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SIMULATION OF THE PROCESS OF MEASURING THE FLOW RATE OF A PULSATING LIQUID FLOW THROUGH AN EXPANDING DEVICE

Abstract

The article presents the results of modeling a differential pressure flowmeter with a flow transducer in the form of an expanding device that measures the flow rate of a pulsating liquid. The article describes a method for obtaining basic modified equations for describing models and presents the structure of the flow transducer. A conical diffuser is used as an expanding flow transducer in operation. In this article, a model of such a flow meter is obtained and the factors influencing the process of measuring the pulsating flow rate of a liquid are investigated. An estimation of the uncertainty of measuring results of the pulsating flow rate using such a transducer is given. The factors influencing the accuracy of flow measurement are investigated.

Key words: pulsating flow, flow rate, modeling, differential pressure flowmeter, expanding device transducer.

Introduction

In the process of measuring the flow rate of liquids and gases, industrial enterprises often must deal with unsteady and pulsating flows. Unsteady flows can be characteristic of many industrial processes, where variables change over time, affecting the dynamics of liquids and gases. An example of such flows may be the pumping of liquid by pumps in pipelines. In such systems, unsteady flows may occur due to changes in flow velocity, for example, when changing the pump supply or changing the pressure in the system. This can lead to turbulence or eddy movements in the liquid. When drilling oil or gas wells, unsteady flows may also occur due to changes in pressure and flow velocity, especially during the processes of pumping liquids to increase production. In liquid storage tanks such as oil, water, or chemicals, the liquid level may change over time. This can create different flows inside the tank, especially when filling or emptying. Other examples of such flows can be observed in the production of chemical products or food additives when substances often flow through reactors or tanks for mixing various liquids or additives. The flows inside such systems will depend on the rate of introduction of components, their concentrations, as well as on the design of the mixer. In heat exchange systems, for example, when cooling or heating liquids in heat exchangers, flows can also be non-stationary due to changes in temperature and flow velocity.

These are just a few examples, and in fact unsteady flows can be characteristic of many industrial processes where variables change over time, affecting fluid dynamics. Therefore, the methods and mathematical apparatus used to simulate stationary flows are not suitable and can lead to significant errors when used to describe unsteady pulsating flows of liquids and gases.

Many theoretical and experimental works have been devoted to the study of pulsating nonstationary flows. These studies use various approaches and methods that can be found in a literary search. For example, works [1, 2] describe the theoretical aspects of improving the method of measuring unsteady flows and the corresponding experimental approaches. Other papers such as the article [3] describe works that summarize previously obtained research results. Another example of modeling unsteady flows is the work [4], where the authors try to describe the motion of a pulsating flow by mathematical modeling, and then verify these results experimentally. Work [5] describes the process of modeling the flow rate of a viscous pulsating flow. One of the recent papers that describes attempts to improve methods for measuring the flow rate of pulsating flows is a study [6]. In [7, 8], the author attempts to simulate the process of measuring the flow rate of pulsating flows using differential flowmeters. In work [9], the authors share the results of studies on measuring the flow rate of a pulsating two-phase flow. The paper [10] presents the results of modeling heat transport in a pulsating flow. Other papers [11, 12] present the results of applying machine learning methods to study and simulate nonstationary flows. In [13], the process of the flow of a pulsating non-Newtonian fluid is studied. The paper [14] presents the results of mathematical and computer modeling of pulsating flow in vertical pipes.

Despite the large number of studies in the framework of this work, the authors are trying to expand the methods of applying approaches to describe pulsating flows, which are described in [7, 8], to improve the method of measuring the flow rate of liquids and gases using differential pressure flowmeter in conditions of unsteady flow. Therefore, within the framework of this work, the authors aim to simulate an inverse differential pressure flowmeter in conditions of unsteady fluid flow. An expanding device of the diffuser type is used as the primary flow transducer in this study.

Materials and Methods

In this case, the authors consider the problem of measuring the flow rate of liquid through an expansion device under conditions of unsteady flow. To solve this problem, authors apply and use the provisions obtained in [7, 8]. The issues of applying these approaches to differential pressure flowmeter with diffusers as primary transducers were investigated by the authors in [15, 16].

To obtain the necessary equations, consider the Euler equation for the one-dimensional case in accordance with [17]:

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x}, \tag{1}$$

where $V(t,x)$ – fluid flow velocity, p – fluid pressure, ρ – fluid density, t – time, x – the coordinate along the central axis of the flow.

To solve this problem, authors will perform the following substitution for the flow velocity:

$$V = u(z),$$

where $z = f \cdot t + \frac{x}{L}$ – a new dimensionless variable, f – frequency, value inversely proportional to time, L – the length of some characteristic body size in the flow. For example, for a diffuser, the given size is the maximum diameter of the expanded section.

Now authors need to express equation (1) in terms of the new velocity. To do this, we perform the following transformations for each partial derivative in equation (1):

$$\frac{\partial V}{\partial t} = \frac{du}{dz}\cdot\frac{\partial z}{\partial t} = f\frac{du}{dz};$$

$$\frac{\partial V}{\partial x} = \frac{du}{dz}\cdot\frac{\partial z}{\partial x} = \frac{1}{L}\frac{du}{dz};$$

$$dz = \frac{\partial z}{\partial t}dt + \frac{\partial z}{\partial x}dx = f\cdot dt + \frac{1}{L}dx;$$

$$\frac{\partial p}{\partial x} = \frac{dp}{dz}\cdot\frac{\partial z}{\partial x} = \frac{dp}{dz}\cdot\frac{f\cdot dt + \frac{1}{L}dx}{dx} = \frac{dp}{dz}\cdot\left(f\frac{dt}{dx} + \frac{1}{L}\right) = \frac{1}{L}\cdot\frac{dp}{dz}.$$

In the last expression, the relation $\frac{dt}{dx} = 0$ due to the mutual independence of variables t and x.

After that, authors will replace the last partial differential expressions in the original equation (1). Then we get the following equation:

$$f\frac{du}{dz}+\frac{u}{L}\frac{du}{dz}=-\frac{1}{\rho\cdot L}\frac{dp}{dz}.$$

Next, authors divide both parts of equality by the value $\frac{1}{L}$ and integrate by the new variable z. In this case, this allows to obtain the following equation:

$$L\cdot f\cdot u+\frac{u^2}{2}+\frac{p}{\rho}=const.$$

Let's transform the last equality into the following form:

$$\frac{u^2}{2}\left(\frac{2L\cdot f}{u}+1\right)+\frac{p}{\rho}=const.$$

After that, authors will return to the original velocity value and make some substitution for the value in brackets:

$$\frac{V^2}{2}(2Sh+1)+\frac{p}{c}=const\,, \tag{2}$$

where $Sh=\frac{L\cdot f}{V}$ – the dimensionless Struhal number.

Applying similar reasoning, after that, the authors can write down the equation for the fluid flow density as a solution to the flow continuity equation in the following form:

$$\rho V(Sh+1)=const\,. \tag{3}$$

The liquid flowing through the flow transducer will be considered homogeneous and incompressible, so it will assume the density of the liquid to be constant, on the one hand. On the other hand, authors neglect the losses in the transducer, assuming them to be insignificant within the framework of this task.

Applying equations (2) and (3) to describe the motion of a pulsating liquid into flow transducers in the form of a conical diffuser in accordance with Figure 1.

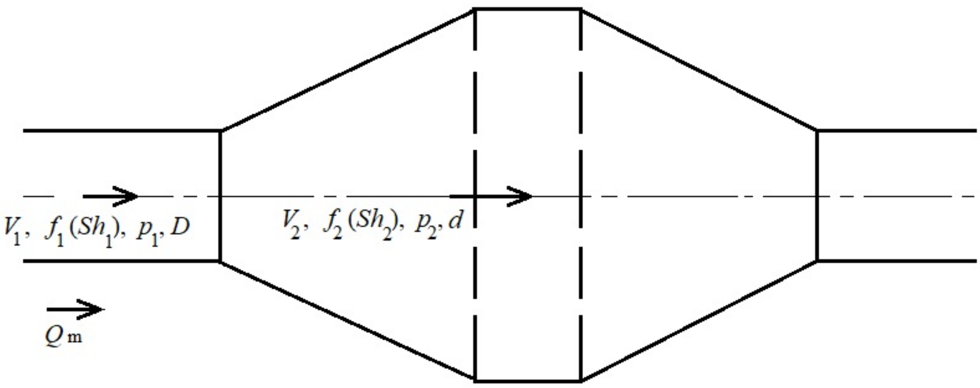

Figure 1 – Flow transducer structure and flow parameters in different cross sections

In accordance with the structure of the transducer and the direction of the pulsating flow, we will draw up the following equations for two sections of the diffuser according to formulas (2) and (3):

$$V_1(Sh_1+1)\frac{\pi D^2}{4}=V_2(Sh_2+1)\frac{\pi d^2}{4}\,. \tag{4}$$

$$\frac{V_1^2}{2}(2Sh_1+1)+\frac{p_1}{\rho}=\frac{V_2^2}{2}(2Sh_2+1)+\frac{p_2}{\rho}\,. \tag{5}$$

The velocity in the first section or in the pipeline is quite high, and the pressure is correspondingly low. In the section where the diffuser expands as much as possible, the flow velocity of the liquid decreases, and the pressure increases here. Therefore, having expressed the velocity in the first section from equation (4), it needs to substitute it into equation (5) to determine the velocity of the liquid in the second section:

$$V_2 = \left[\frac{(2Sh_1+1)^{-1}}{\beta^4\left(\frac{Sh_2+1}{Sh_1+1}\right)^2 - \left(\frac{2Sh_2+1}{2Sh_1+1}\right)}\right]^{1/2}\sqrt{\frac{2\Delta p}{\rho}},$$

where $\beta = \frac{d}{D}$ – diameter ratio of the transducer, $\Delta p = p_2 - p_1$ – pressure difference between flow transducer sections.

From the last equation and equation (3), a formula can be obtained for determining the mass flow rate through the transducer in Figure 1:

$$Q_m = (Sh_2+1)\left[\frac{(2Sh_1+1)^{-1}}{\beta^4\left(\frac{Sh_2+1}{Sh_1+1}\right)^2 - \left(\frac{2Sh_2+1}{2Sh_1+1}\right)}\right]^{1/2}\sqrt{2\Delta p\rho}\cdot\frac{\pi\cdot d^2}{4} \quad (6)$$

As can be seen from the last equation (6), the flow rate of a liquid under the condition of an unsteady flow with an expanding flow transducer depends on the diameter ratio of the transducer and the Struhal numbers or on the frequencies that are additionally measured in the pipeline and in the flow meter. From experimental studies, it is possible to obtain the value of the discharge coefficient for this flow transducer. In the framework of this work, authors will take it equal to one for the convenience of describing our reasoning. The Struhal number is chosen here as a measure characterizing the unsteady flow of the liquid. Putting the Struhal numbers equal to zero in equation (6), we obtain a formula for measuring the flow rate of a liquid in a stationary flow. The proposed method is completely inverse with respect to known flow measurement technologies using differential pressure flowmeters, which are described in [18–20].

Results and Discussions

Let's compare the measured flow rates for stationary and non-stationary flows. To do this, authors will simulate the process of measuring water flow rate using equation (6) for various values of the Struhal numbers. Figure 2 shows the dependence of the mass flow rate on the differential pressure using a similar flowmeter flow transducer to measure water flow rate. The conditions for measuring water flow rate in this case are presented in Table 1.

Figure 2 clearly shows that the presence of Struhal numbers in the flow seriously increases the value of liquid flow rate. This circumstance proves once again that working with non-stationary flows of liquids and gases requires new approaches, and the use of traditional approaches and models can lead to serious errors.

Table 1 – Properties of water

№	Parameter	Value	Units
1	Water pressure	2	bar
2	Water temperature	+10	oC
3	Water density ρ	1000.23	kg/m^3
4	Transducer diameter d	150	mm
5	Pipeline diameter D	100	mm

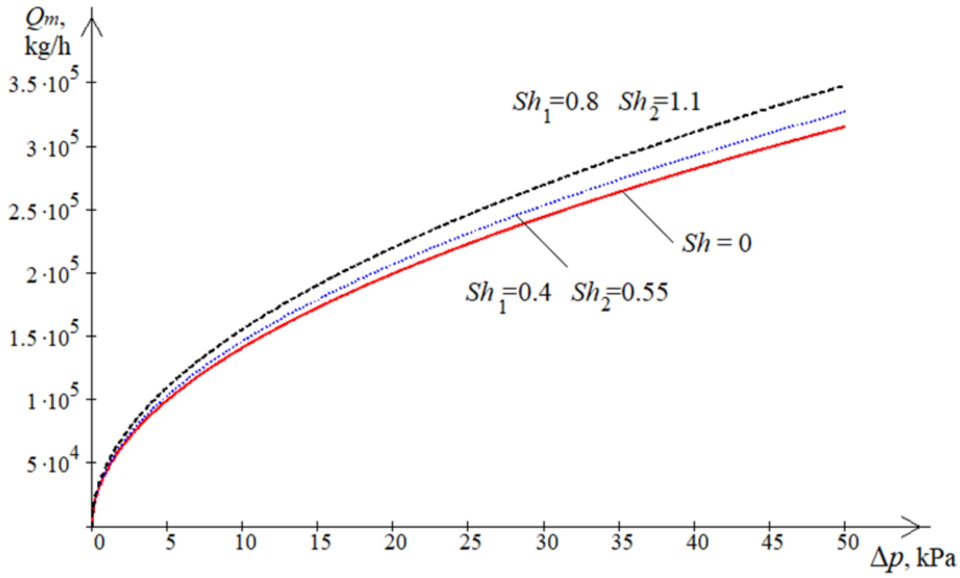

Figure 2 – Measured flow rate under different water flow conditions

Let's evaluate the effect of the relative diameter on the mass flow rate under the same conditions. To do this, authors will construct the dependence of the mass flow rate on the diameter ratio at certain values of the differential pressure. This dependence is shown in Figure 3.

It can be seen from the graph in Figure 3 that with an increase in the diameter ratio of the flow transducer at any values of the differential pressure, the value of the recorded flow rate decreases, on the one hand. On the other hand, a decrease in the diameter ratio leads to a sharp increase in flow through the flow meter. Therefore, to organize the measurement of the flow rate of a pulsating liquid, it is necessary to select the optimal ratio between the recorded flow rate and the diameter ratio.

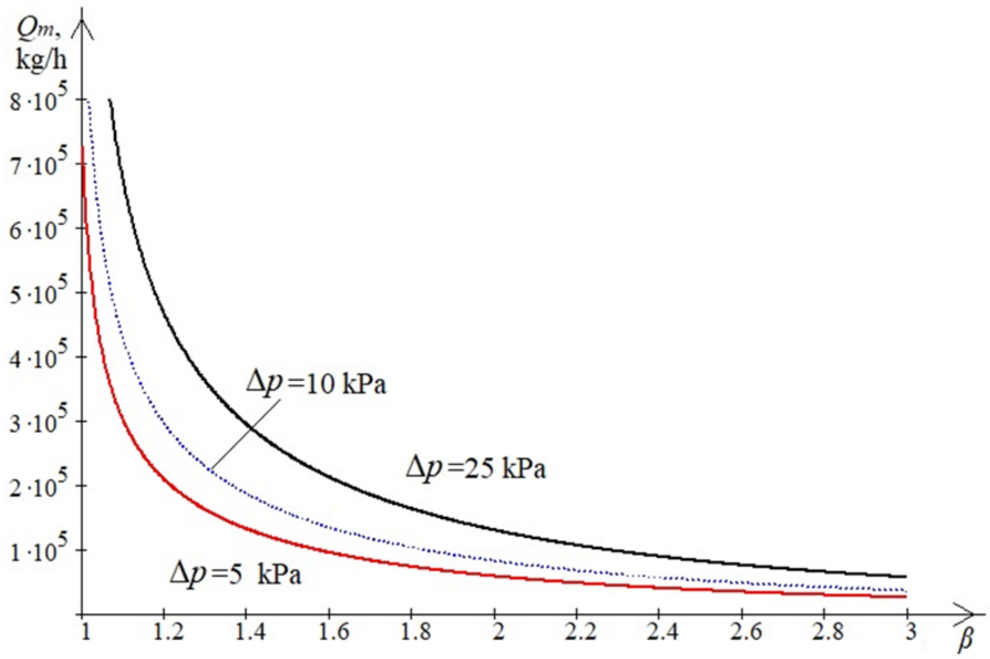

Figure 3 – Dependence of the mass flow rate on the diameter ratio of the transducer

The difference in the Struhal numbers in different sections, characterized by a difference in pressure pulsations, is confirmed by research in [21]. Therefore, this will allow to construct dependencies for measuring the mass flow rate of a liquid on the Struhal numbers in the maximum cross section. Authors will accept the remaining parameters as constant.

Figure 4 shows the dependence of the mass flow rate on the change in the Struhal numbers, which once again demonstrates the strong influence of the pulsation frequency on the measured liquid flow rate.

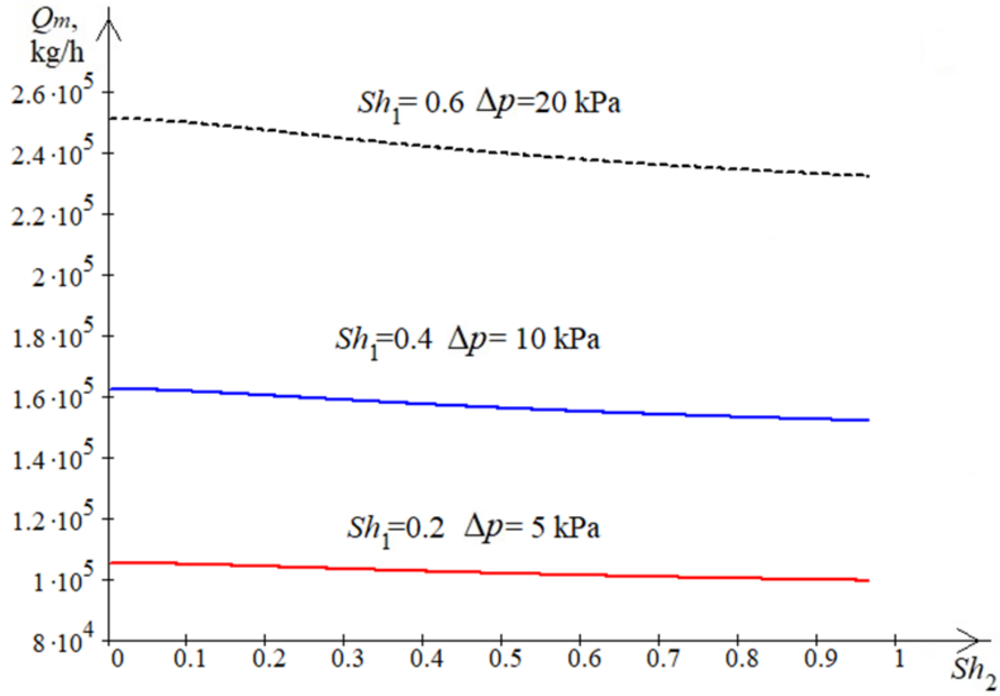

Figure 4 – Dependence of the mass flow rate on the change in the Struhal numbers

Now let's estimate how much the regimes deviate from the stationary flow at different Struhal numbers. To do this, graphs are plotted in Figure 5 that reflect the relative deviations of the mass flow rate at different values of the Struhal numbers from the flow rate in a stationary flow regime. The presence of Struhal numbers in the model leads to significant errors relative to models for stationary flow, which shows the inconsistency of using such models to describe pulsating flows. An increase in the Struhal numbers doubles the flow rate measurement error by almost three times (reaches more than 10%), as can be clearly seen from the graph.

Let's evaluate the uncertainty of measuring liquid flow rate with similar flow transducers, and determine which parameters and values affect the accuracy of measuring liquid flow rate. To obtain a model of the uncertainty of flow rate measurement in accordance with equation (6), we perform a logarithmic differentiation of the equation to move to the relative standard uncertainties of the quantities in this equation:

$$u(Q_m) = \left[\alpha_d^2 \cdot u^2(d) + \alpha_D^2 \cdot u^2(D) + \alpha_S^2 \cdot (u^2(\Delta p) + u^2(\rho)) + \alpha_{f1}^2 \cdot u^2(f_1) + \alpha_{f2}^2 \cdot u^2(f_2)\right]^{1/2}, \quad (7)$$

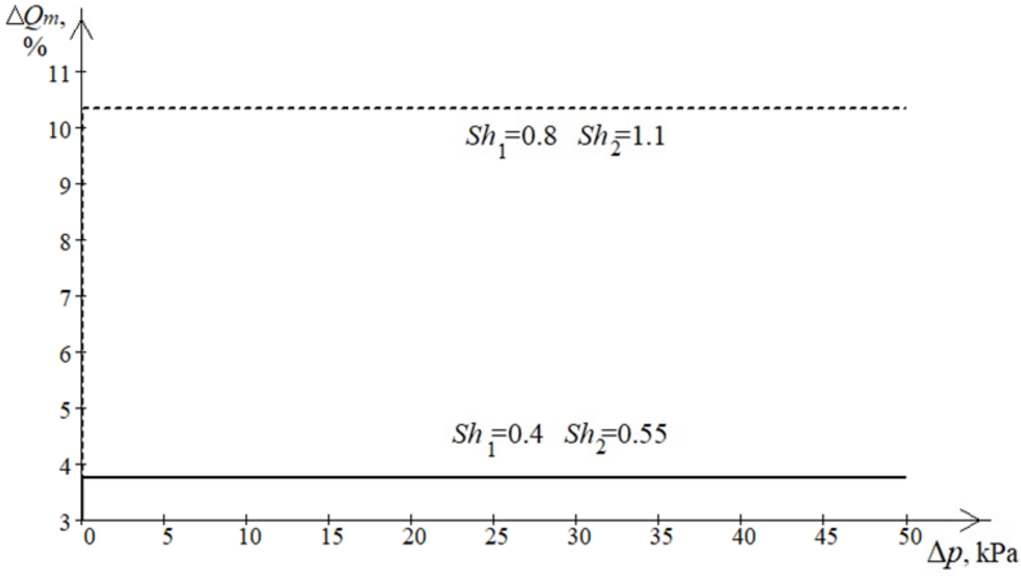

Figure 5 – Relative error of flow measurement respect to stationary mode

where $u(d)-$ the uncertainty of measuring the diameter of the flow transducer, $u(D)-$ the uncertainty of measuring the diameter of the pipeline, $u(\Delta p)-$ the uncertainty of differential pressure measurement, $u(\rho)-$ the uncertainty of density measurement, $u(f)-$ the uncertainty of frequency measurement in different sections of the flowmeter. The sensitivity coefficients in equation (7) are calculated using the following formulas:

$$\alpha_d=\frac{2-\varphi_\beta-3\varphi_{Sh2}}{1+\varphi_{Sh1}-\varphi_{Sh2}};\ \alpha_D=\frac{2+3\varphi_{Sh1}}{1+\varphi_{Sh1}-\varphi_{Sh2}};\ \alpha_S=\frac{1}{2(1+\varphi_{Sh1}-\varphi_{Sh2})};\ \alpha_{f1}=\frac{\varphi_{Sh1}}{1+\varphi_{Sh1}-\varphi_{Sh2}};\ \alpha_{f2}=\frac{\varphi_{Sh2}}{1+\varphi_{Sh1}-\varphi_{Sh2}};$$

$$\varphi_\beta=\frac{2+3\varphi_{Sh1}}{\left(\frac{\beta^4(Sh_2+1)^2}{(Sh_1+1)^2}-\frac{2Sh_2+1}{2Sh_1+1}\right)(Sh_1+1)^2};$$

$$\varphi_{Sh1}=\frac{\beta^4 Sh_1(Sh_2+1)^2/(2Sh_1+1)}{{Sh_1}^2(-Sh_2-1/2)+Sh_1\left[\beta^4\left({Sh_2}^2+2Sh_2+1\right)-2Sh_2-1\right]+0.5\beta^4({Sh_2}^2+1)+(\beta^4-1)Sh_2-0.5};$$

$$\varphi_{Sh2}=\frac{{Sh_2}^2(Sh_1+1)/(2Sh_2+2)}{\beta^4(Sh_1+1){Sh_2}^2+Sh_2\left[\beta^4(2Sh_1+1)-{Sh_1}^2-2Sh_1-1\right]+\beta^4(Sh_1+0.5)-0.5\left({Sh_1}^2+1\right)-Sh_1}.$$

Let's evaluate the uncertainty of flow measurement under various influencing factors. To begin with, under the same conditions as for Figures 2 and 5, authors will construct a dependence for the uncertainty of measuring the flow rate of a liquid on the uncertainty of measuring the differential pressure.

To construct this dependence, we assume the following values to be constant: $u(d)=u(D)=0.01\%$, $u(\rho)=0.05\%$, $u(f)=0.05\%$, $D=100$ mm. This dependence is constructed for two different values of the diameter ratio. As can be seen from Figure 6, as the uncertainty of measuring the differential pressure increases, the uncertainty of measuring the flow rate of liquid increases non-linearly. It can also be seen from this figure that a change in the diameter ratio of the flow transducer does not have a significant effect on the final uncertainty of the flow rate measurement.

The next important value in this model is the oscillation frequency, which affects the formation of Struhal numbers in various sections of the flowmeter. It must necessarily be measured before the flow transducer, and directly in it, in the maximum diameter of the flow transducer. Under similar conditions, authors will construct a dependence for the uncertainty of flow rate measurement on the uncertainty of measuring the frequency of flow pulsation. This dependence is also shown in Figure 7 for different diameter ratios.

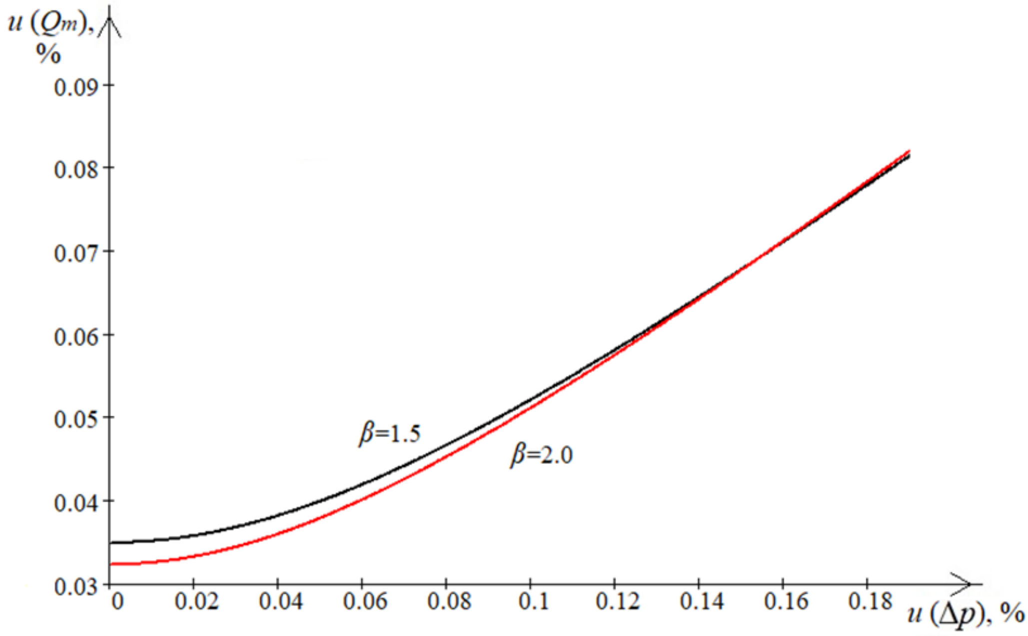

Figure 6 – The dependence of the uncertainty of the flow rate measurement on the uncertainty of the differential pressure measurement

It can be seen from Figure 7 that the uncertainty of flow rate measurement also depends non-linearly on the uncertainty of frequency measurement. The use of more crude frequency measurement sensors, i.e., with an increase in the uncertainty of measuring the frequency of pulsations, will lead to an increase in the uncertainty of measuring the flow rate. It also follows from the figure that an increase in the diameter ratio over a given range of frequency measurement uncertainties results in a slight decrease in flow rate measurement uncertainty.

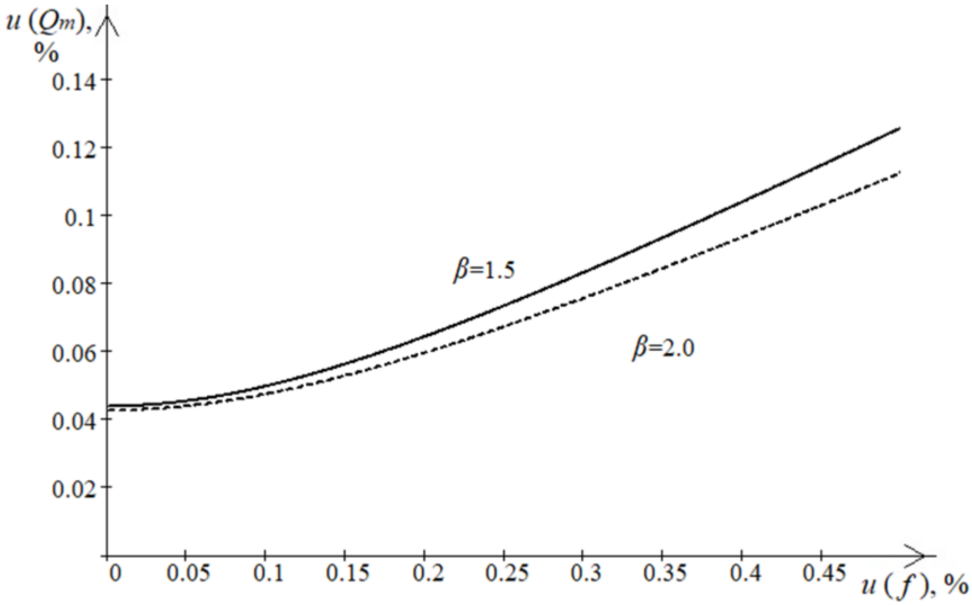

Figure 7 – Dependence of the uncertainty of the flow rate measurement on the uncertainty of the pulsation frequency measurement

The analysis of the influence of various factors on the uncertainty of liquid flow rate measurement shows that the accuracy of a flowmeter with an expanding flow transducer is influenced by the errors of the sensors that are used as part of the measuring system. The diameter ratio has less influence on the accuracy of the flowmeter. The choice of differential pressure sensors and frequency sensors can have a significant impact on the accuracy of flow rate measurement. Therefore, when designing such flowmeters, it is necessary to select high-class precision sensors.

In general, the paper solves the problem of modeling the flow rate measurement of a pulsating non-stationary liquid using an expanding type of flow transducer. The paper shows the fundamental possibility of implementing such flowmeters, which can be useful for measuring flow rate in conditions of unsteady incompressible fluid flow.

If authors discuss the advantages of such flowmeters in comparison with traditional flowmeters with orifice plates, then the proposed flowmeters have lower hydraulic losses. This allows for more efficient use of the flow of energy. With proper calibration and the use of sensors with sufficient accuracy, these flowmeters can provide high accuracy of flow rate measurement even in conditions of unsteady fluid flow. The shape of such flowmeters makes it possible to measure the flow rate at high flow rates and various flow modes. Flow metering systems with such flow transducers allow cleaning devices to pass through themselves, which can greatly facilitate the operation and cleaning of the system. But such flowmeters are not without disadvantages, so let's try to list the main ones for objectivity. The more complex shape of the expansion transducer can lead to higher production costs, as well as take up more space compared to traditional differential pressure flowmeters. For more accurate operation, they must be properly calibrated and installed during mounting.

Although, as with other types of flowmeters, the choice between a particular flowmeter design depends on specific requirements and the operating environment, including measurement range, operating conditions, accuracy, and the company's budget. For this case, the application of this flowmeter in conditions of unsteady and pulsating fluid flow is considered, which is an advantage compared to classical solutions for these conditions.

Conclusions

In the paper, the authors presented a paper on modeling the process of measuring the flow rate of a liquid under conditions of non-stationary and pulsating flow. The principal possibility of solving this problem using expansion flowmeters is shown. Ratios were obtained for measuring the flow rate of an incompressible fluid from the main flow factors based on solving the Euler equation. The paper evaluates the uncertainty of measuring fluid flow rate and analyzes the influencing factors on the accuracy of measuring fluid flow rate. In the future, the authors plan to expand the application of the model for compressible fluid conditions for measuring gas flow rate.

Conflicts of interest

The authors declare that there are no conflicts of interest including any financial, personal, or other relationships with other people or organizations.

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КЕҢЕЙТУ ҚҰРЫЛҒЫСЫ АРҚЫЛЫ ПУЛЬСАЦИЯЛЫҚ АҒЫНДЫ СҰЙЫҚТЫҚТЫҢ ШЫҒЫНЫН ӨЛШЕУ ПРОЦЕСІН МОДЕЛЬДЕУ

Аңдатпа

Мақалада пульсациялық сұйықтық ағынының шығынын өлшеуді жүзеге асыратын, кеңейту құрылғысы түріндегі ағын түрлендіргіші бар айнымалы қысым айырмасы негізіндегі шығын өлшегішін модельдеу нәтижелері берілген. Мақалада модельдерді сипаттау үшін негізгі модификацияланған теңдеулерді алу әдісі сипатталған және ағын түрлендіргішінің құрылымы ұсынылған. Жұмыс барасында мұндай ағынның кеңейту түрлендіргіші ретінде конустық диффузор қолданылады. Жұмыста осындай шығын өлшегіштің моделі алынды және сұйықтықтың пульсациялық ағынын өлшеу процесіне әсер ететін факторлар зерттелді. Осындай түрлендіргіштің көмегімен пульсациялық ағынды өлшеу нәтижелерінің белгісіздігін бағалау процесі көрсетілген. Шығынды өлшеу дәлдігіне әсер ететін факторлар зерттелді.

Тірек сөздер: пульсациялық ағын, сұйықтық шығыны, модельдеу, айнымалы қысым айырмасы шығын өлшегіш, ағынның кеңейту түрлендіргіші.

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МОДЕЛИРОВАНИЕ ПРОЦЕССА ИЗМЕРЕНИЯ РАСХОДА ПУЛЬСИРУЮЩЕГО ПОТОКА ЖИДКОСТИ ЧЕРЕЗ РАСШИРЯЮЩЕЕ УСТРОЙСТВО

Аннотация

В статье представлены результаты моделирования расходомера переменного перепада давлений с преобразователем расхода в виде расширяющего устройства, который выполняет измерение расхода потока пульсирующей жидкости. В статье описан метод получения основных модифицированных уравнений для описания моделей и представлена структура преобразователя расхода. В качестве такого расширяющего преобразователя расхода в работе используется конический диффузор. В работе получена модель такого расходомера и исследованы факторы, влияющие на процесс измерения пульсирующего расхода жидкости. Дана оценка неопределенности результатов измерения пульсирующего расхода с помощью подобного преобразователя. Исследованы факторы, влияющие на точность измерения расхода.

Ключевые слова: пульсирующий поток, расход жидкости, моделирование, расходомер переменного перепада давлений, расширяющий преобразователь расхода.

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