EUGENIJUS MASLAUSKAS

A Investigation of Flow Regime and Physical Properties Influence on Liquid and Gas Mechanical Flow Meters' Characteristics

Summary of Doctoral Dissertation
Technological Sciences, Energetics and Power Engineering (06T)

2014, Kaunas

KAUNAS UNIVERSITY OF TECHNOLOGY
LITHUANIAN ENERGY INSTITUTE

EUGENIJUS MASLAUSKAS

A INVESTIGATION OF FLOW REGIME AND PHYSICAL PROPERTIES INFLUENCE ON LIQUID AND GAS MECHANICAL FLOW METERS‘ CHARACTERISTICS

Summary of Doctoral Dissertation
Technological Sciences, Energetics and Power Engineering (06T)

2014, Kaunas

This scientific work was performed in 2008 – 2013 at the Laboratory of Heat Equipment Research and Testing of Lithuanian Energy Institute.

Scientific supervisor:

Dr. Habil. Antanas PEDIŠIUS (Lithuanian Energy Institute, Technological Sciences, Energetics and Power Engineering – 06T).

Board of Energetics and Power Engineering Science field:

Prof. Dr. Habil. Stasys ŠINKŪNAS (Kaunas University of Technology, Technological Sciences, Energetics and Power Engineering – 06T) – **chairman**;
Prof. Dr. Habil. Juozas AUGUTIS (Vytautas Magnus University, Technological Sciences, Energetics and Power Engineering – 06T);
Dr. Raimondas PABARČIUS (Lithuanian Energy Institute, Technological Sciences, Energetics and Power Engineering – 06T);
Prof. Dr. Gvidonas LABECKAS (Aleksandras Stulginskis University, Technological Sciences, Energetics and Power Engineering – 06T);
Prof. Dr. Habil. Eugenijus UŠPURAS (Lithuanian Energy Institute, Technological Sciences, Energetics and Power Engineering – 06T).

Official opponents:

Prof. Dr. Habil. Stasys Vygantas AUGUTIS (Kaunas University of Technology, Technological Sciences, Measurement Engineering – 10T);
Prof. Dr. Habil. Vytautas MARTINAITIS (Vilnius Gediminas Technical University, Technological Sciences, Energetics and Power Engineering – 06T).

The official defense of the dissertation will be held at 10 a.m. on 7 th November, 2014 at the public session of Board of Energetics and Power Engineering science field in the Session Hall at the Central Building of Lithuanian Energy Institute (Breslaujos g. 3, Room No. 202, Kaunas).

Summary of dissertation sent out on 7 th October, 2014.
The dissertation is available at the libraries of Kaunas University of Technology (K. Donelaičio g. 20, Kaunas) and Lithuanian Energy Institute (Breslaujos g. 3, Kaunas).

KAUNO TECHNOLOGIJOS UNIVERSITETAS
LIETUVOS ENERGETIKOS INSTITUTAS

EUGENIJUS MASLAUSKAS

TEKĖJIMO REŽIMO IR FIZIKINIŲ SAVYBIŲ ĮTAKOS DUJŲ IR SKYSČIŲ MECHANINIŲ DEBITO MATUOKLIŲ CHARAKTERISTIKOMS TYRIMAS

Daktaro disertacijos santrauka
Technologijos mokslai, energetika ir termoinžinerija (06T)

2014, Kaunas

Disertacija rengta 2008 – 2013 m. Lietuvos energetikos institute, šiluminių įrengimų tyrimo ir bandymų laboratorijoje.

Mokslinis vadovas:

Habil. dr. Antanas PEDIŠIUS (Lietuvos energetikos institutas, technologijos mokslai, energetika ir termoinžinerija – 06T).

Energetikos ir termoinžinerijos mokslo krypties taryba:

Prof. habil. dr. Stasys ŠINKŪNAS (Kauno technologijos universitetas, technologijos mokslai, energetika ir termoinžinerija, 06T) – **pirmininkas**;
Prof. habil. dr. Juozas AUGUTIS (Vytauto didžiojo universitetas, technologijos mokslai, energetika ir termoinžinerija, 06T);
Dr. Raimondas PABARČIUS (Lietuvos energetikos institutas, technologijos mokslai, energetika ir termoinžinerija, 06T);
Prof. dr. Gvidonas LABECKAS (Aleksandro Stulginskio universitetas, technologijos mokslai, energetika ir termoinžinerija, 06T);
Prof. habil. dr. Eugenijus UŠPURAS (Lietuvos energetikos institutas, technologijos mokslai, energetika ir termoinžinerija, 06T).

Oficialieji oponentai:

Prof. habil. dr. Stasys Vygantas AUGUTIS (Kauno technologijos universitetas, technologijos mokslai, matavimų inžinerija, 10T);
Prof. habil. dr. Vytautas MARTINAITIS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, energetika ir termoinžinerija, 06T).

Disertacija bus ginama viešame energetikos ir termoinžinerijos mokslo krypties tarybos posėdyje 2014 m. lapkričio 7 d. 10 val. Lietuvos energetikos instituto posėdžių salėje (Breslaujos g.3, 202 kab., Kaunas).

Disertacijos santrauka išsiųsta 2014 m. spalio 7 d.
Su disertacija galima susipažinti Kauno technologijos universiteto (K. Donelaicio g. 20, Kaunas) ir Lietuvos energetikos instituto (Breslaujos g. 3, Kaunas) bibliotekose.

INTRODUCTION

Regardless of development and application of new measurement methods, mechanical meters with rotors are especially important in liquid and gas measurement due to their accuracy and reliability. The main disadvantage of these meters is their great sensitivity to liquid and gas flow regime and to the change of their physical properties, which are determined by type, temperature and pressure of liquid and gas. Complex and expensive procedures and equipment are necessary to determine and ensure stable and permanent operation of such meters. Thus, it is especially relevant to investigate and determine general regularities of measurement characteristics of such meters during variation of flow regime and physical properties of flows as such regularities would provide a possibility to summarise and forecast measurement results and simplify procedures to ensure qualitative measurement characteristics.

Another relevant question is related to growing application of Coriolis mass flow rate meters in liquid and gas measurements. Apart from all advantages, high accuracy, universality, wide range of measured flow rates, it is also important to stress relatively great – yet still poorly investigated – dependence on flow regime, liquid viscosity, mechanical stress and resonant phenomena.

Aim

To investigate how variation of flow regime and liquid and gas viscosity influence characteristics of mechanical flow meters and determine physical mechanism of effects as well as summarise their regularities in order to forecast operation of the meters and variation of the provided results.

Tasks

1. Investigate influence of flow regime ($8 \cdot 10^3 < Re_D < 1.1 \cdot 10^7$) ($Re_D$ for inflow diameter) on air (gas) flow rate measurement using turbine meters and investigate influence of flow regime ($10^3 < Re_D < 7 \cdot 10^5$) on liquid flow rate measurement using rotary meters and provide explanation about the physical mechanism that influences error variance regularities of turbine and rotary meters.
2. Investigate influence of kinematic viscosity ($10^{-6} < \nu < 6 \cdot 10^{-4}$ m^2/s) and flow regime ($1 < R_{ed} < 10^4$) (R_{ed} for pipes' diameter) on the flow rate measurements using Coriolis flow meters.
3. Prepare recommendations for practical application of the results.

Scientific novelty

1. The determined universal regularity of measuring errors' dependence on Re_D of flowmeters with rotating rotors (turbine and chamber flowmeters), which is independent of the meters operating principle and that physical reason is the change of flow regime and the rotor driving and dragging forces ratio when Re_D is changing, led to development of the method how to evaluate the meters' response dependence on Re_D's changes in the narrow ranges, which allows to predict the flow meters' operation, when the flow regime is changing significantly.
2. The increase of Coriolis flow meters' sensing tube phase difference, which is indicated by increase of errors in mass flow rate measurements, when viscosity increases ($\nu \geq 60$ mm^2/s), and is dependent on the decrease of periodic shear stress because of the weakening of secondary flows, was determined.

Practical significance of the work

1. Developed evaluation method for qualitative characteristics of turbine and rotary meters; the method allows reducing the scope of work and expenses for gas and liquid flow meters calibration. Investigation results allow anticipating operation of the meters when the flow regime varies significantly using turbine meters calibration data only in atmospheric pressure facilities or calibration data of rotary meter only in liquid flow of one viscosity.
2. Research results were used in preparation of recommendations to design and legalise compressed natural gas and bioethanol accounting systems and develop their verification methodologies.

Defensive statements

1. The determined variance regularities of measurement errors of turbine and rotary meters when Re_D vary from 10^3 to 10^7 allow anticipating the meters operation in a wide range of Re_D, when errors of turbine meters in the atmospheric pressure air flow or errors of rotary meters in one liquid flow are known.
2. In low flow rate region, measurement errors approach the peak value conditioned by growing influence of rotors' driving forces and slower growth of dragging forces.
3. The peak in the errors curve shows the beginning of a developed turbulence flow regime that is accompanied by essential growth of pressure losses and approach of relative errors to higher negative values according to the universal regularity that depends only on Re_D;

4. Errors are approaching to the stable asymptomatic value when Re_D approaches to 10^6 and balance of dragging and driving forces of the meter's rotors stabilises due to high turbulisation;
5. The mass flow measurement errors in Coriolis flow meters increases, as secondary flows are weakening, when flow regime shifts to laminar or, as secondary flows is disintegrating, when flow regime shifts to turbulent.

Scientific approbation of the dissertation

Publications on the theme of doctoral dissertation were published in four international and Lithuanian conference proceedings. Three scientific publications were published on the two scientific articles, one of which is in a journal in Thomson Reuters WoS data base.

Structure of the dissertation

Dissertation consists of three chapters with subchapters, conclusions, practical recommendations and references. Dissertation volume is 79 pages; it includes 41 figure, 11 tables and 78 references.

1. Review

Gas and liquid flow measurements are significantly important for many practical and scientific tasks, especially those related to issues of energetics. This work mainly concentrates on investigation of gas and liquid flow rate measurement using mechanical (turbine, rotary and Coriolis) meters (further referred to as TM – turbine meters, RM – rotary meters and MM – Coriolis mass meters). TM and RM remain the main instruments of flow measurement due to their reliability, durability, low prices and accuracy. TM are mostly used for measurements of large natural gas flow rates in main pipelines. As the requirements for measurement accuracy become more demanding, calibration with natural gas under working pressures has been recently started to be used. However, such procedures require expensive equipment and expenses for calibrations, and expedience and efficiency of such actions lack scientific evaluation.

RM covers the biggest area of flow measurements of such important and practically used liquids as light petroleum products and biofuels for their large flow rates. In order to get accurate measurement results, it is necessary to know what the influence of viscosity is, or to have special equipment that would allow to perform the evaluation of meters operation under different viscosity. However, in the latter case, every liquid needs different equipment, and production and maintenance of such equipment is expensive.

MM are universal devices that measure flow rates of gas as well as of liquid and allow directly measure mass flow rate and density, and volume flow rate after recalculation with high accuracy. However, these are relatively new devices, whose metrological characteristics dependence on liquid physical properties and external effects must be investigated closely.

When evaluating influence of physical properties and flow regime on flow rate meters operation, the meters can be compared to closed channels and they can be analysed according to hydromechanical principles. Here Re_D is always one of the most important parameters. Nondimensional form of Navier-Stokes equation shows that when Re_D approaches infinity, the friction member disappears. Thus, it can be stated that when a certain Re_D is reached, influence of physical viscosity in the meter decreases to an insignificant value, and meter errors, which are affected by resistance to the flow, should approach a certain asymptotic value.

After summarising the present state of liquid and gas measurement research and its importance for use of energetic resources, the following conclusions might be drawn:

- there are still unexplored issues related to influence of flow regime, gas and liquid viscosity variance on RM and TM measurement errors; regularities of error variance are not determined and there are no sufficient summaries of these regularities relating them to physical results of the mechanism analysis;

- the performed MM investigations on how flow regime, temperature, pressure, rate distribution, flow pulsations and external vibrations influence mass flow rate measurement allow recommendations in what way using these meters the measurements would be more accurate in the field of liquid as well as gas mass flow rate compared to other types of flow meters. However, there are very few investigations carried out on measurement of influence of varied viscosity on mass flow rate or on density, especially in low Re_D range. Many theoretical as well as experimental investigations have been performed using meters with one straight tube that are operated in a narrower flow rate field due to their lower sensitivity and some other characteristics. There are unresolved issues measuring flow rates of two-phase medium (solid additives in liquid or gas in liquid) using MM.

2. Equipment and methods of experimental investigations

Experimental investigations were performed under laboratory and natural (working) conditions. Considering possibilities of the laboratory equipment and used liquids, some investigations of the meters were performed in the laboratory. These are measurements of various liquid viscosity and density under different temperatures and result analysis, investigation of various meters' errors in kerosene Exxol D80 and water flows, and operation of small MM in flows of high viscosity liquids. The results of meters calibration in foreign laboratories were also used. Those investigations that could not be performed using the laboratory equipment due to limited variance interval of liquid viscosity were performed under real conditions in liquid fuel terminals, bioethanol plants or compressed gas filling station.

Laboratory stationary equipment with circulating water and liquid Exxsol D80 (characteristics similar to the kerosene) was used for investigations under laboratory conditions. A device for investigations with liquids of various viscosities had been developed and manufactured to increase the limits of liquid viscosity.

Investigation of large TM was performed following the presented order:

- in the laboratory, TM readings in the aerodynamic facility were compared with the readings of the standard meter when pressure in the facility is close to atmospheric pressure;
- later the meter was sent to laboratories (Pigsar or Karlsruhe in Germany; Force in Denmark) that had increased pressure facilities;

- the calibrated meter then was returned to the laboratory and actions described in the first point were performed.

Figure 1 presents the scheme of the equipment that was used to investigate liquid viscosity's influence on RM, irrespective of investigation conditions (laboratory or natural); liquid density viscosity meter (*5*) was used only when investigations were carried out under natural conditions; meter (*13*) was used in all cases.

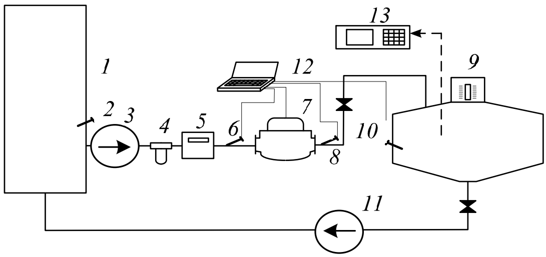
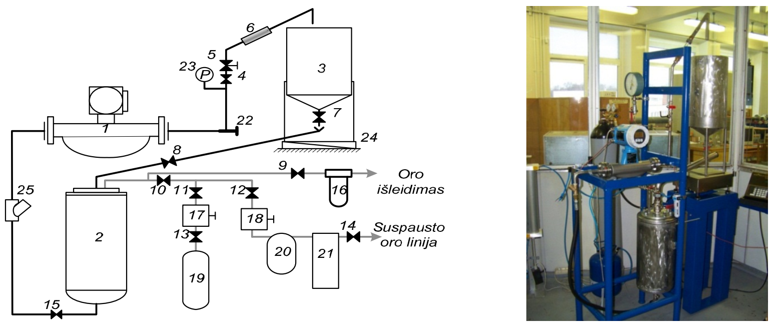


Fig. 1. Equipment scheme for investigation of liquid viscosity influence: *1* – liquid tank; *2, 6, 8 and 10* – temperature meters; *3* – pump; *4* – filter and air (gas) separator; *5* – liquid density and viscosity meter; *7* – the investigated RM; *9* – flowing liquid volume or mass measurement system; *11* – pump returning fluid to the tank; *12* – computerised system for measurement data collection and processing; *13* – liquid density and viscosity meter



a) b)

Fig. 2. Viscous liquid facility for mass meters investigations: a) – scheme; b) – image. Markings: *1* – the investigated meter; *2, 3* – main liquid tank and tank on the scale; *4* – valve for flow start/stop; *5* – flow rate control valve; *6* – control window; *7 ... 15* – valves; *16* – settler; *17*, *18* – high and low pressure reducers; *19* – high pressure gas cylinder; *20* – compensatory cylinder; *21* – air dryer; *22, 23, 24* – devices for temperature, pressure and mass measurement

Investigations of liquid viscosity influence on MM operation were performed in a specially designed and manufactured facility (Fig. 2) in which the flow rate of the liquid is obtained pressing the liquid with pressured air in the main tank.

In order to investigate liquid viscosity influence on density measurement function of these meters, density measurement investigations in MM were performed using experimental liquids with several viscosities (from $\nu = 10^{-6}$ m^2/s to $\nu = 3 \cdot 10^{-3}$ m^2/s).

3. Numerical analysis of rotary meters

The main reason for RM errors is leakages through gaps between vanes and body. Leakages depend on various parameters, the main of which are the following: liquid viscosity and height of the gap. Leakages were investigated using a numerical model and analysing results of the experiments.

Figure 3 presents a simplified task scheme according to which the numerical model was developed. Width of a blade Δx_1 corresponds to the length of the gap, and the depth of the gap between the body and the lower part of the vane is Δx_2. Height of the gap is h_1 and h_2 correspondingly. In order to simplify the task, heights of the gaps between the vane and of the side walls of the meter body are assumed to be equal to h_1.

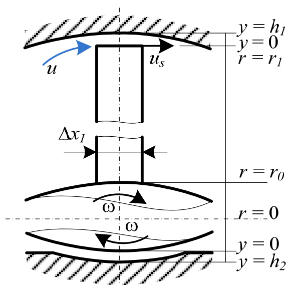


Fig. 3. Task scheme

After adapting conditions of a stationary laminar flow in Navier-Stokes equations system and solving it:

$$\delta = -\frac{|\Delta p|}{12\mu q}\frac{c_0}{1+\dfrac{c_1}{V_k}} - \frac{c_1}{V_k + c_1}; \qquad (1)$$

here μ – dynamic viscosity; Δp – differential pressure between chambers, q – flow rate; V_k – flowing volume during one rotor rotation (chamber volume);

c_0 and c_1 – constant values for all meters that depend on geometric parameters of the meters:

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

and

$$c_1 = \pi \left(L (h_1 r_1 - h_2 r_0) + h_1 \left(r_1^2 - r_0^2 \right) \right); \quad (3)$$

here, r_0 – rotor's radius; r_1 – distance between the centre of the rotor and the upper wall of the chamber.

4. Investigation results of turbine flow rate meters in atmospheric and high pressure air and natural gas flow

The following analysis is of TM errors variance regularities, comparing the measurements under atmospheric and increased pressure. 4 – 6 figures present the main investigation results of TM divided into types according to relative geometric dimensions.

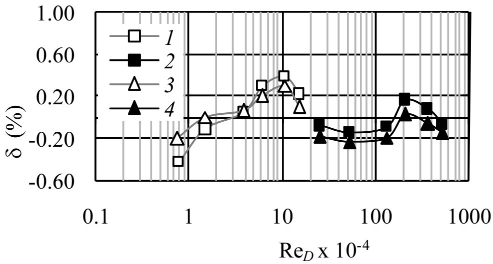


Fig. 4. Error dependence of two TM (type A, DN 150) on Re_D: *1, 3* – atmospheric pressure; *2, 4 – 3.4* MPa pressure

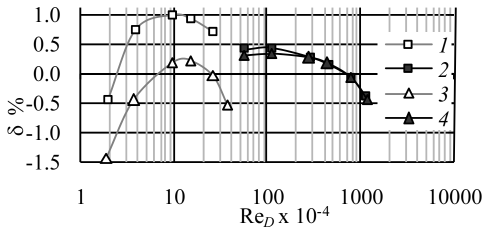


Fig. 5. Error dependence of two TM increased in length (type B, DN 250) on Re_D: *1, 3* – atmospheric pressure; *2, 4* – 3.1 MPa pressure

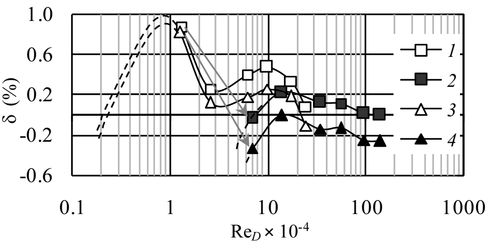


Fig. 6. Error dependence of two TM (type C, DN 150) on Re_D: *1, 3* – atmospheric pressure; *2, 4* – 0.6 MPa pressure

In Fig. 7, investigation results of all meters are presented in one diagram which shows that the widest distribution of errors from +3 % to –1.5 %, is obtained under atmospheric pressure. Increasing the pressure when Re_D reaches $5 \cdot 10^5 \div 10^6$, distribution is $\pm (0.3 \div 0.5)$ %

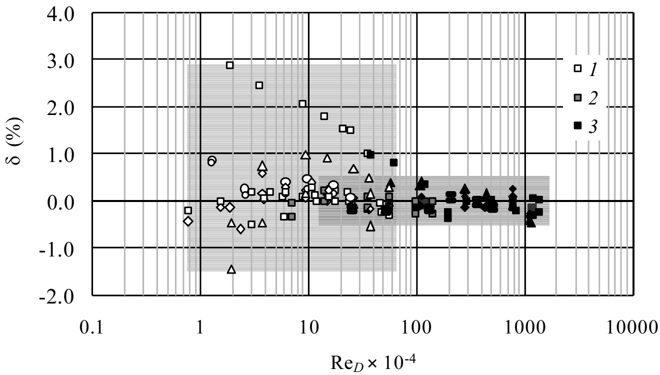


Fig. 7. Comparison of experimental results obtained using meters of various types and sizes under atmospheric and increased pressures: *1* – $\nu = 15.4 \cdot 10^{-6}$ m²/s; *2* – $\nu = 2.74 \cdot 10^{-6}$ m²/s; *3* – $\nu = 0.44 \cdot 10^{-6}$ m²/s

Limits of the latter distribution are until $Re_D \approx 10^5$ when under the atmospheric pressure the distribution of the results does not exceed ± 1 %.

Analysing regularities of errors variance in low pressure flow, it can be concluded that three areas are characteristic to all TM:

- in the first, mechanical friction prevails and driving forces grow faster than hydrodynamic resistance. The main peak, that separates the area where the prevailing dragging force is mechanical friction force from the area with prevailing hydrodynamical resistance force, is reached when dragging and driving forces are in balance. Considering flow conditions that are determined by length and height of the circular channel in front of the turbine, the error peak is usually in $Re_D \approx 5 \cdot 10^4 \div 2 \cdot 10^5$ area. In this area, additional peak appears yet not in all cases; it comes before the main peak. Such error variance for low Re_D is stimulated by formation of rate profile and longitudinal vortexes characteristic to flow regime. Influence of starting to form detached streamlining appearances of the turbine could not be absolutely denied. In this way, strong dependence of transitional appearances on inflow conditions may be the reason for uneven error variance towards the peak value. When the meter is of increased length (a straight section of a round channel between the flow rectifier and the circular channel), there is no additional peak (Fig. 5.). In this case, higher limits of errors variance exist. Transition to high Re_D area is slow and even;

- in the second area, hydrodynamic resistance forces increase more rapidly than driving forces due to increasing turbulence. In this area, errors move towards the negative side;
- in the third area, when Re_D approaches 10^6, errors approach the constant value.

In high pressure flow the following errors' variance regularities were determined:

- the same driving force that prevails over mechanical friction is reached already with low flow rates, and the earlier achieved state is similar to the balance of driving and stopping forces. Nature of the flow starts to change under much lower flow rates and such high level of errors as in case of atmospheric pressure cannot be achieved;
- the greatest error variances occur only in the area of small Re_D since the lowest negative error values must move towards positive values due to increasing density, and the peak value must decrease because resistance increases when Re_D increases and turbulent flow regime is achieved faster. Experimental results demonstrate that error stabilisation is most likely to occur at a level reached under atmospheric pressure and $Re_D \geq 2 \cdot 10^5$;
- in all cases when the main error peak is in the area of low Re_D, even lower than 10^4, and after it, the errors move in wavy manner or very evenly towards negative values, this regularity also remains in case of increased pressure. This shows that in such meters, already when Re_D are low, strongly turbulised flow characteristics start to influence resistance to the meter's rotations, and Reynolds analogy is fully obtained.

5. Results of a rotary meter investigation in flows of different viscosity liquids

Figure 8 demonstrates experimentally determined rotary RM errors' variance regularities in flows of various liquids. The figure shows the following errors' variance tendencies corresponding to liquid viscosity:

- in diesel fuel ($\nu \approx 4 \cdot 10^{-6}$ m^2/s) flow, the error distribution for any flow rate does not exceed ±0.05 %. Since the liquid is viscous, leakages through the gaps and error variances towards negative values are the lowest compared to their values in liquids of lower viscosity;
- when viscosity of liquids gets lower, errors move towards higher negative values due to increasing leakage through the gaps; the lower the liquid viscosity, the more negative values the errors reach. Certain variances of errors whose physical reasons can be related to regularities characteristic to turbine meters also become clear.

Thus, Fig. 8 b) and c) shows that error curves have the expressed peak until which negative errors decrease when flow rate increases.

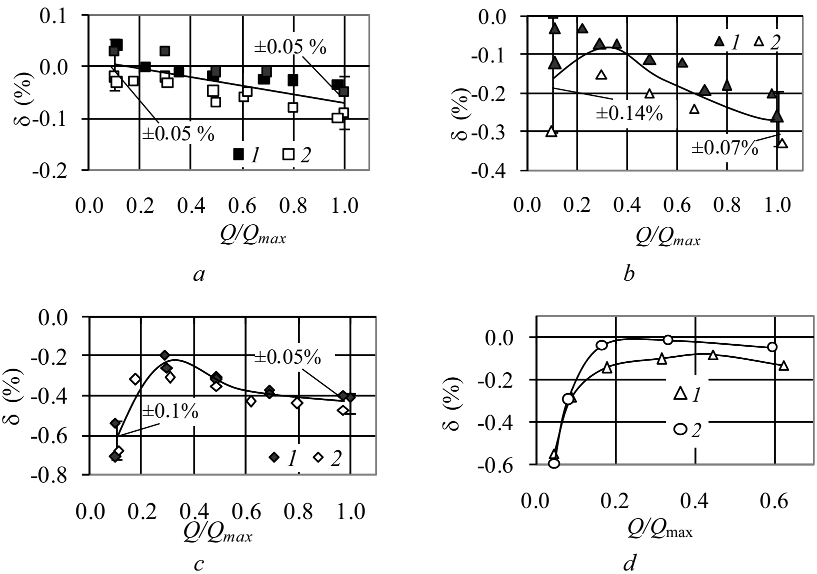


Fig. 8. RM (DN 100) errors measuring in: *a* – diesel fuel; *b* –kerosene Jet-A1; *c* –A-95 petrol flow: *1* and *2* – measurements under laboratory and natural conditions, respectively; *d* – the flow of liquid Exxsol D80: *1* and *2* –DN100 and DN65 size meters respectively under laboratory conditions

It is a result of increasing driving forces and due to it the dragging effect of mechanical friction and viscosity forces becomes relatively smaller until the balance of driving and dragging forces is achieved. When viscosity becomes smaller, the error peak moves towards higher flow rate values. It is reasonable to state that for high viscosity, the error peak also exists, yet its expression is not that strong, and errors are approaching towards negative values only for very low flow rates.

Measurements and calculations of pressure drop show that the error peak correlates with the break of pressure variance curve. From the physical point of view, the break means that flow in RM and flow in a channel can be characterised by analogous regimes. These regularities can be summarised while analysing error dependency on Re_D (Fig. 9) that is directly dependent on liquid kinematic viscosity. These data show that until the peak value, the errors distribute according to Re_D whose variance is determined by changes in liquid kinematic viscosity. In this area, errors' variance depends on mechanical friction of the meter's rotor and hydrodynamic forces that are caused by liquid viscosity. This influence increases with decreasing rotor's speed and driving forces. In case of higher viscosity, leakages are smaller, thus the error peak is reached for lower flow rates.

Errors remain in this level until the flow shifts to turbulence flow regime. Then in the meter, leakages are again increased by higher differential pressure between chambers due to turbulent viscosity, and errors move towards higher negative values. This area is characterised by the universal regularity of errors' variance that does not depend on mechanical friction. Also, when Re_D approaches 10^6, errors' variance rate decreases and they start approaching the asymptomatic value.

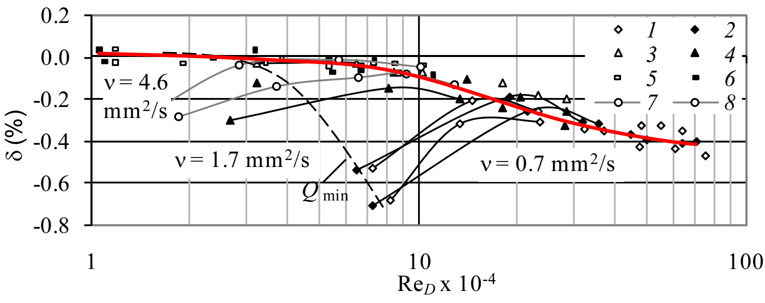


Fig. 9. RM errors when the measured liquid is: *1* and *2*– diesel fuel in laboratories and correspondingly operating places, *3* and *4* – kerosene Jet-A1 in laboratories and operating places, *5* and *6* – A-95 petrol in laboratories and operating places, *7* and *8* – DN100 and DN65 flow meters measurements with liquid Exxol D80

Regardless of surrounding conditions, flow parameters, variety of liquids' physical properties, error curves of different viscosity fluids continue each other in area where hydrodynamic forces exceed mechanical friction forces. Here errors contain in the belt of 0.15 % width. Even the flow rate meters with different geometric parameters (Fig. 9. Curves No. 7 and No. 8) submit to this tendency. This means that RM errors are Re_D function. The curves get separated only for lower flow rates when mechanical friction forces become significant to the hydrodynamic forces.

Numerical modelling of leakages performed using (1) confirms the mechanism that determines the measurement errors. Peculiarities of the liquid flow structure can be influential in the inter-blade space, inflow to the gap and outflow from it, however a detailed analysis in the flow meter is necessary. The obtained results (Fig. 10) show that difference between the experimental errors and the numerical model is more than ±0.05 % just for the lowest viscosity and low flow rates when the effect of the mechanical friction of the meter's moving parts is relatively important.

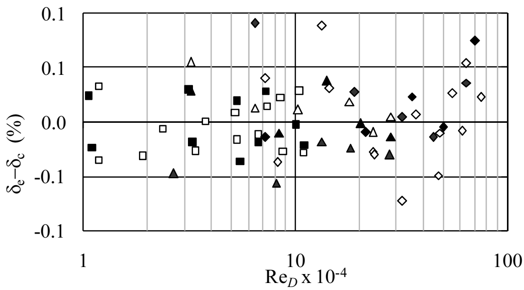


Fig. 10. Difference between the experimental results and data obtained using the numerical model (δ_e- δ_c) for the same viscosity

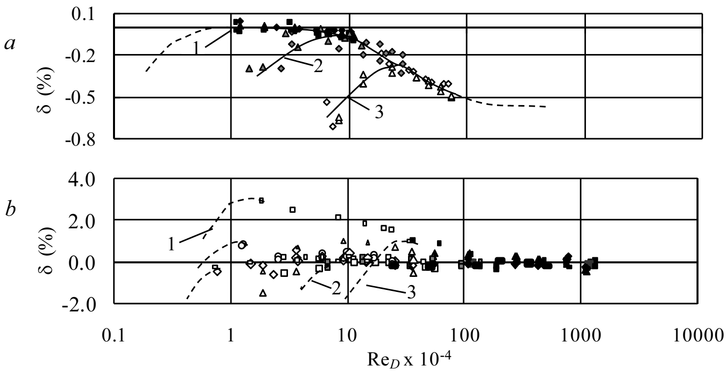


Fig. 11. Comparison of RM and TM errors variance according to Re_D: *a* RM: *1, 2* and *3* – respectively $\nu = 4.6{\cdot}10^{-6}$, $2.3{\cdot}10^{-6} – 1.7{\cdot}10^{-6}$ and $0.7{\cdot}10^{-6}$ m^2/s; *b* TM: *1, 2* and *3* – respectively $\nu = 15{\cdot}10^{-6}$, $2.74{\cdot}10^{-6}$ and $0.44{\cdot}10^{-6}$ m^2/s

For high flow rates, in a liquid of low viscosity results of the numerical modelling differ from the experimental results to higher negative errors although the experimental errors approach the steady asymptotic value. This can be explained by quite simplified assumptions in the numerical modelling.

These results correlate well with TM errors' variance regularities when gas viscosity changes due to the pressure (Fig. 11). It can be concluded that the determined regularities are generally characteristic to mechanical meters with rotating rotors.

6. Investigation of viscosity and pressure influence on Coriolis meters accuracy

Sections 4 and 5 show that errors of flow meters, whose flow rate sensor is a rotating rotor of various types, vary significantly for lower Re_D and approach towards certain asymptotic values for high Re_D. Coriolis meters have no such disadvantages in a relatively narrow viscosity range; however, when they are used to obtain much higher measurement accuracy, many issues arise.

Accuracy of mass meters in flows of different viscosity liquids. Volume flow rate measurements by MM depend directly on errors of density measurement. Density measurement investigations in flows of different viscosity liquids were performed in order to determine the influence of liquid viscosity on volume flow rate measurement (Fig. 12).

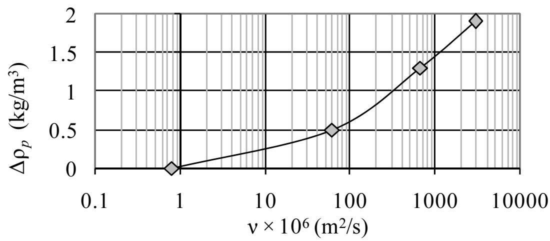


Fig. 12. MM density error dependence on liquid viscosity

The figure shows that when measuring density of different viscosity liquids with the MM, the error increases towards positive errors until 1.9 kg^3/m when viscosity increases from $1 \cdot 10^{-6}$ to $3 \cdot 10^{-3}$ m^2/s. Considering the fact that the highest declared error for density measurement of these meters is $\Delta\rho = \pm 1.0$ kg/m^3, density calibration with working fluids is necessary when this meter is used measuring density and volume of more viscous liquids. In case it is not possible, correction of density measurement function with the working fluid must be performed.

Figure 13 provides MM mass flow rate investigation results in flows of different viscosity liquids.

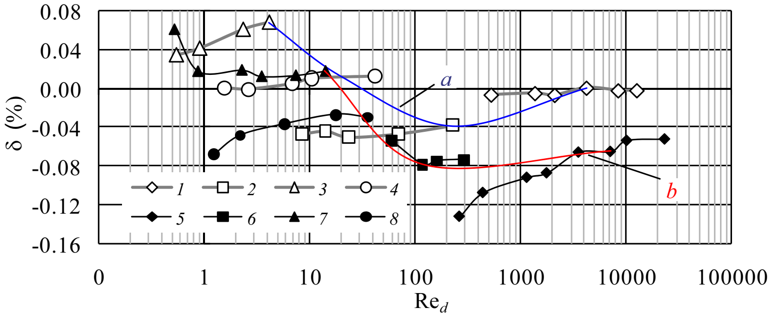


Fig. 13. Errors of two types of MM considering Re_d in flows of various liquids: *1*, *2, 3* and *4* – “U” type; *5, 6, 7* and *8* “Ω” type; *1* and *5* – water; *2* and *6* – oil No. 1 ($\nu = 60 \cdot 10^{-6}$, m^2/s); *3* and *7* – oil No. 2 ($\nu = 600 \cdot 10^{-6}$, m^2/s); *4* and *8* – oil No. 4 ($\nu = 200 \cdot 10^{-6}$, m^2/s). Curves *a* and *b* were drawn through the points of one flow rate $Q = 5.5 \cdot 10^{-5}$ m^3/s of both meters

When the viscosity is low (water flow), mass flow rate measurement error is close to zero and remains constant despite approaching the laminar flow regime according to Re_d. However, when the viscosity is increased and Re_d decreases, at the beginning the errors are negative, yet later they suddenly start moving towards the positive values. For almost all Re_d variance range, the meter’s errors remain within limits of ± 0.1 %. However, for low Re_d, significant variance in errors is observed.

In order to obtain dependency of the flow rate error on viscosity, points of the same flow rate are selected from higher flow rate area with the established errors with minimum variance (high flow rate area) and from different viscosity curves and are marked in viscosity scale in Fig. 14.

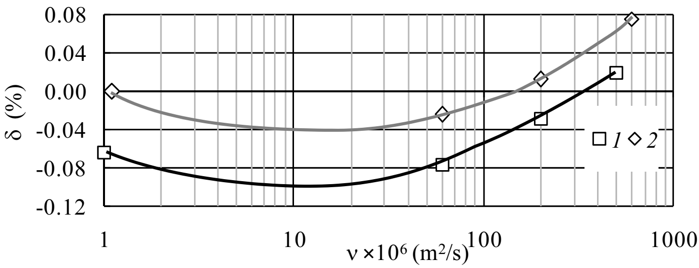


Fig. 14. *1* – “Ω” and *2* – dependency of “U” type MM errors on viscosity of the measured liquid

Figure 15 shows variance of “0” flow rate when the liquid viscosity changes. This viscosity effect on flow rate measurement can happen due to different interaction of periodical shear stresses with inner walls of the tube for different viscosity of the liquid and the same Re_d. Secondary flows with two profiles appear due to tubes vibration in the flat vertical to the tube's axis. These flows are periodical, their frequency coincide with the frequency

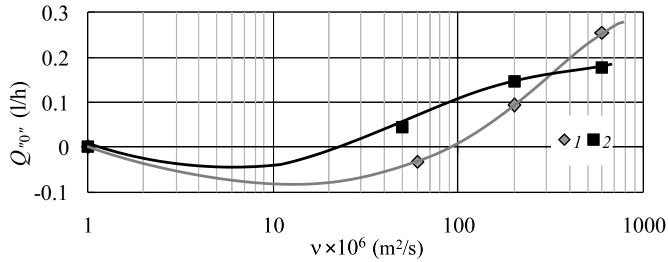


Fig. 15. MM "0" flow rate dependency on the measured liquid viscosity: *1* – "Ω" and *2* – "U" type meters

of tubes vibration, and the phase falls behind with the value that is determined by the fluid interaction with the tube's walls. In case of such flows, periodical shear stresses appear together with a force that additionally affects already vibrating tubes. When the viscosity is low and Re_d is high, secondary flows are almost completely disturbed due to high turbulence, and the flow rate error remains constant or nearly constant in a wide range of Re_d. In case of secondary flow, the additional power caused by periodical shear stresses with the inner surface of the tubes affects the tubes and reduces the difference between phases and causes negative error in the flow rate measurement. Further increase in viscosity causes reduction or disappearance of free vortexes (laminar flow regime), and intensity of secondary flows also decreases.

Pressure influence on mass meters accuracy. When the pressure changes, tension in tubes and resonance frequency changes as well. The measurements were performed while increasing and then decreasing the pressure of constant temperature water and comparing the obtained results with theoretical dependency of water density on pressure and temperature. Density of the used water was measured with a standard density meter. Since the measured water density is very close to the theoretical density, it can be concluded that the same theoretical density dependency on pressure (compressibility) can be applied to the measured water. Figure 16 demonstrates that the higher the pressure of the liquid, the clearer readings deviation from the theoretical value towards positive errors. In the measured range (0–1.5) MPa, this feature is close to linear. Thus, linear density correction recommended in the manufacturers' technical documentation is necessary for small connection diameter MM as well as for bigger connection diameter MM considering the pressure.

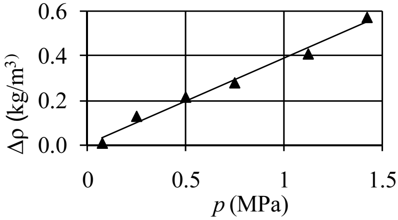
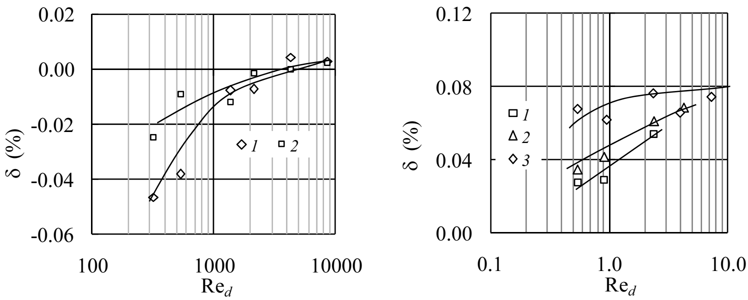


Fig. 16. Density measurement errors under changing pressure

Figure 17 demonstrates MM mass flow rate error variance under changing pressure. When the phase variance increases due to increasing flow rate, curves of different pressure errors approach each other, thus it may be stated that pressure influence also decreases and the phase change affected by pressure shows only “0” change in flow rate. In both cases, displacement to positive errors for increasing pressure is observed.



a) b)

Fig. 17. Density measurement errors under changing pressure: a) measuring silicone oil No. 2 (*1* – 0.1 MPa; *2* – 0.65 MPa; *3* – 15 bar); measuring water (*1*– 0.1 MPa; *2* – 0.65 MPa)

Such pressure influence on “0” flow rate can be explained by the change ratio in phase difference $\Delta\varphi$ and resonance vibration frequency in tubes f due to additional tensions. Figure 16 demonstrates that positive displacement of the density error shows decrease of resonance frequency when pressure increases. MM flow rate is expressed using proportion between flow rate and time difference between the signals of both sensors ($Q \sim \Delta\varphi / f$) that is expressed measuring $\Delta\varphi$ and f. In such way, flow rate change due to pressure change is registered in a fixed value that does not depend on Re_d and is determined by change in phase difference and resonance frequency ratio after the tubes tensions have changed.

Conclusions

1. Regularities of measurement error variation of turbine and rotary flowmeters are determined by analogous physical factors, and Reynolds analogy principles can be applied to summarise the regularities.
2. Two areas were distinguished in the errors' curve that are separated by the peak error (greatest displacement towards positive values) whose value depends on flow regime (Re_D) and ratio of dragging and driving forces of meters' rotors:
   - for $Re_D \leq 2 \cdot 10^5$ area, movement towards the peak value is characteristic; nature of the peak value is determined by increasing the effect of rotor's rotating forces related to increasing Re_D and slower growth of dragging forces in case of transitional flow regime in the channel;
   - the error peak value means the beginning of the turbulent flow regime that is accompanied by essential increase in pressure losses and approach of relative errors towards higher negative values according to the universal regularity that depends only on Re_D.
   - when Re_D is approaching 10^6, developed turbulent flow is reached and as dragging and driving forces of the meter's rotor reach balance, errors approach the constant asymptomatic value.
3. The determined physical causes for error variance of mechanical meters can be applied in practice:
   - to foresee variances of gas flow rate measurement errors of turbine meters under increased pressure when error variance nature is known, under atmospheric pressure, and reasonably consider the purpose to apply calibration to turbine meters fitted in pipelines under working pressures and natural gas;
   - to foresee variances of liquid flow rate measurement errors of rotary meters when results of errors measurement in one liquid are known, and justify introduction of lowest permissible flow rate dependency on the measured liquid viscosity considering limits of the permissible errors.
4. The influence of flow regime and viscosity on the flow measurement using Coriolis flow meters manifests by shifting impact of periodical shear stresses on internal pipe walls of the vibrating tubes, when secondary flows is changing. The shift of errors' toward negative values, when viscosity increases or Re_d decreases depends on the formation and intensification of secondary flows. Errors' shift toward positive values is determined by weakening of the secondary flows, when viscosity further increases.

PUBLICATIONS LIST ON DOCTORAL DISSERTATION THEME

Articles in journals from ISI (Institute of Scientific Information) list with citation index

1. MASLAUSKAS, E.; PEDIŠIUS, N.; ZYGMANTAS, G. Investigation of liquid viscosity influence on flow rate measurement by rotary vane meters. *Mechanika*. ISSN 1392-1207. 2014, vol. 20, p. 158–164.

Articles reffered in Lithuanian Science Council approved list of international databases

1. MASLAUSKAS, E.; PEDIŠIUS, A.; TONKONOGIJ, J. Dujų klampos įtakos turbininiams debito matuokliams tyrimas. *Energetika*. ISSN 0235-7208. 2013. T. 59, Nr.1, p. 50-56. [INSPEC, IndexCopernicus, SCOPUS]

2. MASLAUSKAS, E.; ZYGMANTAS, G. Įrengimo sąlygų įtaka srauto matuoklių metrologinėms charakteristikoms. *Mokslas – Lietuvos ateitis. Pastatų inžinerinės sistemos*. ISSN 2029-2341. 2009. T. 1, Nr. 1, p. 49-51. [IndexCopernicus]

Articles in Lithuanian Republic and International Conference Proceedings

1. BONČKUS, A.; MASLAUSKAS, E. Masės srauto matuoklių kalibruojant vandens skaitiklių patikros įrenginius panaudojimas. *13-osios Lietuvos jaunųjų mokslininkų konferencijos "Mokslas-Lietuvos ateitis" 2010 metų teminės konferencijos Pastatų inžinerinės sistemos straipsnių rinkinys.* Vilnius: Technika, 2010. ISBN 978-9955-28-560-1, p. 21-24.

2. MASLAUSKAS, E.; BONČKUS, A. Evaluation of water volume and flow rate measurement capabilities by reference facility. *7th annual conference of young scientists on energy issues CYSENI 2010*. Kaunas: LEI, 2010. ISSN 1822-7554, p.283-289.

3. KULOKAS, M.; MASLAUSKAS, E. Research of viscosity influence on the density measurements. *8th international conference of young scientists on energy issues CYSENI 2011*. Kaunas: LEI, 2011. ISSN 1822-7554, p. 276-284.

4. MASLAUSKAS, E.; KULOKAS, M. Research of viscosity influence to coriolis mass flowmeters flow rate measurement accuracy. *9th annual conference of young scientists on energy issues CYSENI 2012: international conference*. Kaunas: LEI, 2012. ISSN 1822-7554, p. 440-447.

Information about the Author

Eugenijus Maslauskas was born November 8, 1970 in Rokiškis.
1977 – 1985 m. studied in Onuškis school of Rokiškis district.
1985 – 1988 m. studied in Juodupe secondary school of Rokiškis district.
1988 – 1994 m. studied in department of Telecommunications and Electronics, Kaunas University of Technology, and obtained Bachelor's degree of Electronics Engineering.
2006 – 2008 m. studied in department of Telecommunications and Electronics, Kaunas University of Technology, and obtained Master's degree of Measurement Engineering.
2008 – 2014 m. doctoral studies in branch of Energetics and Power Engineering science at Lithuanian Energy Institute.
E-mail: eugenijus.maslauskas@lei.lt

REZIUME

Nežiūrint į naujų matavimo metodų vystymą ir taikymą, svarbią vietą skysčių ir dujų matavimuose dėl aukšto tikslumo ir patikimumo užima mechaniniai sukieji matuokliai. Pagrindinis šių matuoklių trūkumas – didelis jautrumas skysčio ir dujų tekėjimo režimui ir jų fizikinių savybių pokyčiams, kuriuos lemia skysčio ir dujų rūšis, jų temperatūra ir slėgis. Tai reikalauja sudėtingų ir daug išlaidų reikalaujančių procedūrų ir įrenginių siekiant nustatyti ir užtikrinti stabilias tokių matuoklių charakteristikas. Todėl labai aktualu ištirti ir nustatyti bendruosius tokių matuoklių matavimo charakteristikų kitimo dėsningumus, kintant tekėjimo režimui ir srautų fizikinėms savybėms, kurie sudarytų galimybę apibendrinti ir prognozuoti matavimo rezultatus bei supaprastinti procedūras, skirtas kokybiniams matavimo rodikliams užtikrinti.

Kitas aktualus klausimas susietas su didėjančiu Koriolio masės debito matuoklių taikymu skysčių ir dujų debitams matuoti. Tačiau be teigiamų savybių – aukšto tikslumo, universalumo, plataus matuojamų debitų diapazono, reikia pažymėti taip pat ganėtinai didelį ir mažai ištirtą priklausomumą nuo tekėjimo režimo, skysčio klampos, mechaninių įtempių ir rezonansinių reiškinių.

Darbe atlikta turbininių ir sukiųjų kamerinių matuoklių veikimo analizė patvirtina prielaidas, kad šių matuoklių debito matavimo paklaidų kitimo dėsningumus lemia analogiški fizikiniai veiksniai ir dėsningumų apibendrinimui galima taikyti Reinoldso analogijos principus. Nustatytos mechaninių matuoklių paklaidų kitimo fizikinės priežastys įgalina praktikoje numatyti:

- turbininių matuoklių dujų debitų matavimo paklaidų pokyčius slėgiui pakitus, kai žinomas paklaidų kitimo pobūdis, esant atmosferos slėgiui,

bei pagrįstai svarstyti turbininių matuoklių, įrengtų dujotakiuose, kalibravimo gamtinių dujų sraute, esant darbiniams slėgiams, tikslingumą;

- sukiųjų kamerinių matuoklių skysčių debitų matavimo paklaidų pokyčius, turint paklaidų matavimus viename skystyje.

Nustatyta, kad paklaidų artėjimas link didesnių neigiamų verčių didėjant klampai tuo pačiu mažėjant Re_d lemia antrinių tekėjimų susidarymas ir stiprėjimas, tačiau toliau didėjant klampai antriniai tekėjimai silpnėja ir paklaidos artėja link didesnių teigiamų verčių. Nustatytas žymesnis klampos, slėgio bei rezonansinių reiškinių poveikis „nuliniam“ fazės poslinkiui reiškia nuo Re_d nepriklausantį papildomą paklaidos poslinkį esant mažiems debitams.

UDK 532.57 (043.3)

SL 344. 2014-09-23. 1,75 leidyb. apsk. l. Tiražas 60 egz. Užsakymas 470.
Išleido leidykla „Technologija“, K. Donelaičio g. 73, LT-44029, Kaunas.
Spausdino leidyklos „Technologija“ spaustuvė, Studentų g. 54, LT-51424, Kaunas.