simulation. Numbering is the same as in Fig. 9

At high flow rates in low viscosity liquid, deviation of numerical simulation results from the experimental ones towards more negative errors is observed though experimental errors approach the constant asymptotic value. This may be explained using rather simplified assumptions of numerical simulation. As mentioned above, at higher Re_D number, the flow nature in the chambers as well as in the gap becomes drastically turbulized. Variation rates of rotating and retarding forces become equal and errors approach the constant asymptotic value. Hence, although the numerical simulation estimates basic elements of physical process, the internal flow structure is not estimated.

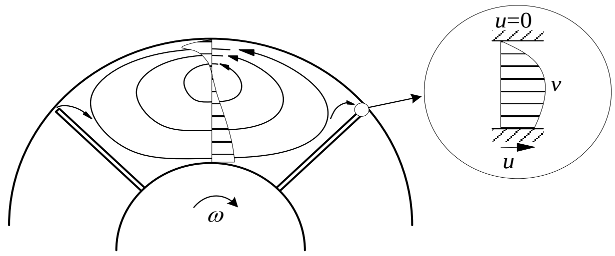

Fig. 11 Simplified scheme of flow in rotary vane meter's chamber at low flow and *Re* number

It is expedient to draw attention to the flow structure in the space between adjacent blades. Due to completely clear reasons, some similarities may be observed with the phenomena observed in case of cavity flow or when surfaces move over cavities [5]. In this case, imaging a space between the blades as a cavity moving in respect of the meter's housing surface (Fig. 11), a vortical flow develops in there, and its structure depends on the cavity's geometry, dimensions and Re_D number number specific to it.

It is most probable that one or more regular vortices may be developed depending on the cavity's depth, width and shapes at low flow rates and Re_D number. At high Re_D number, these vortices disintegrate into fine structures causing the intensive turbulent mixing and increase of pressure losses. It may be observed that the average flow direction nearby the upper wall is directed opposite the cavity movement direction. Thus, an intensive turbulent mixture that occurs in the cavity and whose intensity increases with the increase of the flow rate and the related parameters – rotor speed and Re_D number, changes

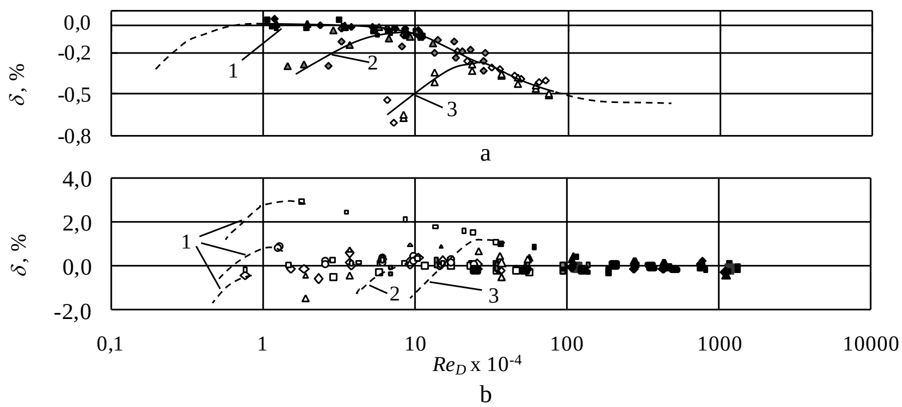

Fig. 12 Comparison of turbine and rotary vane meters errors variation considering Re_D number: a – rotary vane meter: *1*, *2* and *3* - $\bar{\nu}$ = 4.6; 2.3 - 1.7 and 0.7×10^{-6} m^2/s respectively; b – turbine meter: *1*, *2* and *3* - $\bar{\nu}$ = 15; 2.74 and 0.44×10^{-6} m^2/s respectively

the conditions of the leakage through the gaps. In the outcome of these influences, as shown above, total pressure losses increases according to regularity patterns typical for turbulent flow in channels. Moreover, the approach of measurement errors to constant values at high Re_D number may be related to analogous reasons, due to which stabilization of the drag coefficient occurs by flowing rough surfaces when the rough turbulent flow is developed.

These results correlate well with the regularity patterns of turbine meter error variation in case of gas viscosity change from pressure [9] (Fig. 12), i.e. it may be stated in general that the determined regularity patterns are typical for meters with rotors.

In all cases, when the flow in meter passages becomes fully turbulent, dependencies of pressure losses and errors on Re_D number gain universality. Approach of errors towards constant asymptotic values is determined by high flow turbulization degree, due to which the impact of rotor driving and retarding forces reaches equilibrium and liquid leakages further increase proportionally to total flow rate.

4. Conclusions

1. Regularity patterns of rotary vane meter measurement errors are determined by 2 basic factors: pressure difference in the gap between the vanes and housing, and the vane's movement due to the rotor's rotation, which is proportional to the flow rate. Numerical simulation results should estimate peculiarities of the flow structure in between the vane space and its impact on leakages through the gaps. Analysis of regularity patterns, considering Re_D number, enables to summarize results of meter error variation.

2. Approach of measurement error towards the peak value is typical for the low Re_D number. From physics perspective, in this field, leakages and errors depend on mechanical friction of the meter's rotor and hydrodynamic friction due to liquid viscosity. Variation of pressure losses at this Re_D number follows the regularity pattern typical for laminar flow regime.

3. After the errors reach the peak values and Re_D number further increases, the basic increase of pressure losses and approach of relative errors towards more negative values (according regularity pattern dependent exceptionally on Re_D number) are observed. This is a consequence of flow turbulization in the meter passage, though liquid viscosity influence on leakages through the gaps remains.

4. When Re_D number approaches values 10^6, the errors approach the constant asymptotic value. This means that after the flow reaches high turbulization degree, the flow in the gaps becomes turbulent and the equilibrium of the rotor's driving and retarding forces prevails. It may be stated in general that the determined regularity patterns are typical for meters with rotors.

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SKYSČIŲ KLAMPOS ĮTAKOS DEBITO MATAVIMUI SUKIAISIAIS MENTINIAIS DEBITO MATUOKLIAIS TYRIMAS

R e z i u m ė

Eksperimentiniu ir skaitiniu metodais ištirta skysčių klampos įtaka pratekančio tūrio matavimo tikslumui sukiaisiais mentiniais debito matuokliais. Eksperimentiniai tyrimai atlikti 4 skirtingų skystųjų degalų srautuose naudojant tūrinį ir svėrimo metodus.

Eksperimentų rezultatai apibendrinti atsižvelgus į paklaidų kitimą nuo Re_D. Parodyta, kad debito matuoklio paklaidų kreivės turi piką, kuris parodo perėjimą nuo vyraujančio laminarinio tekėjimo į turbulentinį tekėjimo režimą arba kitaip skiriamąją liniją tarp mažų ir didelių Re_D

režimų. Esant mažiems Re_D, pratekėjimai per plyšius tarp menčių ir korpuso labai priklauso nuo mechaninės rotoriaus trinties, o taip pat nuo hidrodinaminio pasipriešinimo, kurį lemia skysčio klampa. Šiose Re_D ribose slėgio nuostolių kitimo dėsningumai analogiški laminariniam tekėjimo režimui. Esant didesniems Re_D, dėl srauto turbulizacijos nusistovi universali paklaidų priklausomybė nuo Re_D. Tačiau klampos įtaka pratekėjimams per plyšius išlieka. Re_D reikšmėms priartėjus prie 10^6, paklaidos artėja prie pastovios asimptotinės reikšmės. Tai srauto plyšyje turbulizacijos pasekmė.

Skaitinis modeliavimas patvirtina pagrindinius teiginius, tačiau išlieka būtinumas įvertinti sudėtingo skysčio judėjimo struktūrą tarpmentinėje erdvėje ir jos įtaką pratekėjimams pro plyšius atsižvelgiant į Reinoldso skaičių.

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INVESTIGATION OF LIQUID VISCOSITY INFLUENCE ON FLOW RATE MEASUREMENT BY ROTARY VANE METERS

S u m m a r y

The influence of liquid viscosity on the flowing volume measurement accuracy by rotary vane meter is investigated experimentally and numerically. Experiments are performed in 4 different liquid fuel (diesel, petrol and 2 type of kerosene) flows using the volumetric and gravimetric methods.

Experimental results are summarized considering errors variation with dependence on Reynolds number Re_D. It is shown that error curves have peak values, which indicate the transition from the dominant laminar flow to the turbulent flow regime or, otherwise, dividing line between low and high Re_D number regions. At low Re_D, number leakages through the gaps between the meter vanes and housing as well as errors strongly depend on mechanical friction of the meter's rotor and hydrodynamic friction due to liquid viscosity. In this Re_D number range, variation of pressure losses follows the regularity pattern typical for the laminar flow regime. At high Re_D number, as a consequence of flow turbulization in the meter passage, error variation follows a unique dependence on Re_D number. However, liquid viscosity influence on leakages through the gaps remains. When Re_D number approaches values 10^6, the errors approach the constant asymptotic value.

Numerical simulation confirms the basic presumption used, but it also shows urgency to estimate peculiarities of a complicated movement structure in between the vanes spaces and their impact on leakages through the gaps, taking into account Re number.

Keywords: liquid measurement, rotary vane meter, viscosity, measurement errors, pressure drop, leakage through gap.

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